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An investigation of the Landing Error Scoring System and clinically assessable sport-related injury risk factors

A thesis

submitted in fulfilment

of the requirements for the degree

of

Doctor of Philosophy in Health, Sport and Human Performance

at

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by

IVANA HANZLÍKOVÁ

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ABSTRACT

Background: Preventing sport-related lower-extremity injuries relies on identifying individuals at risk. The Landing Error Scoring System (LESS) is a clinical injury risk screening tool suitable for large-scale screening without expensive equipment. However, psychometric properties, influencing factors, and differences in methodological procedures reported between studies need further exploration to justify its use. Furthermore, it is debatable whether the double-leg jump-landing (DLJL) task used in the LESS is ecologically valid and reflects sport and injury-specific situations. Moreover, generalised hypermobility, the Movement-Specific Reinvestment Scale (MSRS), and dorsiflexion range of motion (ROM) have all been used to assess injury risk factors, although their influence on dynamic movements remains relatively unexplored.

Aim: To explore the LESS and other clinically assessable sport-related injury risk factors.

Methods: Two systematic reviews were undertaken: one on the psychometric properties of the LESS, and another on factors potentially influencing LESS scores. LESS outcomes between different final LESS score calculation methods, self-selected landing distance and landing distance set to 50% of body height, and *Pre* and *Post* information sessions on LESS scoring criteria and prior performance were compared using Generalised Estimating Equations, odds ratios, *t*-tests, McNemar's, and Wilcoxon signed ranks tests. To determine which jump-landing task best represented the kinematics of a sport-specific and high injury risk task (i.e., unanticipated cutting), the degree of association based on intraclass correlation coefficients (ICC) of three-dimensional whole-body kinematics and ratings of subjective difficulty between unanticipated cutting and four jump-landings were compared using Friedman tests with post-hoc Wilcoxon signed-rank tests. Spearman rank correlation coefficients were calculated to investigate the relationship between LESS, Beighton hypermobility, and MSRS scores. Furthermore, multiple regression models were used to compare three-dimensional whole-body cutting kinematics between asymptomatic hypermobile and non-hypermobile participants, and between cutting kinematics and participants' dorsiflexion ROM.

Results: The overall LESS score demonstrated good-to-excellent reliability (ICC 0.81 to 0.99) and most LESS items had moderate-to-excellent validity against three-dimensional motion analysis measurements. However, the predictive value of the LESS for non-contact lower-extremity injuries remains uncertain. Therefore, the LESS is suitable to evaluate jump-landing kinematics in a clinical setting, but more work is required to ascertain and support its use as a tool to screen for risk of injury. Sex, previous Anterior Cruciate Ligament (ACL) injury, and neuromuscular training programme significantly influenced LESS scores ($p \leq 0.042$). The final LESS score calculation method, landing distance, and knowledge of scoring criteria and prior performance altered LESS outcomes. The kinematics of the DLJL were the least associated with those of cutting (ICC 0.00 to 0.81), and rotated DLJL (ICC 0.34 to 0.81) and rotated single-leg jump-landing ($SLJL_{rot}$) kinematics (ICC 0.31 to 0.80) were the most strongly associated with cutting. Participants rated the $SLJL_{rot}$ as the most difficult task. Asymptomatic hypermobile participants and participants with greater MSRS scores did not present more high-risk movement patterns that could predispose them to ACL injury during jump-landing or cutting. However, dorsiflexion ROM may influence cutting kinematics and contribute to ACL injury risk.

Conclusion: Overall, the evidence supports using the LESS for screening of risky movement patterns linked with non-contact lower-extremity injuries. However, incorporating $SLJL_{rot}$ into the LESS may improve its predictive value for sport-related injuries. The use of clinical measures of dorsiflexion ROM may be useful in cutting sports for screening purposes, but not necessarily MSRS or asymptomatic hypermobility.

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LIST OF ABBREVIATIONS

ACC	Accident Corporation Compensation
ACL	Anterior Cruciate Ligament
CI	Confidence intervals
CMAS	Cutting Movement Assessment Score
COM	Centre of mass
DLJL	Double-leg jump-landing
$DLDJ_{rot}$	Rotated double-leg jump-landing
d_{ss}	Self-selected distance
$d_{50\%}$	Distance of 50% of body height
GEE	Generalised Estimating Equation
GJH	Generalise joint hypermobility
GRADE	Grading of Recommendations Assessment, Development and Evaluation
GRF	Ground reaction force
HREC	Human Research Ethics Committee
IC	Initial contact
ICC	Intraclass correlation coefficient
IMU	Inertial measurement unit
LESS	Lading Error Scoring System
MSRS	Movement-Specific Reinvestment Scale
NOS	Newcastle – Ottawa Quality Assessment Scale
OR	Odds ratio
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analysis

RoB 2.0	Risk of Bias in randomised trials
ROBINS-I	Risk Of Bias in Non-randomised Studies - of Interventions
ROM	Range of motion
SEM	Standard error of measurement
SD	Standard deviation
SLJL	Single-leg jump-landing
$SLJL_{rot}$	Rotated single-leg jump-landing
TIP	Team-sport Injury Prevention cycle
TRIPP	Translating Research into Injury Prevention Practice
WBLT	Weight-Bearing Lunge Test
2D	Two-dimensional
3D	Three-dimensional

RESEARCH OUTPUTS ARISING FROM THIS DOCTORAL THESIS

Published and submitted manuscripts presented in the thesis

Chapter 3

Hanzlíková, I., & Hébert-Losier, K. (2020). Is the Landing Error Scoring System reliable and valid? A systematic review. *Sports Health, 12*(2), 181-188. (Appendix A1)

Chapter 4

Hanzlíková, I., Athens, J., & Hébert-Losier, K. (2020). Factors influencing the Landing Error Scoring System: Systematic review with meta-analysis. *Journal of Sport Science and Medicine in Sport. 24*(3), 269-280. (Appendix A2)

Chapter 5

Hanzlíková, I., Athens, J., & Hébert-Losier, K. (2020). Clinical implications of Landing Error Scoring System calculation methods. *Physical Therapy in Sport, 44*, 61-66. (Appendix A3)

Chapter 6

Hanzlíková, I., & Hébert-Losier, K. (2020). Clinical implications of landing distance on Landing Error Scoring System scores. *Journal of Athletic Training.* Advance online publication. https://doi.org/10.4085/68-20

Chapter 7

Hanzlíková, I., & Hébert-Losier, K. (2020). Landing Error Scoring System scores change with knowledge of scoring criteria and prior performance. *Physical Therapy in Sport, 46*, 155-161. (Appendix A4)

Chapter 8

Hanzlíková, I., Richards, J., Athens, J., & Hébert-Losier, K. (2021). Which jump-landing task best represents lower extremity and trunk kinematics of unanticipated cutting manoeuvre? *Gait & Posture, 85,* 171-177. (Appendix A5)

Chapter 9

Hanzlíková, I., & Hébert-Losier, K. (2020). Do asymptomatic generalised hypermobility and knee hyperextension influence jump landing biomechanics? *European Journal of Physiotherapy*. Advance online publication. https://doi.org/10.1080/21679169.2020.1769721

Chapter 10

Hanzlíková, I., Richards, J., Athens, J., & Hébert-Losier, K. (2021). The influence of asymptomatic hypermobility on unanticipated cutting kinematics. *Sports Health.* Advance online publication. https://doi.org/ 10.1177/1941738121999063

Chapter 11

Hanzlíková, I., Masters, R. S. W., & Hébert-Losier, K. (2021). Propensity for conscious control of movement is unrelated to asymptomatic hypermobility or injury-risk scores. *Journal of Sport and Exercise Science*, *5*(1), 13-20. (Appendix A6)

Chapter 12

Hanzlíková, I., Richards, J., & Hébert-Losier, K. (under review). The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics.

Appendix A7

Hébert-Losier, K., **Hanzlíková, I.**, Zheng, C., Streeter, L., & Mayo, M. (2020). The 'DEEP' landing error scoring system. *Applied Sciences, 10*(3), 892-904.

Conference presentations arising from this thesis

Hanzlíková, I., & Hébert-Losier, K. (2018). *Landing Error Scoring System: Injury risk screening tool.* Presented at the Sport and Exercise Science New Zealand Annual Conference, Dunedin, New Zealand. (Poster presentation, Appendix B1).

Hébert-Losier, K., **Hanzlíková, I.**, & Beaven, C. (2018). *Comparing two Landing Error Scoring System protocols: Same but different!* Presented at the Sport and Exercise Science New Zealand Annual Conference, Dunedin, New Zealand. (Oral presentation, Appendix B2).

Hanzlíková, I., & Hébert-Losier, K. (2019). *Landing Error Scoring System calculation method can make an important difference!* Presented at the European Collage of Sport Science Congress, Prague, Czech Republic. (Poster presentation, Appendix B3).

Hébert-Losier, K., **Hanzlíková, I.**, Zheng, C., Streeter, L., & Mayo, M. (2019). *The deep Landing Error Scoring System.* Presented at the ISB/ASB Conference, Calgary, Canada. (Poster presentation, Appendix B4).

Hébert-Losier, K., & **Hanzlíková, I.** (2019). *Landing Error Scoring System (LESS) - LESS knowledge, more useful!* Presented at the ISB/ASB Conference, Calgary, Canada. (Poster presentation, Appendix B5).

Hanzlíková, I., & Hébert-Losier, K. (2019). *How to land safely!* Presented at the SPRINZ Strength & Conditioning Conference, Auckland, New Zealand. (Workshop presentation).

Hanzlíková, I., Masters, R. S., & Hébert-Losier, K. (2019). *Propensity for conscious control of movement is unrelated to hypermobility or injury-risk scores.* Presented at the Australasian Skill Acquisition Network Conference, Cambridge, New Zealand. (Oral presentation, Appendix B6).

Hanzlíková, I., & Hébert-Losier, K. (2019). *Do generalised hypermobility and knee hyperextension influence Landing Error Scoring System scores?* Presented at the Sport

and Exercise Science New Zealand Annual Conference, Palmerston North, New Zealand. (Oral presentation, Appendix B7).

Hanzlíková, I., Richards, J., & Hébert-Losier, K. (2020). *The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics.* Presented at the Sport and Exercise Science New Zealand Annual Conference, Christchurch, New Zealand. (Oral presentation, Appendix B8).

CHAPTER 1:

General introduction

1.1 Introduction

Sport and physical activity have many health benefits, hence encouraging physical activity participation is a public health priority (Kohl et al., 2012; Warburton & Bredin, 2017). However, increased participation in physical activities increases the likelihood of sustaining sport-related injuries, which can lead to disability, kinesiophobia, limited mobility, and potentially inactivity (Finch & Owen, 2001; Tiirikainen, Lounamaa, Paavola, Kumpula, & Parkkari, 2008). Therefore, physical activity promotion requires strong injury prevention initiatives.

Lower-extremity injuries account for more than half of the injuries in sport and result from either contact or non-contact mechanisms (Hootman, Dick, & Agel, 2007). Contact injuries are challenging to predict and prevent due to the external mechanisms involved. In contrast, non-contact lower-extremity injuries are often associated with biomechanical and neuromuscular risk factors, both of which are potentially modifiable through preventive programmes (Emery, Roy, Whittaker, Nettel-Aguirre, & Van Mechelen, 2015; Parkkari et al., 2011; Webster & Hewett, 2018). The identification of athletes with poor movement control and high-risk biomechanical features who would benefit from injury prevention programmes is one approach to injury prevention.

Poor biomechanical control can be identified with three-dimensional (3D) motion analysis, which provides reliable and accurate measures to quantify human movement. Three-dimensional motion analysis is considered the “gold standard” tool for quantifying human movement non-invasively (van der Kruk & Reijne, 2018). However, 3D motion analysis requires a considerable financial outlay as well as time and space to perform the analysis, which limits its practical application and use for large-scale screening of injury risk factors in physically active individuals. The use of two-dimensional (2D) approaches using standard video cameras is a more viable option for large-scale screening in sport. Studies comparing 2D to 3D motion analysis report adequate consistency, validity (Maykut, Taylor-Haas, Paterno, DiCesare, & Ford, 2015; McLean et al., 2005b; Willson & Davis, 2008), and reliability (Munro, Herrington, & Carolan, 2012) of 2D systems for quantifying kinematics, although some systematic differences exist between methods.

The Landing Error Scoring System (LESS) is one clinical assessment tool where 2D video cameras are used to assess injury risk (Padua et al., 2009). The LESS is a 17-item clinical-based assessment that relies on the use of two standard video cameras, one placed to capture motion in the frontal plane (i.e., front view) and the other to capture motion in the sagittal plane (i.e., side view). The LESS was designed to identify participants displaying potentially high-risk biomechanical patterns for Anterior Cruciate Ligament (ACL) injury during a double-leg jump-landing task in a clinical or field setting. The double-leg jump-landing task used during LESS assessment (Figure 1) requires participants to jump horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately jump upward for maximal vertical height (Padua et al., 2009).

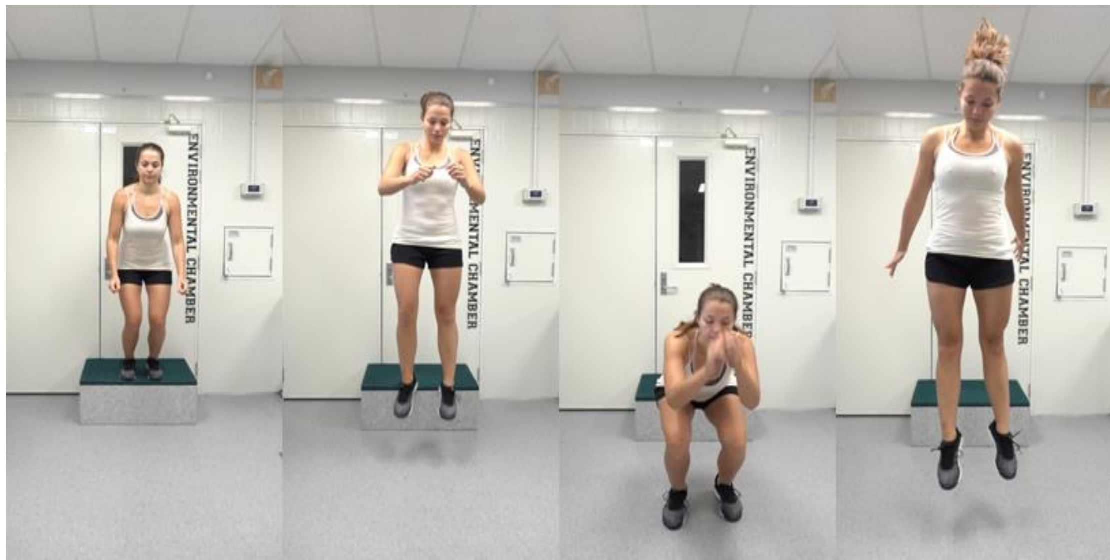


Figure 1. The jump-landing task used in the Landing Error Scoring System.

Clinicians evaluate the frontal and sagittal plane videos from the LESS, visually evaluate aberrant lower-extremity and trunk kinematics at initial ground contact and peak knee flexion, and note the number of "movement errors" observed. A subjective assessment of the quality of movement between initial contact and peak knee flexion is also considered in LESS performance. Movement items 1 to 15 are scored as 0 (error absent) and 1 (error present). The assessment of the frontal plane includes knee valgus, stance width, foot rotation, lateral trunk movement, and foot contact symmetry (Table 1). The assessment of the sagittal plane includes trunk flexion, hip flexion, and knee flexion at initial contact, ankle plantar flexion at initial contact, and displacement of the trunk, hip, and knee joint during landing (Table 1). The last two items (16 and 17) of the LESS are subjective in nature and assess the overall sagittal plane displacement and

quality of landing, which are scored from 0 to 2 errors: 0 for a soft/excellent landing, 1 for an average displacement and landing, and 2 for a stiff/poor landing (Table 1). The minimum LESS score is 0 and the maximum score is hypothetically 19 errors, but it is unlikely to have a wide and narrow stance (items 7, 8) and an internal and external foot rotation (items 9, 10) at the same time. As such, a more realistic maximum score for the LESS is 17 errors, with a higher score indicating a greater number of landing errors and poorer landing biomechanics.

The LESS is frequently used in research, clinical practice, and sporting environments to: identify athletes at high-risk of injuries (Beese, Joy, Switzler, & Hicks-Little, 2015; Smith et al., 2012a); monitor changes in landing biomechanics (Bell, Pennuto, & Trigsted, 2016; Bell, Smith, Pennuto, Stiffler, & Olson, 2014; Distefano et al., 2013a); characterise the relationship between injury risk factors (Mohammadi, Shojaadin, Letafatkar, Ebrahimi, & Eslami, 2017; Stiffler, Pennuto, Smith, Olson, & Bell, 2015); and establish the effects of injury prevention programmes (DiStefano et al., 2016; Padua et al., 2012). It is essential that testing methods provide outcomes that are reproducible and valid so that changes in scores reflect meaningful changes in function of individuals and identify individuals with differing abilities. Therefore, it is necessary to understand the psychometric properties of the LESS and potential factors which can influence the LESS scores. Furthermore, differences in the methodological procedures reported between studies using the LESS are apparent. For instance, studies have used different final LESS score calculation methods (Garbenytė-Apolinskienė, Šiupšinskas, Salatkaitė, Gudas, & Radvila, 2018; Kraus, Schütz, & Doyscher, 2019; O'Malley, Murphy, Persson, Gissane, & Blake, 2017; Onate, Cortes, Welch, & Van Lunen, 2010) and different jump distances (Distefano et al., 2013a; Onate et al., 2010). Moreover, some clinicians explain LESS items and give feedback on individuals' landing technique after the LESS test. However, the influence of knowledge of the LESS scoring criteria and of one's performance on LESS outcomes is unknown. These differences in the methodological procedures of the LESS need to be explored to ensure that outcomes from assessments are reproducible and comparable between studies to improve healthcare management and scientific inference.

Table 1. Landing Error Scoring System (LESS) operational definitions of errors. Adapted from Padua et al. (2009).

Item	Definition of error	Score
1.	Knee flexion < 30°	0 or 1
2.	Thigh is in line with the trunk (hips not flexed)	0 or 1
3.	Trunk is vertical or extended at the hips (i.e., not flexed)	0 or 1
4.	Heel-to-toe or flat-foot landing at initial contact	0 or 1
5.	Centre of the patella is medial to the midfoot at initial contact.	0 or 1
6.	Midline of the trunk is flexed to the left or the right side of the body at initial contact	0 or 1
7.	Feet are positioned greater than shoulder width apart (acromion processes) at initial contact	0 or 1
8.	Feet are positioned less than shoulder width apart (acromion processes) at initial contact	0 or 1
9.	Foot is externally rotated more than 30° between initial contact and maximum knee flexion	0 or 1
10.	Foot is internally rotated more than 30° between initial contact and maximum knee flexion	0 or 1
11.	One foot lands before the other foot or 1 foot lands heel to toe and the other foot lands toe to heel	0 or 1
12.	Knee flexes less than 45° between initial contact and maximum knee flexion	0 or 1
13.	Thigh does not flex more on the trunk between initial contact and maximum knee flexion	0 or 1
14.	Trunk does not flex more between initial contact and maximum knee flexion	0 or 1
15.	At the point of maximum medial knee position, the centre of the patella is medial to the midfoot	0 or 1
16.	Joint displacement: *Soft (0), Average (1), Stiff (2)*	0 or 1 or 2
17.	Overall impression: *Excellent (0), Average (1), Poor (2)*	0 or 1 or 2

The LESS examines landing during a double-leg jump-landing task (Figure 1). Even though this task is frequently used in the literature (Cortes et al., 2007; Delahunt, Monaghan, & Caulfield, 2006; Herrington & Munro, 2010; Hewett et al., 2005; Kernozek & Ragan, 2008; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005), it has several disadvantages. The most important disadvantage is that this movement does not have realistic representation in sports that have the highest rate of overall lower-extremity injury, where non-contact injuries represent between 20 to 40% (Hootman et al., 2007). These sports include American football, soccer, netball, volleyball, and basketball where it is common to land on one leg and injuries often involve complex movements, such as side-cutting, pivoting, or cross-cutting (Hootman et al., 2007; Kobayashi et al., 2010). Krosshaug et al. (2016) criticised the double-leg jump-landing task, advancing that it is a poor screening method to predict ACL injury in sports as it is not challenging enough or reflective of common sport movements. The authors of the LESS admitted that some elements connected with non-contact ACL injury mechanisms are not present in the double-leg jump-landing task (Padua et al., 2009). Compared to the double-leg jump-landing task, cutting manoeuvres show six times greater knee valgus moments (Kristianslund & Krosshaug, 2013), which predispose athletes to non-contact ACL injuries (Dallinga, Benjaminse, & Lemmink, 2012; Hewett et al., 2005). Also, pivoting tasks present significantly greater knee valgus angles and loading at initial contact than cutting and jump-landing tasks (Cortes, Onate, & Van Lunen, 2011; Herrington & Munro, 2010). Therefore, there appears to be a need for injury screening methods to be further representative of sport-related and injury-related tasks, such as side-step cutting, whilst keeping the task viable for large-scale screening. Incorporating single-leg landing and rotational movements may offer an alternative to the double-leg jump-landing used in the LESS assessment. All of the mentioned aspects of the LESS are explored in this thesis (Figure 2).

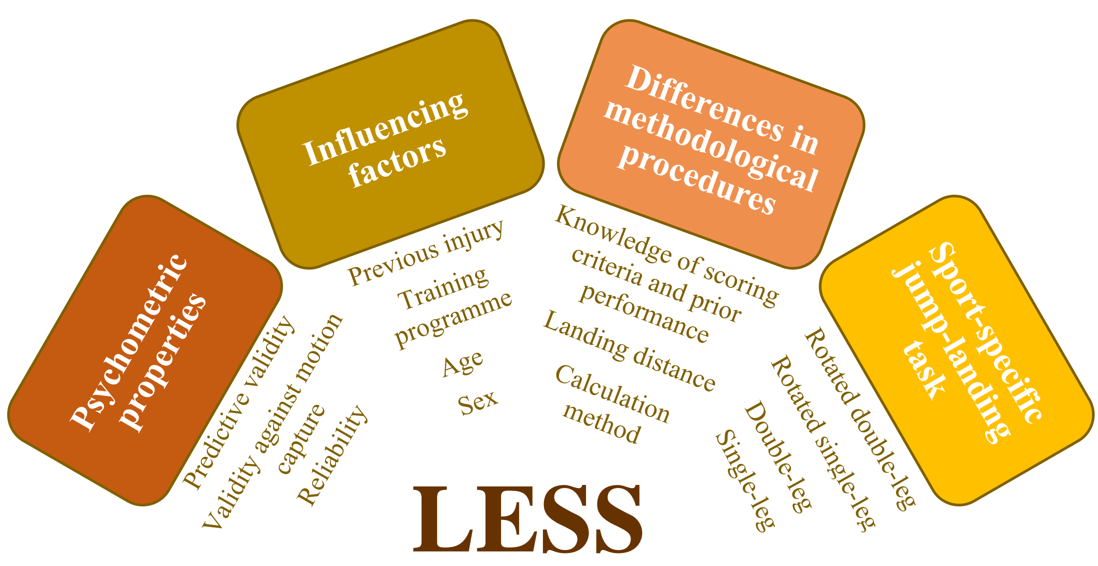


Figure 2. Aspects of the Landing Error Scoring System (LESS) explored in this thesis.

The LESS is a clinical screening tool identifying poor movement control during landing. Other clinically assessable factors that have been identified as indicators of higher injury rates in sport include generalised hypermobility (Pacey, Nicholson, Adams, Munn, & Munns, 2010), movement-specific reinvestment (Masters & Maxwell, 2008), and ankle range of motion (ROM) into dorsiflexion (Fong, Blackburn, Norcross, McGrath, & Padua, 2011).

Generalised joint hypermobility is a condition characterised by increased movement in multiple joints beyond normal ranges expected in a given population (Castori et al., 2017). Based on a review that includes different ethnic groups and populations, the overall prevalence of generalised joint hypermobility is reported to be between 10 to 20% (Remvig, Jensen, & Ward, 2007b). The scientific literature has identified generalised hypermobility as an important risk factor for knee injuries (Dallinga et al., 2012; Donaldson, 2012; Pacey et al., 2010), including to the ACL (Goshima, Kitaoka, Nakase, & Tsuchiya, 2014; Sundemo et al., 2019). Two prospective studies have demonstrated increased risk of ACL injury with increased hypermobility of the knee joint specifically (Hewett, Myer, Ford, & Succop, 2006b; Myer, Ford, Paterno, Nick, & Hewett, 2008b). Studies have shown that generalised joint hypermobility may affect movement; for example, hypermobile individuals

demonstrate altered movement patterns during stair climbing (Luder et al., 2015) and gait (Fatoye, Palmer, Van der Linden, Rowe, & Macmillan, 2011; Galli et al., 2011; Rombaut et al., 2011; Simonsen et al., 2012) compared to non-hypermobile individuals. However, most published studies have explored movement patterns in symptomatic hypermobile individuals or individuals with inherited well-defined disorders, and there is currently a lack of evidence concerning the asymptomatic hypermobile population (Fatoye et al., 2011; Galli et al., 2011; Rombaut et al., 2011). Furthermore, studies involving hypermobile individuals typically do not explore more dynamic and demanding tasks associated with higher injury risk in the sport environment (Wetters, Weber, Wuerz, Schub, & Mandelbaum, 2016). Therefore, the identification of movement patterns specific to asymptomatic hypermobile individuals during jump-landing and side-step cutting manoeuvres could facilitate the development and implementation of targeted recommendations, exercises, and injury prevention programmes for this population.

The theory of reinvestment proposes that consciously controlling and monitoring one's own movements can constrain or inhibit more effective automatic control processes, which can potentially lead to movement disruption (Masters & Maxwell, 2008). The Movement-Specific Reinvestment Scale is a valid and reliable measure of the propensity for conscious involvement in movement (Masters, Eves, & Maxwell, 2005; Wong, Masters, Maxwell, & Abernethy, 2008). The Movement-Specific Reinvestment Scale has been associated with greater movement error under psychological pressure in sport (Maxwell, Masters, & Poolton, 2006), higher fall incidence in older adults (Wong et al., 2008), more severe functional impairment after stroke (Orrell, Masters, & Eves, 2009), and greater self-reported knee pain (Selfe et al., 2015). However, the association between the Movement-Specific Reinvestment Scale and jump-landing biomechanical control has not been studied to date and may be an important injury risk factor to consider.

Ankle dorsiflexion ROM plays a prominent role in landing biomechanics and technique (Fong et al., 2011; Hoch, Farwell, Gaven, & Weinhandl, 2015; Mason-Mackay, Whatman, & Reid, 2017). Previous studies have concluded that limited passive dorsiflexion ROM is related to lower ankle, knee, and hip sagittal plane displacement and greater ground reaction forces during single-leg and double-leg landings (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017). The

magnitude of the ground reaction forces during landing has been strongly associated with impact stresses on the body structures and is a risk factor for lower-extremity injuries, in particular to the ACL (Leppänen et al., 2017; Podraza & White, 2010). Therefore, limited dorsiflexion ROM is considered to contribute to lower-extremity injury during landing (Mason-Mackay et al., 2017). However, it is currently unknown whether dorsiflexion ROM is associated with specific movement patterns that may predispose individuals to non-contact lower-extremity injuries during side-step cutting manoeuvres, which are common in sports with the highest incidence of ankle and knee injuries (Hootman et al., 2007; Kobayashi et al., 2010).

All of these factors may contribute to greater risk of sport-related injuries. However, their association with jump-landing and/or sport-related side-step cutting movement patterns have not been fully explored (Figure 3).

Figure 3. Clinically assessable injury risk factors explored in this thesis.

1.2 Thesis aims

Preventing injuries while maintaining an active lifestyle limits the negative impacts of injuries on individuals and societies, while optimising health-enhancing benefits of physical activity. The prevention of sport-related lower-extremity injury occurrence relies largely on identifying individuals at high risk of injuries. Sport and health

professionals involved in the training and care of sport teams are in close contact with athletes and have the opportunity to assess and influence their injury risk. Most of the current methods of screening for lower-extremity risky movement patterns are expensive, time-consuming, undertaken by experts, and generally inaccessible outside of elite sports. Valid and reliable clinical tests could increase accessibility of injury risk assessment methods beyond elite athletes and decrease the overall prevalence of sport-related injuries. The LESS is a convenient clinical injury risk screening tool suitable for large-scale screening without expensive laboratory equipment. However, some aspects of the LESS need to be explored to justify its common use. Furthermore, several risk factors identified in the scientific literature are easily assessable in clinical and sport environments, although their influence on sport-specific or dynamic tasks are largely unexplored. Therefore, the overall purpose of this thesis is to assist healthcare and sport professionals to understand and assess their athletes' sport-related injury risk factors using clinically implementable tests. There are four sections to this thesis to address four overarching aims:

- Explore the psychometric properties and influencing factors of the LESS.
- Examine differences in the methodological procedures reported between studies using the LESS and their influence on LESS outcomes.
- Identify a more sport and injury-specific task than the double-leg jump-landing task currently used in the LESS to inform screening practices.
- Investigate asymptomatic hypermobility, movement-specific reinvestment, and dorsiflexion ROM and their influence on jump-landing and/or side-step cutting movement patterns.

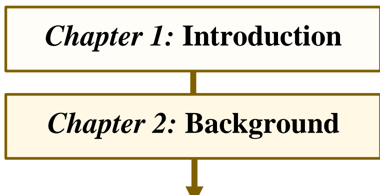
The series of studies within this thesis aims to increase our understanding of the LESS, clinically assessable lower-extremity injury risk factors, and their associations to sport-related tasks to inform injury prevention efforts. Furthermore, the results of this thesis should help to develop a more effective clinical screening tool for sport-related injury risks.

1.3 Thesis structure

The thesis comprises thirteen chapters divided into four sections (Figure 4). Chapters 1 and 2 provide the introduction and background to the thesis. Sections 1 to 3 address

several aspects of the LESS. Specifically, Section 1 consists of two literature reviews (Chapters 3 and 4) that aim to systematically review and critically appraise the literature concerning the psychometric properties of the LESS and factors which can influence LESS scores. Section 2 contains three chapters (Chapters 5 to 7), which explore the differences in the methodological procedures reported between studies using the LESS and their potential influence on LESS outcomes. Section 3 consists of one chapter (Chapter 8) and identifies a jump-landing task variation which best represents kinematics of unanticipated side-step cutting with a premise to incorporate a more injury and sport-specific task in the LESS testing to improve its ecological validity. The last section (Section 4) addresses other clinically assessable injury risk factors. Specifically, Section 4 contains four chapters (Chapter 9 to 12) and explores the influence of three injury risk factors (generalised hypermobility, movement-specific reinvestment, and ankle dorsiflexion range of motion) on landing and/or side-step cutting biomechanics. The final chapter (Chapter 13) summarises the key findings of the thesis and discusses the limitations and implications for future research.

All chapters except Chapter 1, Chapter 2, and Chapter 13 are standalone pieces of research work. These pieces of work include systematic literature reviews and cross-sectional studies that are either published, accepted, or currently under peer-review. Therefore, these chapters incorporate the journal format. Chapter 3 to 12 begin with a prelude to explain the rationale for the study and how each chapter is linked to the larger narrative. To assist in consistency and readability, a single reference list is presented at the end of the thesis.



Section 1: Literature reviews

- *Chapter 3:* Is the Landing Error Scoring System reliable and valid? A systematic review
- *Chapter 4:* Factors influencing the Landing Error Scoring System: Systematic review with meta-analysis

Section 2: Differences in the LESS methodological procedures

- *Chapter 5:* Clinical implications of Landing Error Scoring System calculation methods
- *Chapter 6:* Clinical implications of landing distance on Landing Error Scoring System scores
- *Chapter 7:* Landing Error Scoring System scores change with knowledge of scoring criteria and prior performance

Section 3: Sport and injury-specific jump-landing task

- *Chapter 8:* Which jump-landing task best represents lower extremity and trunk kinematics of unanticipated cutting manoeuvre?

Section 4: Clinically assessable injury risk factors

- *Chapter 9:* Do asymptomatic generalised hypermobility and knee hyperextension influence jump-landing biomechanics?
- *Chapter 10:* The influence of asymptomatic hypermobility on unanticipated cutting kinematics
- *Chapter 11:* Propensity for conscious control of movement is unrelated to asymptomatic hypermobility or injury-risk scores
- *Chapter 12:* The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics

Figure 4. Thesis structure. LESS, Landing Error Scoring System.

CHAPTER 2:

Background

2.1 Prevalence and burden of sport-related injuries

In New Zealand, the total cost of sport-related injuries to the Accident Corporation Compensation (ACC) is increasing and the number of claims is still high despite injury prevention efforts (Figure 5 and Figure 6). The mean cost per sporting injury claim has increased from 7,206 NZD (2002-2007) to 8,248 NZD (2012-2016), which is 12% greater than the rate of inflation over the same period of time (King et al., 2018). Sport-related injuries are also common in other countries. The highest prevalence of injuries across 35 countries are in adolescents (Pickett et al., 2005), with the annual incidence of medically treated sporting injuries estimated to be 30 injuries per 100 youths (Emery & Tyreman, 2009). In the United States of America, 5,013 athletes participating in 12 different sports resulted in 10 million USD in direct medical costs per year from sport-related injuries (Knowles et al., 2007).

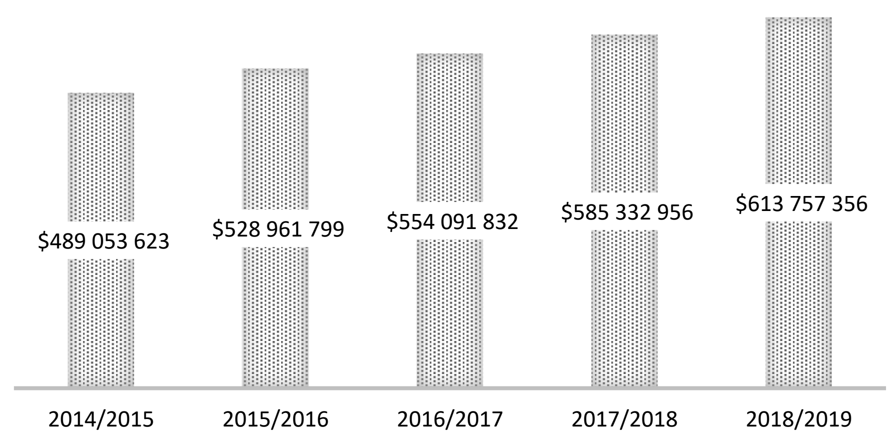


Figure 5. Total cost of sport-related injuries in New Zealand across the last five fiscal years (ACC Analytics & Reporting, 2020).

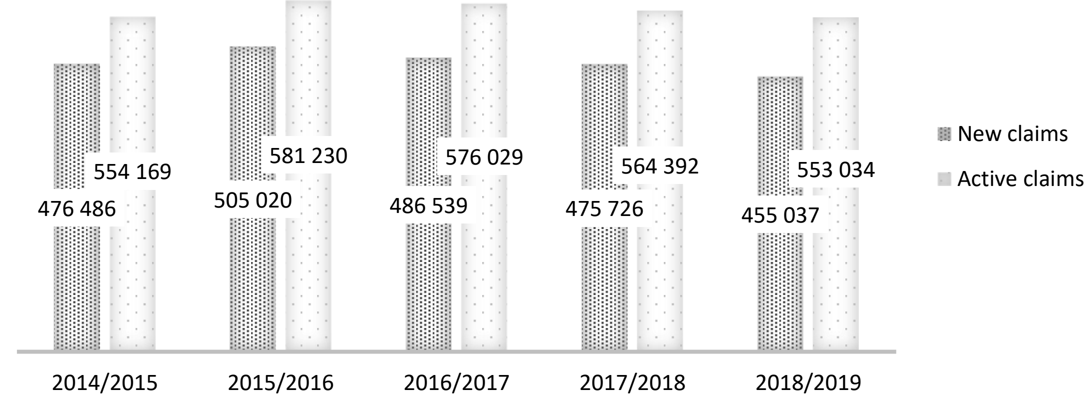


Figure 6. Number of sport-related injuries in New Zealand across the last five fiscal years (ACC Analytics & Reporting, 2020).

Lower-extremity injuries account for 50% of all sport injuries, with the ankle and knee being the most commonly injured sites (Hootman et al., 2007). Ankle injuries are the most frequent injuries of the musculoskeletal system (Fong, Hong, Chan, Yung, & Chan, 2007). From 1,076 elite collegiate athletes in the United States of America, 27% sustained foot and ankle injuries over a two-year period (Hunt et al., 2017). In female elite sports, the greatest number of foot and ankle injuries were seen in cross-country running, gymnastics, soccer, and basketball (Hunt et al., 2017; Nelson, Collins, Yard, Fields, & Comstock, 2007); whereas for males, the greatest number of injuries were seen in cross-country running, American football, rugby, soccer, and basketball (Fong et al., 2007; Hunt et al., 2017; Nelson et al., 2007). The most frequent diagnosis of foot and ankle injuries were ligament sprains with incomplete tears (83%), fractures (5%), ligament sprains with complete tears (4%), and contusions (2%) (Nelson et al., 2007). Similar to elite sports, running and soccer have been shown to have the highest incidence of foot and ankle injuries in recreationally active populations (Luciano & Lara, 2012). In New Zealand alone, the annual incidence of ankle sport-related injuries exceeds 50,900 and cost the ACC over $49M in 2019 (ACC Analytics & Reporting, 2020). The impact on individuals as well as society is even higher when one considers the loss of earnings and the negative health consequences of residual symptoms later in life. Following acute ankle sprains, up to 40% of individuals can suffer from residual symptoms (Gerber, Williams, Scoville, Arciero, & Taylor, 1998). The most common residual symptom is chronic ankle instability, which is a leading cause of post-traumatic

ankle joint osteoarthrosis (Hirose, Murakami, Minowa, Kura, & Yamashita, 2004; Valderrabano, Hintermann, Horisberger, & Fung, 2006).

The knee represents the region with the second highest sport injury rate (Hootman et al., 2007). Sports with the highest incidence of knee injuries in the United Stated of America are American football, soccer, basketball, volleyball, and gymnastics (Swenson et al., 2013). The most commonly injured knee structures are the Medial Collateral Ligament (26 to 36%), Anterior Cruciate Ligament (ACL, 23 to 25%), patella or patellar tendon (22 to 30%), torn cartilage including meniscus injury (19 to 23%), Lateral Collateral Ligament (3 to 8%), and Posterior Cruciate Ligament (2 to 3%) (Shea, Grimm, Ewing, & Aoki, 2011; Swenson et al., 2013). In 2019, sport-related knee injuries had a higher annual incidence compared to ankle injuries in New Zealand, reaching 62,716 cases and a much higher cost of 117M NZD as these often require surgical interventions and longer rehabilitation times (ACC Analytics & Reporting, 2020; Knowles et al., 2007; Rechel, Collins, & Comstock, 2011). The costs are even higher when considering that athletes following sport-related knee injuries frequently report negative health consequences, such as poorer knee function, greater risk of being overweight/obese, and early onset of post-traumatic osteoarthrosis (Ajuied et al., 2014; Badlani, Borrero, Golla, Harner, & Irrgang, 2013; Whittaker, Woodhouse, Nettel-Aguirre, & Emery, 2015).

ACL injuries are common sport-related knee injuries that occur predominantly in males aged 19 to 25 years and females aged 14 to 18 years (Sanders et al., 2016), with a three to six times greater incidence in female compared to male athletes participating in the same landing or cutting sports (Arendt, Agel, & Dick, 1999; Prodromos, Han, Rogowski, Joyce, & Shi, 2007). Over 2,774 New Zealanders suffered ACL injuries in 2019 during sporting activities, costing the ACC close to 38M NZD (ACC Analytics & Reporting, 2020), see Figure 7 and Figure 8. The costs of ACL injuries are high because the majority involve surgical reconstruction. The annual incidence rate of primary ACL surgeries in New Zealand for 2009–2016 was 58.2 per 100,000 person-year and was greater in males than in females (72.2 and 44.9, respectively) (Sutherland, Clatworthy, Fulcher, Chang, & Young, 2019). The mean treatment costs of ACL reconstruction surgery including medical treatment, income replacement, ancillary services, and rehabilitation was 11,157 NZD between years 2000 and 2005 (Gianotti, Marshall, Hume, & Bunt, 2009). In the United States of

America, there are about ¼ million new ACL injuries every year with associated lifetime costs reaching 7.6 to 17.7 billion USD (Mather III et al., 2014). Moreover, ACL injuries have devastating consequences for individuals, especially athletes and youths, as they have one of the longest return-to-sport times among sport-related injuries (Ardern, Webster, Taylor, & Feller, 2011). Due to the severity of these injuries and important functional role of the ACL, only 55% of athletes return to competitive sport levels within the first year after successful ACL reconstruction (Ardern, Taylor, Feller, & Webster, 2014). Only two in three individuals return to their preinjury sport level overall following reconstruction (Ardern et al., 2011). ACL injuries have also been reported to lead to early post-traumatic knee osteoarthrosis with associated pain and functional impairment, regardless of whether treatment is surgical or conservative, and have a high re-injury rate (Øiestad et al., 2010; Wiggins et al., 2016). Specifically, 21% of individuals younger than 25 years and 20% of individuals who return to a high-risk sports are reported to sustain a second ACL injury (Wiggins et al., 2016). Due to its prevalence, considerable cost, long disability time, and high re-injury rate, ACL injury is one of the sport injuries that has attracted considerable preventative efforts and research.

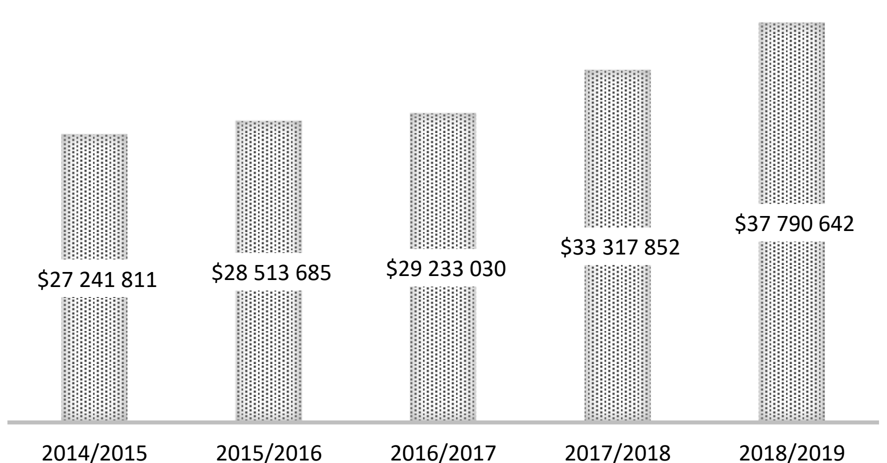


Figure 7. Total cost of sport-related Anterior Cruciate Ligament injuries in New Zealand across the last five fiscal years (ACC Analytics & Reporting, 2020).

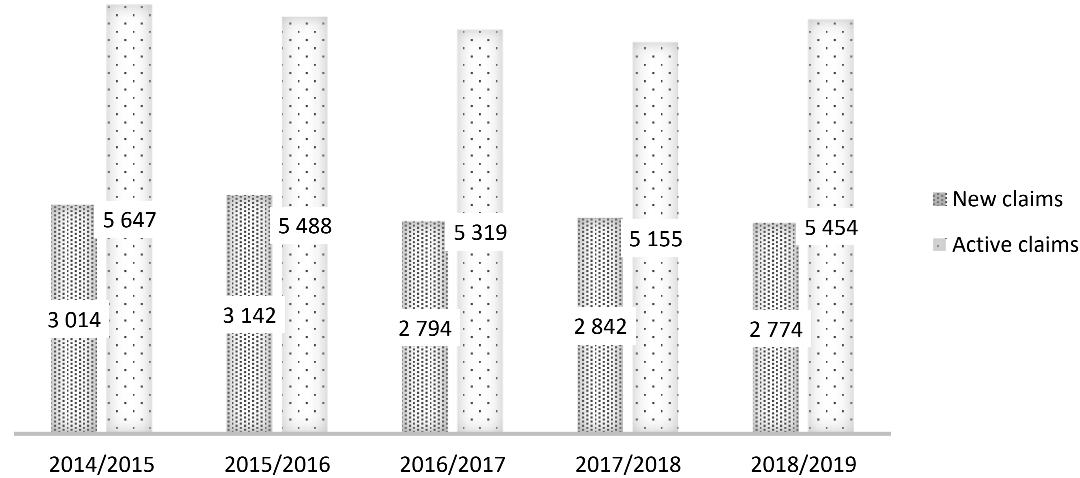


Figure 8. Number of Anterior Cruciate Ligament sport-related injuries in New Zealand across the last five fiscal years (ACC Analytics & Reporting, 2020).

2.2 Sport-related injury prevention models

Due to the severe consequences of sport-related injuries on individuals and society, several prevention models specific to sport-related injuries have been developed. One of the first recognised models of sports injury prevention was described by van Mechelen et al. (1992). The model outlined four stages: establish the extent of the problem, establish the aetiology and mechanisms of injury, introduce preventive measures, and assess their effectiveness (van Mechelen et al., 1992). In 2006, Finch proposed another sport injury prevention model: Translating Research into Injury Prevention Practice (TRIPP). The TRIPP model targets a number of limitations associated with the van Mechelen et al. (1992) four-stage model and conceptualises a series of necessary steps in building evidence-base prevention measures for implementation in a real-world context (Finch, 2006). The TRIPP has six stages (Figure 9). Stage 1 involves injury surveillance, which establishes the extent of the injury problem and provides vital information for informing all other stages; e.g., the epidemiological monitoring of injury incidence rates across regions or countries or sports, quantifying the burden of sport injury, and establishing risk of injury across different sports. Stage 2 involves establishing the aetiology of the injury. This stage corresponds to understanding the mechanisms of injury and identifying potential risks and protective factors. Stage 3 develops preventive measures, which need to be strongly guided by Stage 2. Stage 4 evaluates the efficacy by assessing preventive measures that

arise from Stage 3 under ideal conditions, i.e., laboratory testing on a small number of participants. Stage 5 involves the development and understanding of the implementation context. This stage is necessary to understand how the research outcome from Stage 4 can be translated into action and then implemented into the real world and in the field of sports. Stage 6 is the final stage, which evaluates how effective are the developed preventive measures when applied to the real-word context.

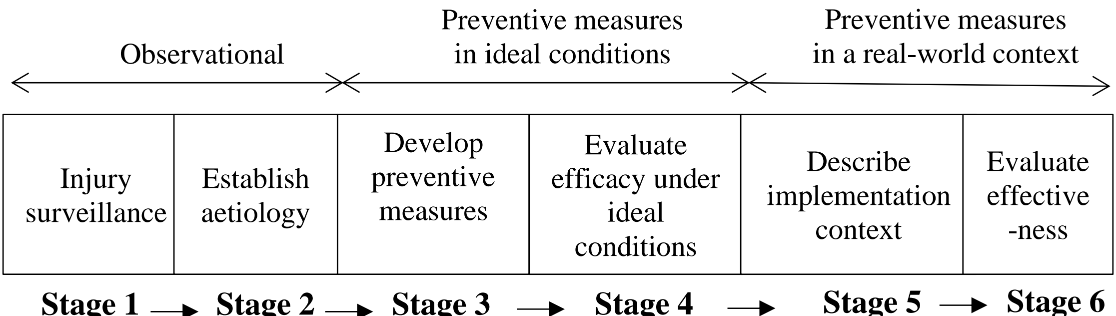


Figure 9. Translating Research into Injury Prevention Practice (adapted from Finch, 2006).

In 2019, O’Brien, Finch, Pruna, and McCall (2019) developed the Team-sport Injury Prevention cycle (TIP), which reflects an everyday injury prevention approach for sport medicine staff in professional team sports. The TIP involves three stages: (re)evaluate, identify, and intervene. The evaluation stage addresses the type, incidence, severity, and burden of injuries in the team. This stage also analyses which injury prevention strategies are currently in place and underlying rationale. The second stage explores the risk factors and mechanism of injuries identified in stage one by analysing the team’s internal data and determining how these map to the scientific literature. Furthermore, this phase also involves identifying barriers and facilitators for implementation of specific injury prevention strategies; e.g., previous experience, lack of time to implement complex prevention programmes, and lack of acceptance from players. The intervention stage plans the content and delivery of injury prevention strategies needed based on the previous stages. The implemented injury prevention strategies are (re)evaluated in the first stage against the team’s internal data. The TIP is a dynamic, cyclic process where prevention strategies are modified and there is an ongoing evaluations process (O’Brien et al., 2019).

2.3 Sport-related injury aetiology models

Understanding the aetiology of injury is required for successful injury prevention. In the basic biomechanical model according to McIntosh (2005), injury results from a transfer of energy to the tissue and the relationship between load and load tolerance determines the injury outcome of an event. The mechanical properties of human tissue, such as stiffness, ultimate strength, and critical stress, differ between tissues and govern how the body responds to mechanical load. Besides tissue properties, the characteristics of the load, velocity, magnitude of energy transferred, and frequency of repetition of the load all play a role in injury aetiology. The biomechanical injury risk factors explain how an event can either result in an excessive mechanical load, which a tissue cannot tolerate, or reduce the load tolerance levels of a tissue to a point where the tissue cannot tolerate normal mechanical loading. Injury prevention programmes based on this basic biomechanical model focus on reducing the load applied to the human body below a critical injury tolerance criteria or increasing positive adaptation of the body to improve its capacity to tolerate and react to loading (McIntosh, 2005).

Sport injuries, similar to other injuries and diseases, are typically multifactorial in aetiology. Therefore, medical, behavioural (i.e., psychological, sociological, and organisational), physiological, and biomechanical factors must be taken into account to assess the cause of injury. The multifactorial epidemiological model of Meeuwisse (1994) accounts for all of the factors involved in sport-related injury occurrence, examines the contribution of various factors to injury aetiology, and explores the relationship between them. The injury may result from a single inciting event, or from a complex interaction between internal and external risk factors (Figure 10). Internal risk factors (e.g., age, sex, body composition, health, biomechanics, skill level, anatomy, physical fitness, and psychological factors) predispose athletes to injury; however, these factors alone are rarely sufficient to cause injury. External factors (e.g., type of shoes, rules, weather, field condition, opponent behaviours, and equipment) may also predispose an athlete to injuries; but again, these factors on their own are not sufficient for injury to occur. An inciting event, such as a tackle, contact with an opponent, or slip, is typically needed to produce an injury. This model is applicable to acute as well as overuse injuries. However, acute injuries may have a smaller contribution of internal and external risk factors, with the key cause usually being an

inciting event. On the other hand, overuse injuries typically have a larger contribution of other risk factors to injury incidence (Meeuwisse, 1994).

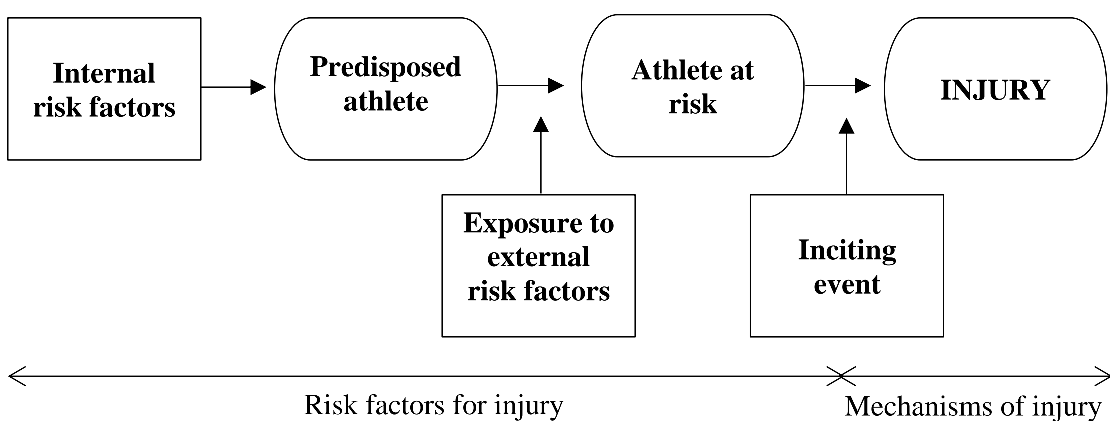


Figure 10. Multifactorial epidemiological model (adapted from Meeuwisse, 1994).

Bahr and Krosshaug (2005) argued that a comprehensive injury mechanism model should also address a precise description of the inciting event. Therefore, the events leading to the injury situation (e.g., playing situation, opponent behaviour, and description of whole-body and joint biomechanics at the time of injury) were added to the Multifactorial epidemiological model. In 2007, Meeuwisse, Tyreman, Hagel, and Emery (2007) concluded that the linear approach of the Multifactorial epidemiological model does not reflect the true nature of sport-related injury and does not account for what happens after injury. Therefore, a Dynamic model of aetiology in sport injury was developed to address these limitations (Figure 11). In addition to the previous model, the Dynamic model developed by Meeuwisse et al. (2007) includes the possibility that athletes may be exposed to potentially injurious events, but may not necessarily sustain an injury. Rather, positive or negative adaptations may occur to modify the internal and external risk factors. Furthermore, if an inciting event results in injury, recovery consisting of healing period, rehabilitation, medication, etc. will facilitate re-entry into sport participation. However, there is potential for new internal risk factors in an athlete returning to sport, such as changes in strength, neuromuscular control, kinesiophobia, as well as external risk factors, e.g., change in equipment and bracing. If the recovery from injury is inadequate or athletes decide to modify or ceases their sport participation after the injury, these athletes are removed from the model for that sport. Due to the cyclic nature of this dynamic model, there are constant changes in the risk factors

considered and an athlete can enter or re-enter the injury chain at any point (Meeuwisse et al., 2007).

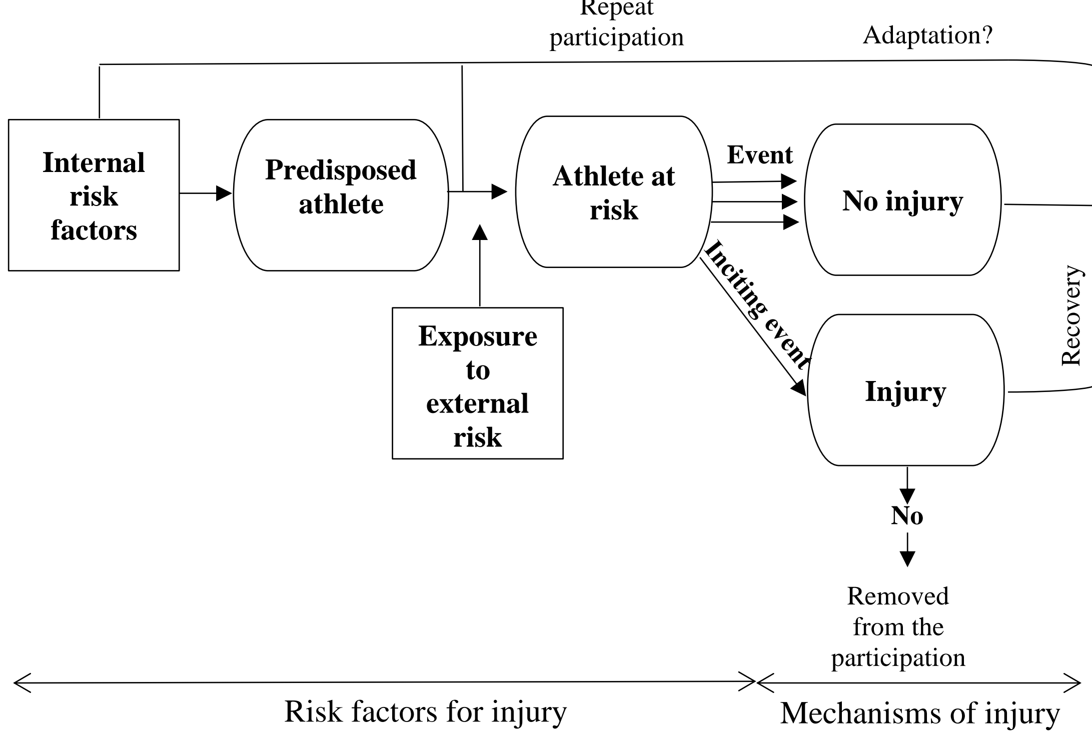


Figure 11. Dynamic model of aetiology in sport injury (adapted from Meeuwisse et al., 2007).

All the injury aetiology models mentioned facilitate a deeper understanding of injury; however, the aetiology of injury is complex, dynamic, multifactorial, and context dependent (Bittencourt et al., 2016; Windt, Zumbo, Sporer, MacDonald, & Gabbett, 2017). A complex systems approach for sport-related injuries moving from risk factors to risk pattern recognition is needed to consider the interconnected and multidirectional interactions between all factors that contribute to sport-related injuries (Bittencourt et al., 2016).

2.4 Anterior Cruciate Ligament injury

ACL injuries are acute injuries that result from either contact or non-contact mechanisms. Non-contact ACL injuries account for 70% of ACL injuries in sport, and are typically associated with landing, change of direction, or sudden deceleration (Hewett, Torg, & Boden, 2009; Kobayashi et al., 2010; Myer, Ford, Khoury, Succop, & Hewett, 2010; Wetters et al., 2016). Even though many studies exist, there is no complete understanding or agreement regarding the exact mechanisms of ACL injuries.

That said, there is a strong assumption that the mechanism of ACL injury is multiplanar, comprising of knee internal rotation, knee valgus, and anterior translational movements of the tibia (Wetters et al., 2016). Cadaver studies support a multiplanar mechanism, showing that internal rotation alone is not sufficient to cause the ACL to rupture (Dai, Herman, Liu, Garrett, & Yu, 2012). Knee valgus alone can cause ACL injury, but only when the Medial Collateral Ligament is already ruptured (Dai et al., 2012). Video analysis also supports a multiplanar mechanism, showing that valgus loading, and lateral compression of the joint generate internal rotation and anterior translation of the tibia, resulting in ACL rupture (Koga, Muneta, Bahr, Engebretsen, & Krosshaug, 2015; Montgomery et al., 2016; Olsen, Myklebust, Engebretsen, & Bahr, 2004; Waldén et al., 2015).

Various external and internal risk factors of non-contact ACL injuries have been identified in the literature, including footwear, surface, bracing, weather, age, sex, previous injury, and anatomical, genetic, cognitive, and hormonal variations (Dai et al., 2012; Smith et al., 2012b, 2012c). However, neuromuscular and biomechanical factors are often highlighted as important factors to address in the prevention of non-contact ACL injuries, as these are potentially modifiable factors through training interventions (Emery et al., 2015; Parkkari et al., 2011; Webster & Hewett, 2018). For instance, a meta-analysis of meta-analyses showed that, overall, 67% of all non-contact ACL injuries can be prevented through prevention training programmes in female athletes (Webster & Hewett, 2018). There are fewer studies exploring the effectiveness of ACL prevention programmes in male athletes, although a meta-analysis reported an 85% ACL risk reduction in male athletes following an ACL injury prevention programme (Sadoghi, von Keudell, & Vavken, 2012). A more recent prospective randomised control trial identified a 77% reduction in overall ACL injury incidence in competitive collegiate male soccer players following the FIFA 11+ prevention programme (Silvers-Granelli, Bizzini, Arundale, Mandelbaum, & Snyder-Mackler, 2017). These findings indicate that a large proportion of non-contact ACL injuries can be prevented by specific training programmes, which predominantly concentrate on movement control and technique feedback (Sugimoto et al., 2016). Identifying athletes with poor movement control and high-risk biomechanics who would benefit the most from injury prevention programmes may enhance adherence to programmes and promote targeted interventions, reducing overall cost and burden to athletes and medical staff.

2.4.1 Biomechanical risk factors in the sagittal plane

According to Newton's third law of motion, every action encounters an equal and opposite reaction. When an athlete lands or performs a cutting manoeuvre, the surface pushes back with an equal and opposite reaction force. The peak ground reaction force (GRF) is greater than the athlete's body mass due to deceleration. For example, a typical magnitude of the vertical component of the GRF during running is 1 to 3 times body weight; triple jump is 7 to 13 times body weight; and basketball rebound is 2 to 7 times body weight (Panzer, 1988).

The landing technique can influence the magnitude of the GRF (Table 2). During stiff landings, the GRF encountered during activity is primarily absorbed by anatomic (i.e., bones and cartilage) and static (i.e., ligaments) joint stabilisers rather than muscles, which stresses the involved joint structures (Boden, Torg, Knowles, & Hewett, 2009; Hewett, Ford, Hoogenboom, & Myer, 2010). A study comparing stiff and soft landings showed that during soft landings, the hip and knee joints flex about 9° more and the ankle plantarflexes about 5° more (Devita & Skelly, 1992). The muscular work performed at the hip and knee was 54% and 46% larger during soft landings, respectively, indicating that muscles surrounding these joints absorbed more impact energy compared with the stiff landing condition (Devita & Skelly, 1992). On the other hand, ankle plantar flexors performed 14% more work in the stiff than soft landing condition (Devita & Skelly, 1992). Overall, muscles absorbed 19% more kinetic energy during soft landings, reducing the overall stress on the body structures (Devita & Skelly, 1992).

Table 2. Vertical ground reaction forces for soft, normal, and stiff landings from a selection of peer-reviewed journal articles.

Author	**Landing height**	**Type of landing**	**Mean vGRF (BW)**
Dufek and Bates (1990)	40, 60, and 100 cm	Soft (max knee angle > 105°)	6.0 to 9.5
		Normal (max knee angle: 70 to 105°)	6.8 to 10.0
		Stiff (max knee angle < 70°)	9.0 to 13.3

Zhang, Bates, and Dufek (2000)	32, 62, and 103 cm	Soft (mean knee flexion angle: 77.0 ± 10.7°)	5.9
		Normal (mean knee flexion angle: 58.7 ± 9.9°)	6.7
		Stiff (mean knee flexion angle: 36.7 ±12.0°)	8.5
Self and Paine (2001)	30.5 cm	Soft (min knee flexion angle: 66.6 ± 8.3°)	4.3
		Stiff (min knee flexion angle: 48.8 ± 12.4°)	5.9
		Stiff landing on the heel (min knee flexion angle: 45.5 ± 7.7°)	6.7
Myers et al. (2011)	40 cm	Soft (mean knee ROM: 55.4 ± 8.8°)	1.6
		Stiff (mean knee ROM: 36.8 ± 11.1°)	2.6

Abbreviations: vGRF, vertical ground reaction force; BW, times body weight; max, maximal; min, minimal; ROM, range of motion.

The literature provides evidence that the magnitude of the GRF and associated peak knee flexion angles during landing are risk factors for ACL injuries (Leppänen et al., 2017). For example, greater posterior and vertical GRFs (Sell et al., 2007; Sigward, Cesar, & Havens, 2015; Sigward & Powers, 2007) and lower peak knee flexion angles (Kristianslund, Faul, Bahr, Myklebust, & Krosshaug, 2014; Weir, Alderson, Smailes, Elliott, & Donnelly, 2019) are associated with greater knee valgus moments and proximal tibia anterior shear forces; and therefore, increased loading of the ACL (Hewett et al., 2005). The association between ACL injury incidence and greater vertical GRF has also been shown in a prospective study exploring female athletes (Leppänen et al., 2017). Another prospective study conducted by Hewett et al. (2005) showed that female athletes who suffered an ACL injury had 10° less maximal knee flexion, were more prone to asymmetrical (between legs) loading, and had a 20% larger vertical GRF compared to uninjured athletes during a double-leg jump-landing task. Furthermore, the vertical GRF was significantly correlated with the knee valgus angle at initial contact (Hewett et al., 2005).

Reduced knee and hip flexion angles at initial contact do not necessarily reduce impact forces during landing (Yu, Lin, & Garrett, 2006); however, these are still important risk factors. From a biomechanical perspective, the ACL elongates in the final 30° of knee extension, suggesting that landing with extended knees may elongate

the ACL and increase injury risk (Sugimoto et al., 2015). Moreover, stiff landings have been shown to result in 23% greater peak ACL forces, which occur 10 to 20 milliseconds post initial contact and dissipate to zero by 60 milliseconds post contact (Laughlin et al., 2011). These findings indicate that the knee position close to initial contact is a critical determinant of ACL loading (Laughlin et al., 2011). Similarly, other studies have demonstrated that ACL loading increases as the knee flexion angle at initial contact decreases in several close kinetic chain movements (Fleming et al., 1999; Heijne et al., 2004).

In addition to the knee and hip position in the sagittal plane, the landing position of the foot also influences the GRF. For instance, during a basketball rebound activity, the vertical GRF for a toe-heel landing was 4 times body weight compared to 6 times body weight for a flat-foot landing (Dufek & Bates, 1991). Ankle dorsiflexion range of motion has been shown to play a prominent role in landing biomechanics and technique (Fong et al., 2011; Hoch et al., 2015). Greater ankle dorsiflexion range of motion has also been related to decreased knee valgus angles and increased hip and knee sagittal plane displacements, and lower GRFs during landing (Boden et al., 2009; Cronström, Creaby, Nae, & Ageberg, 2016; Fong et al., 2011; Hoch et al., 2015). Individuals who have sustained an ankle injury typically have limited dorsiflexion, which results in a more erect landing posture, greater GRFs, and a higher re-injury rate (Beazell et al., 2012; Gribble & Robinson, 2009; Hoch et al., 2015). In addition, limited ankle dorsiflexion has been shown to be a strong predictor of ankle sprains (de Noronha, Refshauge, Herbert, & Kilbreath, 2006), and has been linked to a higher incidence of patellar tendinopathy (Backman & Danielson, 2011).

The simultaneous flexion of the hip and knee joint also plays a key role in ACL injury. In closed-chain kinetics movements, such as landing, the vertical GRF causes the knee to flex, which in turn causes the hip to flex. This simultaneous flexion of the hip and knee assures that the tibia and femur can harmoniously roll and glide on each other without over-tensioning the ACL. If the hip flexes more slowly than the knee, the tibia undergoes anterior translation that may result in ACL injury (Dingenen et al., 2015; Hashemi et al., 2011). Disturbance in the hip and knee simultaneous flexion can happen when the trunk is upright or leaning backwards at initial contact (Dingenen et al., 2015; Hashemi et al., 2011). The upright position of the trunk causes the centre of mass (COM) to be positioned posteriorly relative to the knee joint, and encourages the

knee to flex more than the hip (Dingenen et al., 2015; Hashemi et al., 2011). Landing with an upright trunk position also decreases knee flexion angles, hip extensor moments, and plantar flexion angles, and increases peak vertical GRFs, knee valgus angles, knee valgus moments, and knee extensor moments (Nagano, Ida, Akai, & Fukubayashi, 2011; Pollard, Sigward, & Powers, 2010; Shimokochi, Ambegaonkar, Meyer, Lee, & Shultz, 2013; Shimokochi, Yong Lee, Shultz, & Schmitz, 2009). Moreoever, increased knee extensor moments are associated with increased quadriceps activation (Shimokochi et al., 2009). Contraction of the quadriceps muscles with the knee close to extension produces anterior tibial translation (DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004), increases patellar tendon loading (van Eijden, Weijs, Kouwenhoven, & Verburg, 1987), and may be a contributing factor to ACL injury, patellofemoral pain, and patellar tendinopathy (DeMorat et al., 2004; Dye, 2005; Edwards et al., 2010). There is evidence that females are more prone to being quadriceps dominant and activate their quadriceps before their hamstring muscles during landing. On the other hand, males are more prone to activate their hamstrings first, which decreases anterior tibial translation and increases the knee flexion angle (Hewett, Stroupe, Nance, & Noyes, 1996; Huston & Wojtys, 1996). Therefore, an erect trunk position during landing may contribute to ACL injury, and flexing of the trunk forward may be an appropriate technique to decrease quadriceps activation and encourage hamstrings activation to protect the ACL and other knee structures from injury (Shimokochi et al., 2009).

2.4.2 Biomechanical risk factors in the frontal plane

The COM is located in the trunk segment in upright stance and is the target of resultant GRF during most activities. The trunk contains approximately half of the body's mass; and therefore, changes in trunk position meaningfully influence COM position. Consequently, trunk control is important for moderating GRFs. For instance, lateral trunk flexion moves the COM laterally. The direction of the GRF tracks the movement of the COM, and moves laterally as well, which produces a greater lateral lever arm relative to the knee joint (Figure 12). This increased lever arm directly influences and increases knee valgus moments (Hewett & Myer, 2011). Furthermore, in reaction to lateral trunk flexion, the hip adductor moment needs to increase to maintain upright stance, which results in even greater knee valgus moments and higher strain of the ACL and the Medial Collateral Ligament (Hewett & Myer, 2011). Based on video analyses

of ACL injuries, lateral trunk movement is often coupled with knee valgus collapse (Boden et al., 2009; Ireland, 2002; Krosshaug et al., 2007; McLean, Huang, Su, & Van Den Bogert, 2004a). Moreover, positive associations between trunk lateral flexion angles and peak knee valgus moments have been described during a cutting manoeuvre (Cronström et al., 2016; Cronström et al., 2017; Dempsey et al., 2007; Jamison, Pan, & Chaudhari, 2012; Jones, Herrington, & Graham-Smith, 2015). All this research suggests that lateral trunk flexion is one factor worth considering in ACL injury mechanisms and prevention programmes.

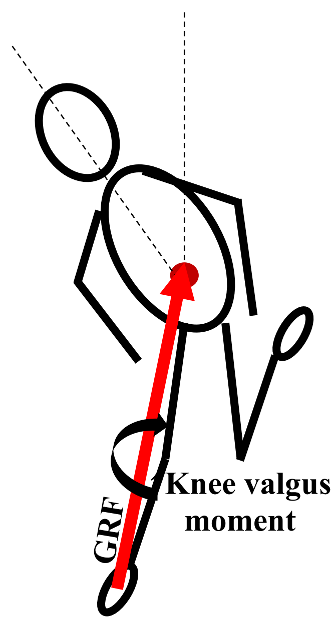


Figure 12. Impact of trunk lateral flexion on knee valgus moment.

A prospective study by Zazulak and colleagues (2007) showed that lateral trunk displacement after a sudden force release was the strongest predictor of knee ligament injuries, and specifically of ACL injuries in female athletes. Lateral trunk displacement predicted knee ligament injuries in female athletes with 100% sensitivity and 72% specificity. A history of low back pain was also a predictor of knee ligament injuries (Zazulak et al., 2007). It is well known that low back pain can result in long term trunk motor control disruption (Radebold, Cholewicki, Panjabi, & Patel, 2000; Reeves, Cholewicki, & Milner, 2005) and alterations in trunk muscle recruitment patterns (van Dieën, Selen, & Cholewicki, 2003), which are present even after full recovery and return to prior levels of competition (Cholewicki et al., 2002; Reeves, Cholewicki, & Silfies, 2006). Similar to ACL injuries, individuals with patellofemoral pain present significantly greater lateral trunk flexion angles during single-leg squats (Nakagawa,

Maciel, & Serrão, 2015; Nakagawa, Moriya, Maciel, & Serrão, 2012). Therefore, poor neuromuscular control and proprioception of the trunk and pelvis in the frontal plane can create excessive lateral movement during dynamic tasks, and has been highlighted as an important risk factor for knee injuries (Hewett et al., 2010; Hewett & Myer, 2011).

A prospective investigation has shown that female athletes who suffered an ACL rupture had 8.4° greater knee valgus angles at initial contact and 7.6° greater knee valgus angles at maximal knee flexion during a double-leg vertical drop-jump task (Hewett et al., 2005). In the same study, the knee valgus moment was 2.5 times greater in injured athletes and predicted ACL injuries with a 73% specificity and 78% sensitivity (Hewett et al., 2005). The knee valgus position during cutting manoeuvres or single-leg landings increases the lever arm of the GRF relative to the knee joint (Figure 13A), which leads to increased knee valgus moments (Hewett et al., 2010; Jones et al., 2015; Jones, Herrington, & Graham-Smith, 2016; Kristianslund et al., 2014; McLean, Huang, & van den Bogert, 2005a; McLean, Lipfert, & Van Den Bogert, 2004b). During cutting manoeuvres, a knee valgus angle of 2° can lead to an 40 Nm change in valgus moment (McLean et al., 2004b), which is a considerable amount given that knee ligament damage has been reported to occur between a knee valgus moment of 125 to 210 Nm in cadavers (Seering, Piziali, Nagel, & Schurman, 1980). Likewise, a wide lateral leg plant is a major determinant of peak knee valgus moment as it creates a GRF vector that falls lateral to the knee joint (Figure 13B) during cutting manoeuvres or single-leg landings (Dempsey et al., 2007; Havens & Sigward, 2015; Jones et al., 2015; Kristianslund et al., 2014). The wide lateral plant has also been associated with increased knee internal rotation moments during cutting manoeuvres (Dempsey et al., 2007).

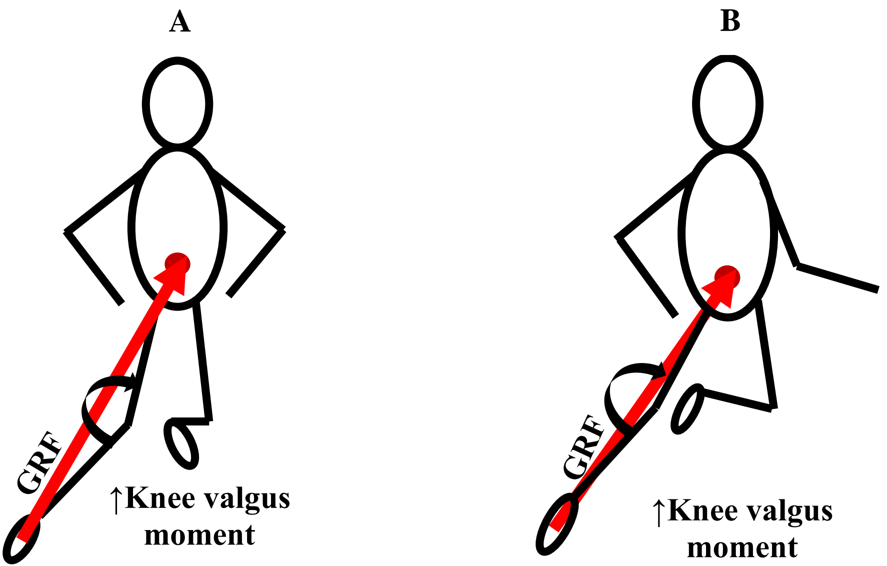


Figure 13. A) Impact of the knee valgus angle on knee valgus moment. B) Impact of wide lateral leg plant on knee valgus moment.

2.4.3 Biomechanical risk factors in the transverse plane

As described above, trunk position and control in the coronal plane can meaningfully influence knee loading. The same principles apply to trunk position and control in the transverse plane. For instance, trunk rotation angles towards the stance lower extremity have been positively associated with peak knee valgus moments during cutting manoeuvres, indicating that trunk control in the transverse plane may also contribute to knee injuries (Dempsey et al., 2007; Frank et al., 2013).

Foot position in the transverse plane may contribute to ACL injuries, with an internally rotated foot position leading to a laterally directed GRF vector relative to the knee joint. This orientation of the GRF vector can increase the moment arm and increase knee valgus moments (Dempsey et al., 2007; Jones et al., 2016; Sigward & Powers, 2007). At the same time, an external rotation of the tibia together with knee valgus can cause an impingement of the ACL against the intercondylar notch and increase ACL loading (Fung & Zhang, 2003). Furthermore, greater external rotation of the foot increases susceptibility to ankle eversion, which leads to increased knee valgus, internal rotation of the tibia, and ACL loading (Ford, Myer, Toms, & Hewett, 2005b; Loudon, Jenkins, & Loudon, 1996). Therefore, a neutral foot position is considered the safest strategy during dynamic tasks as it most likely results in forces being absorbed

in the sagittal plane, limiting transverse and coronal plane forces and movements (Jones et al., 2016).

To conclude, aetiology of non-contact injuries in sport is multifactorial in nature. When considering some of the biomechanical risk factors previously linked with ACL injury occurrence, it becomes evident that numerous factors are involved and that the entire body and kinetic chain needs consideration. Therefore, assessing a single joint or single plane of motion is insufficient. Furthermore, it is important to note that although some athletes may present with several high injury risk factors, it does not mean that they will sustain an injury. Similarly, some athletes may present with minimal to no injury risk factors and nevertheless sustain an injury.

SECTION 1

Literature reviews

Prelude: This thesis concentrates on the use of clinically implementable tests that can be used in practice and sporting environments with a premise to decrease the rate of sport-related injuries. Chapter 1 highlighted the Landing Error Scoring System (LESS) as a movement-based injury risk screening tool that is relatively easy to administer, suitable for testing large cohorts, and can be used both in clinics and in the field without expensive laboratory equipment. The LESS was developed by Padua and colleagues in 2009. Since, the LESS is a frequently used clinical tool in practice and research to evaluate 'risky' movement patterns during a double-leg jump-landing task. It is essential that testing methods used in clinics and science provide outcomes that are reproducible and valid so that changes in scores reflect meaningful changes in function at an individual-level and are able to identify individuals with differing abilities. Besides psychometric properties, understanding the factors that may influence outcomes of testing procedures is necessary for the correct interpretation of results in specific populations.

Systematic reviews of the literature use explicit and comprehensive methods to summarise the literature on a specific topic and are at the top of the hierarchy of evidence (Evans, 2003). To date, there has been no systematic evaluation of the psychometric properties of the LESS or factors that can influence LESS outcomes. Considering the common use of the LESS in research and practice, clarifying its psychometric properties and the factors affecting LESS scores is vital to ensure the most appropriate implementation and interpretation of the LESS. Such an understanding is important to inform several aspects of research and practice. Specifically, large-scale screening initiatives, the monitoring of changes in risk factors over time, determining the effects of injury prevention programmes and rehabilitation, and identifying athletes at high risk of injuries.

CHAPTER 3

Is the Landing Error Scoring System reliable and valid? A systematic review

Hanzlíková, I., & Hébert-Losier, K. (2020). Is the Landing Error Scoring System reliable and valid? A systematic review. *Sports Health, 12*(2), 181-188. (Appendix A1)

Prelude: The first literature review presented in this chapter systematically summarises the literature that addresses the psychometric properties of the Landing Error Scoring System (LESS). The aim of this chapter is to provide a comprehensive overview of studies addressing the reliability, validity against motion capture, and predictive validity of the LESS to inform clinical and scientific practice.

3.1 Introduction

Increased participation in physical activities increases the likelihood of sustaining sport-related injuries (Tiirikainen et al., 2008). Non-contact mechanisms explain approximately 18% of injuries in game situations and 37% of injuries in practice or training situations (Hootman et al., 2007). Neuromuscular and biomechanical factors are key in the prevention of non-contact injuries, as modifiable through targeted training interventions (Emery et al., 2015; Parkkari et al., 2011).

The LESS is a clinical assessment tool (Padua et al., 2009) often used in research to identify individuals at high risk of sustaining non-contact injuries and quantify changes in neuromuscular and biomechanical performance subsequent intervention across sports (DiStefano et al., 2018; DiStefano, Padua, DiStefano, & Marshall, 2009; Fox, Bonacci, McLean, & Saunders, 2017) and performance levels (Kraus et al., 2019; Scarneo et al., 2017). The LESS has also been used in participants with a history of injury (James, Ambegaonkar, Caswell, Onate, & Cortes, 2016; Lam & McLeod, 2014) and after Anterior Cruciate Ligament (ACL) reconstruction (Bell et al., 2014; Gokeler et al., 2014) to quantify residual functional impairments and outcomes from rehabilitation.

It is essential that testing methods provide outcomes that are reproducible and valid so that changes in scores reflect meaningful changes in function of individuals and identify individuals with differing abilities. In the LESS, lower scores should reflect a reduction in injury risk and high injury risk movement patterns. The LESS was previously addressed in critically appraised topics (Markbreiter, Sagon, McLeod, & Welch, 2015; Pointer, Reems, Hartley, & Hoch, 2017; Ramang, 2017) and literature reviews (Bird & Markwick, 2016; Fox, Bonacci, McLean, Spittle, & Saunders, 2016; Chimera & Warren, 2016; McCunn, aus der Fünten, Fullagar, McKeown, & Meyer, 2016; Read, Oliver, Croix, Myer, & Lloyd, 2019); however, no systematic review has critically appraised and summarised research on its psychometrics properties (reliability and validity). Such a systematic review is warranted to ensure the justified use of the LESS in large-scale screening initiatives, monitoring changes in risk factors, establishing the effects of injury prevention programs, and identifying athletes at high risk of injuries. Therefore, our aim was to systematically review and critically appraise studies addressing the psychometrics properties of the LESS.

3.2 Methods

3.2.1 Protocol and registration

Literature review methods and inclusion criteria were specified in advance and registered on PROSPERO (CRD42018107210).

3.2.2 Eligibility criteria

Studies that used the LESS as a main outcome measure and examined its reliability, validity against motion capture, and predictive validity were included for review regardless of participant, intervention, or study design characteristics. Only original research published in English in peer-reviewed (abstract available) journals were considered. Letters to the Editor, symposium publications, conference abstracts, books, expert opinions, critically appraised topics, and literature reviews were excluded. Studies using modified versions of the original LESS protocol (e.g., iLESS, real-time LESS, and automated quantification of the LESS) were excluded (Hueber, Hall, Sage, & Docherty, 2017; Mauntel et al., 2017; Schussler et al., 2014).

3.2.3 Information sources and search strategy

Three electronic databases (Figure 14) were searched using the keywords “Landing Error Scoring System” on March 28, 2018. Psychometric property terms were not included in the search strategy to favour an all-inclusive approach and avoid missing studies that addressed the reliability or validity of the LESS as part of their methodology without it being a primary aim. In addition, a hand search of the reference lists of all included studies was conducted.

3.2.4 Study selection

The electronic search was conducted by one reviewer. Duplicate hits were removed first. Titles, abstracts, and full texts were screened sequentially for inclusion and exclusion criteria. In case of uncertainty regarding inclusion, a second reviewer was consulted.

3.2.5 Data collection process

Data concerning study design, population (number, sex, age, and activity level), LESS testing procedures, LESS scores, statistical analysis, and main results were extracted from studies using a standardised template by one reviewer, with the completeness of

extraction verified by a second reviewer. The study design was reported according Parab & Bhalerao (2010). Studies were categorised into the following subcategories: reliability, validity against motion capture, and LESS predictive value for injury incidence. Four authors were contacted by email to request additional information regarding eight of the included studies. Three authors responded, with two authors providing additional data for two studies.

3.2.6 Risk of bias in individual studies

Two reviewers independently assessed the methodological quality of included studies (n = 10) using the Newcastle – Ottawa Quality Assessment Scale (NOS) adapted for cross-sectional studies (Modesti et al., 2016). Potentially identifiable information from studies was removed prior to quality appraisal to reduce assessment bias. The two reviewers achieved a consensus rating on all quality scores without the need for a third reviewer.

The NOS uses a "star system", wherein more stars indicates a superior methodological quality. The NOS adapted for cross-sectional studies awards a maximum of 10 stars: 5 for selection (representativeness of the sample, sample size, non-respondents, and ascertainment of the exposure), 2 for comparability, and 3 for outcome (assessment of outcome and statistical test). Reviewers agreed that for the statistical test item, the highest star rating would be allocated for the reporting of confidence intervals, quartiles, or limits of agreement. The methodological quality of studies was divided into three groups based on the number of stars awarded: weak (0-3 stars), moderate (4-6 stars), and strong (7-10 stars). Given that the reliability for NOS adapted for cross-sectional studies has not yet been determined, we assessed intra- and inter-rater reliability of our scores. Based on intraclass correlation coefficient (ICC) and confidence intervals values, intra-rater (ICC, 0.98; 95% CI, 0.94-0.99) and inter-rater (ICC, 0.94; 95% CI, 0.80-0.98) reliability of scores was excellent (Mukaka, 2012). Finally, the level of evidence for each study was determined using the Oxford Centre for Evidence-Based Medicine 2011 table.

3.2.7 Summary measures

Descriptive statistics were computed using Microsoft Office Excel 2016 and expressed in terms of means and SDs, minimum to maximum ranges (min to max), percentages (%), and counts (n). Weighted mean ± SD values based on sample size were computed

to describe age and LESS scores of participants across studies. ICC values were interpreted according to Koo & Li (2016) using thresholds of 0.50, 0.75, and 0.90 to indicate moderate, good, and excellent reliability, with ICCs < 0.50 indicating poor reliability. Standard error of measurement and minimal detectable change values were calculated for reliability studies when possible. Percentage of agreement between individual LESS items or categories based on LESS score (excellent, good, moderate, and poor) and three-dimensional (3D) motion capture was reported for construct validity.

3.3 Results

3.3.1 Study selection

Figure 14 illustrates the search strategy and study selection process. A total of ten studies met inclusion requirements and were reviewed.

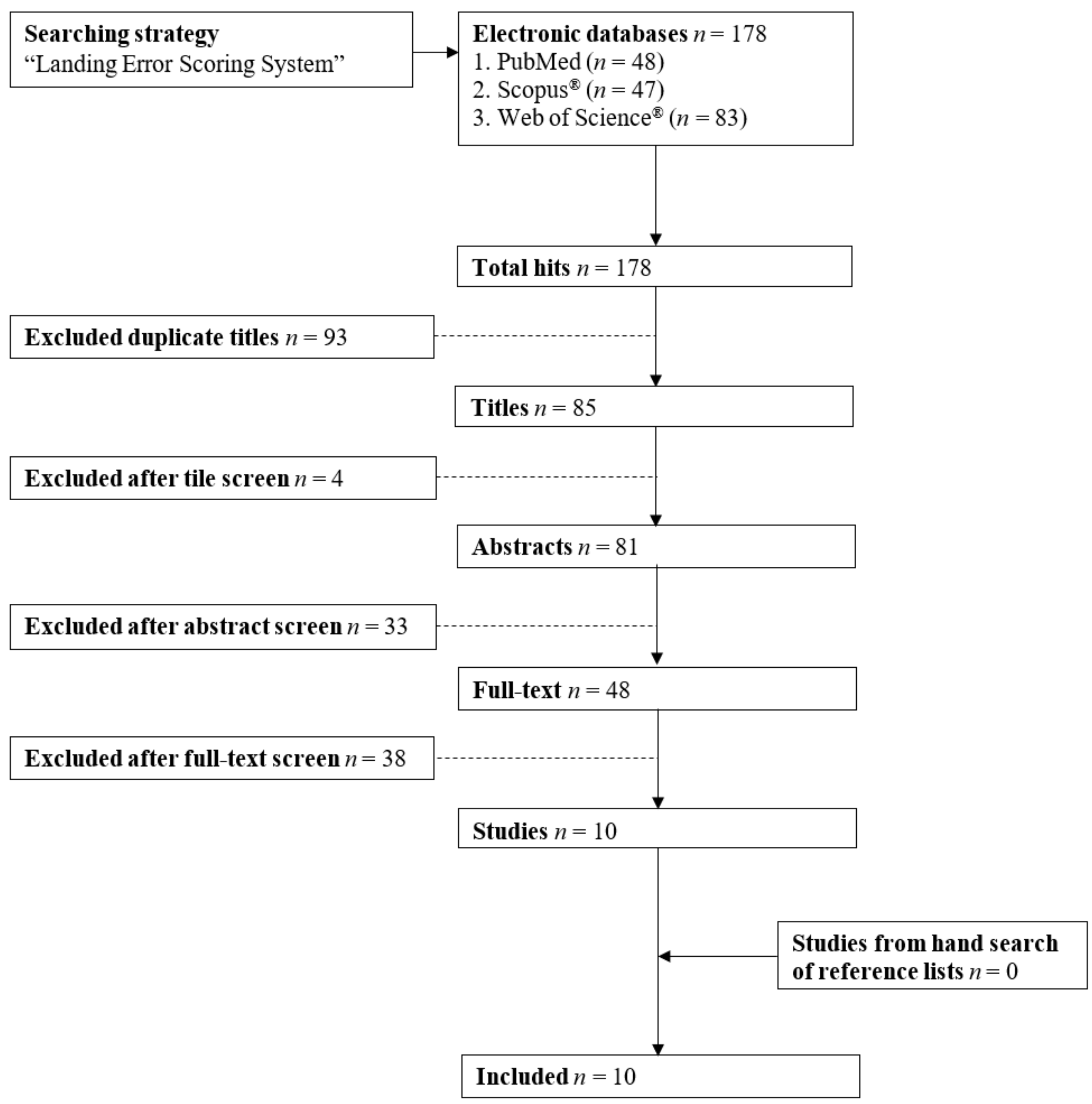


Figure 14. Flow chart of the search strategy and study selection process for Chapter 3.

3.3.2 Study characteristics

Since the majority of studies did not report descriptive characteristics of the sample used for reliability assessment, study characteristics were calculated from all participants tested with the LESS in included studies (Table 3 and 4). The study sample size ranged from 13 participants (Scarneo et al., 2017) to 2,691participants (Padua et al., 2009). A total of 3,835 participants were represented across the ten studies. All studies tested physically active populations. Sex distribution was described in all studies, totalling 2,102 males (55%) and 1,733 (45%) females. The mean age was

reported in all but one (Padua et al., 2009) of the ten studies. The weighted mean age was 15.7 ± 2.0 years with minimum mean age 13.9 (Padua et al., 2015) and maximum mean age 28.5 years (Dar, Yehiel, & Cale' Benzoor, 2019). Overall LESS scores were reported in all but one (Onate et al., 2010) of the ten studies. Note that for interventional studies, LESS score before intervention was included in calculation. The calculated weighted mean for overall LESS score was 5.2 ± 1.7 errors with minimum mean LESS score 4.4 errors (Padua et al., 2015) and maximum mean LESS score 6.5 errors (Beese et al., 2015). Only three studies reported the range of LESS scores (Dar et al., 2019; Fox et al., 2017; James et al., 2016), with the smallest and largest values being 0.0 errors (Dar et al., 2019; Fox et al., 2017) and 13.3 (James et al., 2016) errors.

3.3.3 Risk of bias within studies

Quality scores, levels of evidence, and study designs are presented in Appendix C. Overall, studies were of moderate quality based on the NOS adapted for cross-sectional studies (10-point scale: mean 7.0 ± 1.5 points, range: 4 -9). The level of evidence ranged between 2 and 4 based on the Oxford Centre for Evidence-Based Medicine 2011 table.

3.3.4 Psychometric properties of the Landing Error Scoring System

3.3.4.1 Reliability

Reliability values for LESS were reported in nine studies (Beese et al., 2015; Dar et al., 2019; Fox et al., 2017; James et al., 2016; Onate et al., 2010; Padua et al., 2009; Scarneo et al., 2017; Smith et al., 2012a; Wesley, Aronson, & Docherty, 2015) and derived from a total of 191 participants (Table 3). Both intra- and inter-rater reliability of the total LESS score was good to excellent based on ICCs (0.82-0.99 and 0.83-0.92, respectively). In addition to data reported in Table 3, Onate et al. (2010) reported percentage agreement and kappa statistics between novice and expert raters for all individual LESS items, except for hip flexion at initial contact (IC) and hip flexion at maximal knee flexion, which were not clearly addressed. There was no significant agreement between raters for knee and trunk flexion at IC, and moderate agreement (65% agreement; $\kappa=0.533$; $p = 0.011$) between raters for overall impression. For the remaining items, agreement between novice and expert raters ranged from 80 to 100% ($\kappa = 0.459$-1.0; $p < 0.015$). Only one study assessed the inter-session reliability of the overall LESS score (Scarneo et al., 2017), which was good (ICC, 0.81).

3.3.4.2 Validity against motion capture system

Two studies reported the validity of the LESS against "gold standard" 3D motion capture (Onate et al., 2010; Padua et al., 2009). Padua et al. (2009) found that numerous lower-extremity kinematics and kinetics jump-landing measures significantly differed between participants subdivided into four quartiles based on excellent (LESS ≤ 4), good (4 < LESS ≤ 5), moderate (5 < LESS ≤ 6), and poor (LESS > 6) LESS performances. Accordingly, the authors concluded the LESS is a valid clinical assessment tool for detecting poor jump-landing biomechanics (Padua et al., 2009). Onate et al. (2010) dichotomised 3D motion capture data into 0 and 1 to match LESS scoring and investigated the association between LESS scores and 3D motion data using phi correlations and percentage agreements. The last two items (joint displacement and overall impression) were not included due to the subjective nature of scoring and the authors did not report any results for the hip flexion at IC and hip flexion at maximal knee flexion. Poor agreement (10 % to 42%) was found for knee flexion at IC, lateral trunk flexion at IC, and symmetric foot contact at IC. Moderate agreement (68% to 74%) was found for trunk flexion at IC, knee valgus at IC, stance width (narrow), and knee valgus displacement. The remaining LESS items showed excellent agreement (84% to 100%). Hence, Onate et al. (2010) concluded that validity of the LESS was item dependent.

3.3.4.3 Landing Error Scoring System predictive value for injury incidence

Two studies (Padua et al., 2015; Smith et al., 2012a) with total sample size of 921 participants reported the predictive value of the LESS for non-contact ACL injury incidence (Table 4). The longitudinal cohort study conducted (Padua et al., 2015) concluded that the LESS has a screening potential for non-contact ACL injury, identifying 5 errors as an optimal cut-off point, yielding a sensitivity of 86% (95% CI, 42% to 99%) and specificity of 64% (95% CI, 62% to 67%). On the other hand, the case control study (Smith et al., 2012a) did not find any significant relationship between LESS score and risk of suffering ACL injury, either for all participants as a combined group ($p = 0.32$) or for subgroups of males ($p = 0.67$), females ($p = 0.16$), high school ($p = 0.37$), and college ($p = 0.66$) participants. Likewise, there was no significant relationship between LESS as categorical variable (i.e., poor, moderate, good, and excellent performances) and non-contact ACL injury incidence ($p = 0.35$).

One study (James et al., 2016) compared preseason LESS scores between soccer players with no previous lower-extremity injury who suffered an injury in the following season and those who remained uninjured (Table 4). Lower-extremity injury was defined as any injury that caused players to miss one or more practices or games. There were no statistically significant differences (p = 0.83) in preseason LESS scores between those who sustained a lower-extremity injury and those who remained uninjured.

Table 3. Summary of studies reporting reliability of the Landing Error Scoring System (LESS)

Study (year)	Quality[a] (Category)	Sample size [study sample size]	Population	Age, y[b]	LESS score[b]	Intra-rater	Inter-rater	Inter-session
Padua et al. (2009)	6 stars (moderate)	50 (M: 25, F:25) [2691]	US military freshmen	Not specified	4.9 ± 1.7	ICC = 0.91 SEM = 0.42 MDC = 1.16	ICC = 0.84 SEM = 0.71 MDC = 1.97	x
Onate et al. (2010)	4 stars (moderate)	19 (M: 0, F: 19) [19]	Division I college soccer players	19.6 ± 0.8	Not specified	x	ICC = 0.84	x
Smith et al. (2012a)	8 stars (strong)	10 [92]	College and high school athletes	18.3 ± 2.0	5.1 ± 1.95[c]	ICC = 0.97 SEM = 0.52 MDC = 1.44	ICC = 0.92	x
Beese et al. (2015)	8 stars (strong)	40 (M: 0, F: 40) [40]	Soccer players and multisport athletes	15.2 ± 1.2	6.5 ±1.9	ICC = 0.91 SEM = 0.48 MDC = 1.33	x	x
Wesley et al. (2015)	7 stars (moderate)	5 [36]	Athletes	19.3 ± 1.15[c]	5.0 ± 2.0	ICC = 0.99 SEM = 0.19	x	x

						MDC = 0.53		
James et al. (2016)	6 stars (moderate)	34 (M: 19, F: 15) [34]	NCAA division I soccer players	19.6 ± 1.2	5.4	ICC = 0.95	x	x
Fox et al. (2017)	6 stars (moderate)	10 (M: 0, F: 10) [32]	Sub-elite netball players	23.2 ± 3.1	4.9 ± 2.3	Cohen κ = 0.93	Cohen κ = 0.75	x
Scarneo et al. (2017)	9 stars (strong)	13 (M: 2, F: 11) [13]	Recreational active population	21 ± 2	6.2 ± 1.7	x	x	ICC = 0.81 SEM = 0.81 MDC = 2.25
Dar et al. (2019)	8 stars (strong)	10 [49]	Recreational active population	28.5 ± 5.6	4.8 ± 2.3	ICC = 0.82 (CI = 0.571-0.947)	ICC = 0.83 (CI = 0.451-0.956)	x

CI, confidence intervals; F, females; ICC, intraclass correlation coefficient; M, males; MDC, minimal detectable change; NCAA, National Collegiate Athletic Association.

[a] Methodology quality assessment score based on Newcastle – Ottawa Quality Assessment Scale adapted for cross-sectional studies, weak (0-3 stars), moderate (4-6 stars), and strong (7-10 stars) (Modesti et al., 2016).

[b] Mean ± SD for age (years) and LESS scores (errors) are shown for all of the participants in the study, not the subsample assessed for reliability.

[c] Weighted mean and weighted SD.

Table 4. Summary of studies exploring Landing Error Scoring System (LESS) predictive value for injury incidence

Study (year)	Quality[a] (Category)	Study sample size	Type of lower-extremity injury	Population	Age, y[b]	LESS score uninjured[b]	LESS score injured[b]	Significance value
Smith et al. (2012a)	8 stars (strong)	92 (U:64, I: 28)	Non-contact ACL	College and high school athletes	18.3 ± 2.0	5.0 ± 2.0	5.5 ± 1.9	$p = 0.320$
Padua et al. (2015)	8 stars (strong)	829 (U: 822, I: 7)	Non-contact ACL	Elite-youth soccer players	13.9 ± 1.8	4.4 ± 1.7	6.2 ± 1.8	$p = 0.005$
James et al. (2016)	6 stars (moderate)	34 (U: 11, I: 10)	Any injury that causes to miss one or more practice	NCAA Division I soccer players	19.6 ± 1.2	5.8 ± 3.4	5.5 ± 2.5	$p = 0.830$

ACL, Anterior Cruciate Ligament; I, injured, NCAA, National Collegiate Athletic Association; U, uninjured.

[a] Methodology quality assessment score based on Newcastle – Ottawa Quality Assessment Scale adapted for cross-sectional studies, weak (0-3 stars), moderate (4-6 stars), and strong (7-10 stars) (Modesti et al., 2016).

[b] Mean ± SD for age (years) and LESS (errors).

3.4 Discussion

3.4.1 Reliability

Findings from nine studies of relatively strong methodological quality indicate good to excellent intra-rater, inter-rater, and inter-session reliabilities. Noteworthy is that reliability of the overall LESS score has been derived from uninjured military freshmen and sportspeople with a mean age between 15 to 28 years. Although LESS has been used in younger (DiStefano et al., 2018; Pryor et al., 2017) and injured (Gokeler et al., 2014; Kuenze, Foot, Saliba, & Hart, 2015) individuals; generalisability of reliability findings across these population groups is not confirmed. Furthermore, the findings showed that some individual items in LESS scoring are less reliable than others (Onate et al., 2010). More specifically, no significant agreement between raters was found for knee and trunk flexion at IC and moderate agreement for overall impression. Given that knee flexion during landing and stiff landing with less ankle, knee, hip, and trunk flexion are key risk factors for knee injury incidence (Devita & Skelly, 1992; Leppänen et al., 2017; Podraza & White, 2010), the lack of agreement in these LESS metrics is of concern. In the LESS, a knee flexion at initial contact of less than 30° defines an error. Accurately determining an angular measure from visual observations is challenging (Ekegren, Miller, Celebrini, Eng, & Macintyre, 2009; Knudson, 1999), which can explain the lower reliability of the knee flexion angle at IC item. The overall impression item is subjective in nature, and the representation of an excellent, average, and poor landing may differ between raters. One solution could be to use a video analysis software to objectively assess angle-related items during LESS scoring to decrease the subjective nature of items. Although outcomes from such assessments might be more accurate; the scoring process would take more time. To decrease scoring time and improve consistency of LESS ratings, the automated quantification of the LESS using markerless motion capture technology has been developed recently (Dar et al., 2019; Mauntel et al., 2017). The markerless method is as reliable as expert LESS raters (Mauntel et al., 2017). The time and cost saving benefits of the markerless method, however, needs to be weighed against the additional hardware and software expenditures.

3.4.2 Validity against motion capture system

Some of the most frequently addressed biomechanical risk factors linked with ACL injury include increased knee valgus angle and moment (Cronström et al., 2017; Dempsey, Elliott, Munro, Steele, & Lloyd, 2012; Dempsey et al., 2007; Hewett et al., 2005; Krosshaug et al., 2007; McLean et al., 2007), and increased ground-reaction force resulting from stiff landing (Decker, Torry, Wyland, Sterett, & Steadman, 2003; Devita & Skelly, 1992; Chappell et al., 2005; Chappell, Yu, Kirkendall, & Garrett, 2002; Pollard et al., 2010; Shimokochi et al., 2013; Shimokochi et al., 2009). Padua et al. (2009) associated poor LESS scores with decreased peak knee and hip flexion angles and increased peak knee valgus angles and moments. Onate et al. (2010) found that the validity of LESS items was strictly item dependent. Again, one of the main concerns is that angles are difficult to estimate visually. A small kinematic difference (e.g., knee angle 29°= error present; knee angle 30° = error absent) in performance can result in poor agreement between clinical LESS scoring and motion capture scoring. Onate et al. (2010) suggested creating a range of acceptable angular values (e.g., knee angle at IC between 25° to 30°) to improve scoring validity, although no further studies were undertaken.

The validity of the LESS against motion capture system was strictly item dependent (Onate et al., 2010), which might mean modification of the original LESS scoring template. The fact that most of the LESS items representing the key biomechanical factors for ACL injury showed moderate to excellent agreement to laboratory-based measures nonetheless supports its use as a tool to clinically and visually estimate jump-landing movement patterns linked with ACL injury.

3.4.3 Landing Error Scoring System predictive value for injury incidence

Two studies of strong methodological quality explored the predictive value of the LESS for ACL injury incidence, and report equivocal results (Padua et al., 2015; Smith et al., 2012a). Padua et al. (2015) employed a prospective study design. Of the 829 elite young soccer players with a mean age of 13.9 ± 1.8 years, 7 participants suffered a non-contact ACL injury during the 2.5-year observation period. Based on the data, 5 errors were identified as an optimal cut-off point for distinguishing between athletes with low and high risk of ACL injury. Sample size calculations and post-hoc power analyses were not reported.

The study conducted by Smith et al. (2012a) assessed a population of college and high school athletes from a range of sports with a mean age of 18.3 ± 2.0 years. The study was designed as a prospective cohort with 5047 screenings within a 3-year period. Smith et al. (2012a) did not find any significant relationship between LESS scores and risk of ACL injury.

The lack of agreement in the predictive value of the LESS between studies can be explained by differences in sampled populations in terms of age, main sporting events, and exclusion criteria [Smith et al. (2012a) excluded athletes with a history of ACL injury, whereas Padua et al. (2015) did not]. Furthermore, the lack of statistical power in both studies (Padua et al., 2015; Smith et al., 2012a) is a limiting factor to the generalisation of results.

One moderate quality study (James et al., 2016) recorded preseason LESS scores of soccer players without lower-extremity injury history and did not find any significant difference between participants who sustained an injury during the following season and those who remained uninjured. The study is deemed to have several limitations that could explain the lack of association between LESS and lower-extremity injuries, including the relatively small sample size (n = 34), short follow-up period, and lack of differentiation between contact and non-contact mechanisms of injury. Fundamentally, the LESS was developed as an injury risk screening tool that identifies poor biomechanical control, which is a risk factor for non-contact, rather than contact, lower-extremity injuries. Thus, the relevance of the findings from James et al. (2016) is questioned.

Based on the current scientific evidence, the predictive value of the LESS for non-contact lower-extremity injury incidence remains uncertain. Studies with a greater statistical power are needed to affirm the relationship between LESS scores and non-contact ACL injury incidence, as well as incidence of other non-contact lower-extremity injuries.

3.4.4 Limitations

This systematic review combines data across studies to detail the reliability, validity against motion capture, and predictive validity of the LESS. The main limitations of this review were the varied methodological quality of studies and inability for meta-analysis of data due to lack of detail. Another important limitation is that populations

included, testing protocols, and calculations of total LESS score varied across studies. Population characteristic – for example, age, sex, and activity level – can significantly influence LESS scores (Beutler, de la Motte, Marshall, Padua, & Boden, 2009; Kraus et al., 2019; Smith et al., 2012a), and therefore the results of this literature review are most relevant to uninjured military freshmen and sportspeople with a mean age between 14 to 28 years. Furthermore, most studies used ICC to measure the inter-rater reliability. Cohen´s Kappa is designed to measure the inter-rater reliability of categorical variables (Viera & Garrett, 2005) and therefore would be more suitable for the LESS.

3.5 Conclusion

The current evidence indicates that the overall LESS score has good to excellent intra-rater, inter-rater, and inter-session reliability. The ability of the individual LESS items to visually estimate jump-landing movement patters against 3D motion capture is item dependent; however, noteworthy is the moderate to excellent concurrent validity of the items addressing key knee injury risk factors. The LESS predictive value for non-contact ACL injury and other non-contact lower-extremity injury incidence cannot be ascertained based on the current scientific evidence. Therefore, construct validity of the LESS as a clinical injury-risk screening tool remains uncertain. Larger scale multi-centre studies are needed to confirm the association between LESS scores and ACL injury incidence, as well as other non-contact lower-extremity injury incidence.

CHAPTER 4

Factors influencing the Landing Error Scoring System: Systematic review with meta-analysis

Hanzlíková, I., Athens, J., & Hébert-Losier, K. (2020). Factors influencing the Landing Error Scoring System: Systematic review with meta-analysis. *Journal of Sport Science and Medicine in Sport. 24*(3), 269-280. (Appendix A2).

Prelude: The previous chapter summarised the psychometric properties of the Landing Error Scoring System (LESS) and highlighted that differences in sampled populations may be the reason for inconsistent findings between studies exploring predictive values of the LESS for non-contact Anterior Cruciate Ligament (ACL) injuries. Furthermore, one of the stated limitations of Chapter 3 was that the populations varied across studies, which can significantly influence LESS outcomes. Therefore, the aim of Chapter 4 is to critically appraise and summarise research addressing age, sex, previous injuries, and intervention programmes as factors potentially influencing LESS scores. The results of Chapter 4 may assist in establishing population specific thresholds defining injury risk and may help to identify the most effective intervention programmes for improving LESS scores and reducing injury risk.

4.1 Introduction

The LESS is an easy and convenient field-based testing method that examines the presence of biomechanical movement patterns previously linked to non-contact ACL injury (Padua et al., 2009). The LESS involves the performance of a double-leg jump-landing task and relies on the use of two standard video cameras, one placed to capture the motion from front view and other to capture the motion from side view. Clinicians evaluate the frontal and sagittal plane videos from the LESS and visually evaluate aberrant lower-extremity and trunk kinematics between initial ground contact (IC) and peak knee flexion and note the number of "movement errors" observed. The LESS consists of 17 items. Movement items 1 to 15 are scored as 0 (error absent) and 1 (error present). The last two items (16 and 17) of the LESS are subjective in nature and assess the overall sagittal plane displacement and quality of landing which are scored from 0 to 2 errors. The minimum LESS score is 0 and the maximum score is hypothetically 19 errors. However, it is unlikely that an individual presents a wide and narrow stance or an internal and external rotation of the foot simultaneously. Consequently, the real maximum score is 17 errors. A higher score means a greater number of landing errors, poorer landing biomechanics, and greater risk of non-contact lower-extremity injuries (Padua et al., 2009).

A recent systematic review of the literature concluded that the overall LESS score has good to excellent intra-rater (intraclass correlation coefficient [ICC], 0.82-0.99), inter-rater (ICC, 0.83-0.92), and inter-session (ICC, 0.81) reliability (Hanzlíková & Hébert-Losier, 2020b). Validity of the overall LESS score against three-dimensional (3D) jump-landing biomechanics was good when individuals were divided into four quartiles based on LESS scores, although the validity of the individual LESS items against 3D motion capture was item dependent (Hanzlíková & Hébert-Losier, 2020b). Poor agreement (10% to 42%) between 3D motion data and LESS ratings was found for knee flexion at IC, lateral trunk flexion at IC, and symmetric foot contact at IC. The remaining LESS items showed moderate to excellent agreement (68% to 100%) (Onate et al., 2010). Padua et al. (2015) concluded from a prospective investigation that LESS scoring had a good sensitivity (86%) and acceptable specificity (64%) to identify risk of non-contact or indirect-contact ACL injury. More specifically, the relative risk of ACL injury was 10.7 times greater when LESS scores were ≥ 5 errors. However, Smith et al. (2012a) did not find any significant relationship between LESS and primary ACL

injury incidence in their case-control analysis. Based on the recent review (Hanzlíková & Hébert-Losier, 2020b), the predictive value of the LESS for non-contact ACL injury and other non-contact lower-extremity injury incidence is unclear. The reasons for the conflicting results are likely due to under-powered sample sizes and differences in sampled populations in terms of age, proportion of females and males, and injury history (Padua et al., 2015; Smith et al., 2012a). All of these factors can potentially influence LESS scores and explain between study differences in findings.

Due to its clinical-friendly focus and minimal use of equipment, space, and time; the LESS lends itself well to movement screening initiatives involving a large number of athletes and is often used in practice and research (DiStefano et al., 2018; Pryor et al., 2017; Welling, Benjaminse, Gokeler, & Otten, 2016). Therefore, it is important to understand what factors might impact LESS scores for the proper interpretation of outcomes. To date, there has been no systematic evaluation of factors that can influence LESS scores. Therefore, the aim of this systematic review with meta-analysis was to systematically review the literature addressing age, sex, previous injury, and intervention program as influencing factors of the LESS. The results of this systematic review with meta-analysis may assist in establishing thresholds defining injury risk for different sexes, age groups and previous injuries and may guide prevention effort in intervention programs with highest impact on gross movement jump-landing biomechanics.

4.2 Methods

4.2.1 Protocol and registration

A systematic review with meta-analysis was undertaken and followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines (Moher, Liberati, Tetzlaff, & Altman, 2010). Literature review methods and inclusion criteria were specified in advance, and prospectively registered with PROSPERO (CRD42018107210).

4.2.2 Eligibility criteria

Studies using the LESS as main outcome measure and reported age, sex, previous injury, or intervention program were included regardless of participants, intervention, or study design. Only original research (excluding case reports) in the English language

published in peer-reviewed journals were considered. Studies using modified versions of the original LESS, e.g., real-time LESS (Schwartz, Talmy, Olsen, & Dudkiewicz, 2020), iLESS (Schussler et al., 2014), automated quantification of the LESS (Mauntel et al., 2017), or LESS with additional items (Pryor, Burbulys, Root, & Pryor, 2020) were excluded.

4.2.3 Search strategy and study selection

Three electronic databases [PubMed (1950-), Web of Science® (1965-) and Scopus® (1970-)] were searched using the key words "Landing Error Scoring System". The final search was undertaken on 1st April 2020, by one reviewer (IH). Titles, abstracts, and full texts were screened sequentially for inclusion and exclusion criteria. In case of uncertainty regarding inclusion, a second reviewer (KHL) was consulted. Reference lists of included articles were hand searched for additional records.

4.2.4 Data collection process

Data concerning study design, population (number, sex, age, and activity level), LESS scores, statistical analysis, and results concerning LESS were extracted from articles using a standardised template by one reviewer (IH), with the completeness of extraction verified by a second reviewer (KHL). We contacted seven authors by email to request additional information from ten studies (Dar et al., 2019; DiStefano et al., 2018; DiStefano, DiStefano, Frank, Clark, & Padua, 2013b; DiStefano et al., 2016; DiStefano et al., 2009; Gokeler et al., 2014; James et al., 2016; Padua et al., 2009; Pryor et al., 2017; Smith et al., 2012a). Two authors responded (Dar et al., 2019; Gokeler et al., 2014), with one author (Dar et al., 2019) providing additional data for one study.

4.2.5 Risk of bias within studies

Three validated risk of bias assessment tools: Newcastle – Ottawa Assessment Scale adapted for cross-sectional studies (NOS; Modesti et al., 2016), revised tool for Risk of Bias in randomised trials (RoB 2.0; Sterne et al., 2019), and Risk Of Bias in Non-randomised Studies - of Interventions (ROBINS-I; Sterne et al., 2016) were used. Two reviewers (IH and KHL) independently assessed the risk of bias of included studies. Prior to assessment, the two reviewers met to discuss and familiarise themselves with the scales. All identifiable information (i.e., authors, affiliations, countries, and sources of publication) were removed from articles by a third party to blind the two reviewers (IH and KHL) and reduce the assessment bias. The risk of bias for each study was

assessed specifically for the LESS outcome score as recommended (Büttner et al., 2020). Disagreements in the risk of bias assessment scores were resolved by discussion between the reviewers. Consensus scores are presented in this review article.

The RoB 2 assessed the risk of bias across six domains through which bias can be introduced into the results of randomised controlled trials (Sterne et al., 2019). The ROBINS-I assessed the risk of bias across seven domains through which bias might be introduced into non-randomised interventional studies (Sterne et al., 2016). Both the RoB2 and ROBINS-I tools have been rigorously developed and recommended to assess the risk of bias in sport and exercise medicine (Büttner et al., 2020). The risk of bias in outcomes from the observational studies were assessed using the NOS as it is a suitable alternative to the ROBINS-I (Sterne, Higgins, Reeves, Savović, & Turner, 2017). Using the NOS star system, a maximum of two stars for each numbered item can be allocated, with an overall maximum of 10 stars. Therefore, more star indicates superior methodological quality and lower risk of bias. Reviewers agreed to award the highest score in the statistical test section for the reporting of confidence intervals, quartiles, limits of agreement, or standard errors.

In addition, the level of evidence for each study was determined using the Oxford Centre for Evidence-Based Medicine 2011 table. The level of evidence ranges from 1 to 5, with 1 indicating the highest level of evidence and 5 the lowest. Study design was categorised according to Parab and Bhalerao (2010). Furthermore, the outcomes of the meta-analysis were evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) scale (GRADE, 2004). No study was excluded based on risk of bias assessment, level of evidence, or study design.

4.2.6 Data analysis and synthesis

Descriptive statistics were computed using Microsoft® Office Excel 2016 and expressed in terms of means and standard deviations (mean ± SD) weighted based on sample size, minimum to maximum ranges (min to max), percentages (%), and counts (*n*). Note that for interventional studies, LESS score pre-intervention was included in calculating and analysing study characteristics. Hedge's *g* was calculated as a measure of effect size when data were reported in sufficient detail. Thresholds for interpreting the magnitude of the effect were: $g < 0.20$ for trivial, $0.20 \leq g < 0.50$ for small, $0.50 \leq g < 0.80$ for medium, and $g \geq 0.80$ for large (Lakens, 2013).

Five or more studies are needed to achieve reasonable power from a random effect model meta-analysis (Jackson & Turner, 2017). Therefore, meta-analysis was attempted when at least five studies reported results in sufficient detail. Three meta-analyses were undertaken exploring sex, previous injury, and intervention program as potential influencing factors of LESS scores. Heterogeneity was explored statistically using Cochrane Q and quantified using I^2. The Q test has a low power in meta-analysis when studies have small sample sizes or are few in numbers (Higgins & Green, 2011). Therefore, statistical significance for Cochrane Q was set to $p < 0.10$. The I^2 was interpreted according Higgins et al. (2011), with 0% to 40% indicating "heterogeneity might not be important", 30% to 60% "moderate heterogeneity", 50% to 90% "substantial heterogeneity" and 75% to 100% "considerable heterogeneity". When meta-analysis had one moderator and heterogeneity was significant, a random effect model was used to account for both within-study and between-study variance. For meta-analysis with two moderators, a mixed effect model was used. Raw mean difference between scores with associated 95% confidence intervals [CI] were calculated for all meta-analyses. Statistical significance was set at $p \leq 0.05$, and clinical meaningfulness of differences in LESS score means was set at one error based on Padua et al. (2009) who identified one error change in total LESS score to be associated with moderate to large differences in biomechanical variables previously linked to ACL injury. Meta-analysis calculations were undertaken in RStudio® Version 1.1.456 with R version 3.5.1 using the metafor package (Viechtbauer, 2010). Note that if meta-analysis was not possible due to small number of studies, a qualitative analysis was undertaken.

4.2.7 Risk of bias across studies

Funnel plots were constructed for every meta-analysis to assess publication bias. Egger's test (model of weighted regression with multiplicative dispersion) was performed on the random effect model for each meta-analysis to assess funnel plot asymmetry as suggested by the metafor package (Viechtbauer, 2010).

4.3 Results

4.3.1 Study selection

The systematic database search generated 252 hits related to the Landing Error Scoring System. Following the removal of duplicates, 114 studies remained. An additional 63

studies were removed following title (not original research $n = 6$), abstract (not original research $n = 35$; not in English language $n = 5$), and full text screen (modified version of the LESS $n = 13$; age, sex, previous injury, or intervention program not explored $n = 4$), with one article subsequently identified via hand searching of reference lists. Fifty-two studies met inclusion and were reviewed (Figure 15).

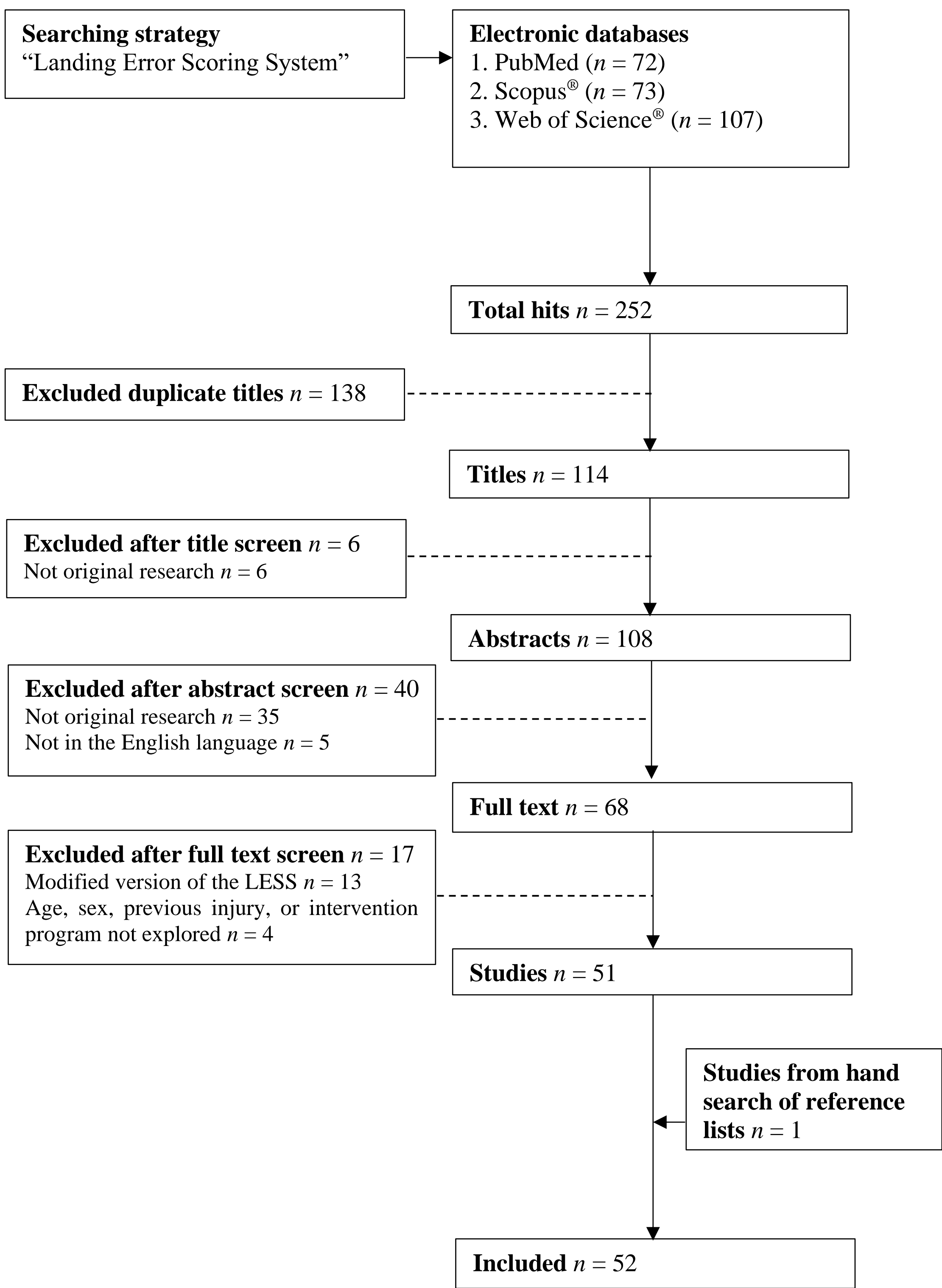


Figure 15. Flow chart of the search strategy and study selection process for Chapter 4.

4.3.2 Study characteristics

All studies reported the number of participants tested with the LESS. The sample size ranged from 11 (Pfile, Gribble, Buskirk, Meserth, & Pietrosimone, 2016) to 2,753 (Beutler et al., 2009) participants. A total of 11,672 participants were represented across the 52 studies. Four studies did not specify the activity levels of their cohorts (Bell et al., 2014; Gokeler et al., 2014; John et al., 2019; Kuenze et al., 2015). All remaining studies (92%) tested individuals engaged in some level of physical activity (see Table 5). Sex distribution was described in 51 (98%) studies, totalling 6,925 males (59%) and 4,669 (40%) females, with the sex not reported for the remaining 78 participants (1%) in one study (O'Malley et al., 2017). The mean age was reported in 46 (88%) studies (weighted mean: 16.2 ± 1.3 years), with the average ranging from 11 (DiStefano et al., 2018) to 28 (Dar et al., 2019) years.

The overall LESS score was reported in 47 (90%) studies. The calculated weighted mean for overall LESS score was 4.9 ± 1.7 errors using pre-intervention LESS scores for computations. The minimum reported mean LESS score for a group was 2.0 (Welling et al., 2016) and maximum was 8.1(O'Malley et al., 2017) errors. Only four studies reported the range of individual LESS scores (Dar et al., 2019; Fox et al., 2017; Hébert-Losier, Hanzlíková, Zheng, Streeter, & Mayo, 2020; James et al., 2016), with a minimum of 0.0 (Dar et al., 2019; Fox et al., 2017) and maximum of 13.3 (James et al., 2016) errors (average of three trials).

4.3.3 Risk of bias within studies

The NOS adapted for cross-sectional studies was used for 33 (64%) studies. Out of a maximum of 10 stars, 2 studies scored two stars (DiFabio et al., 2018; John et al., 2019), 4 studies four stars (Arslan, Ertat, Karamizrak, İŞleğen, & Arslan, 2019; de la Motte, Gribbin, Lisman, Beutler, & Deuster, 2016; Everard, Harrison, & Lyons, 2017; Kraus et al., 2019), 7 studies five stars (Herman et al., 2019; Kraus et al., 2019; Lam & McLeod, 2014; Lepley et al., 2013; Scarborough et al., 2019; Theiss et al., 2014; Tran et al., 2020), 10 studies six stars (Beutler et al., 2009; Fox et al., 2017; Hébert-Losier et al., 2020; James et al., 2016; Kuenze, Trigsted, Lisee, Post, & Bell, 2018; Mohammadi et al., 2017; Padua et al., 2009; Šiupšinskas, Garbenytė-Apolinskienė, Salatkaitė, Gudas, & Trumpickas, 2019; van Melick, van Rijn, Nijhuis-van der Sanden,

Hoogeboom, & van Cingel, 2019; Welling et al., 2018), 2 studies seven stars (Jacobs, Riveros, Vincent, & Herman, 2018; Wesley et al., 2015), 7 studies eight stars (Beese et al., 2015; Bell et al., 2014; Biese et al., 2019; Dar et al., 2019; Everard, Lyons, & Harrison, 2018; Padua et al., 2015; Smith et al., 2012a), and 1 study nine stars (DiStefano et al., 2018). The RoB 2 was used for 9 (17%) studies. There was some concern regarding risk of bias in 3 studies (Parsons, Carswell, Nwoba, & Stenberg, 2019; Parsons, Sylvester, & Porter, 2017; Welling et al., 2016), and a high risk of bias in the remaining 6 studies (Akbari, Sahebozamani, Daneshjoo, Amiri-Khorasani, & Shimokochi, 2019; DiStefano et al., 2013b; DiStefano et al., 2016; DiStefano et al., 2009; O'Malley et al., 2017; Pryor et al., 2017). The ROBINS-I was used for 10 (19%) studies. Risk of bias was considered moderate in 4 of these studies (Distefano et al., 2013a; Kuenze et al., 2015; Pfile et al., 2016; Scarneo et al., 2017) and serious in the remaining 6 studies (Bell et al., 2016; Garbenytė-Apolinskienė et al., 2018; Gokeler et al., 2014; Owens et al., 2013; Padua et al., 2012; Stiffler et al., 2015). The level of evidence ranged between 2 and 4 based on the Oxford Centre for Evidence-Based Medicine 2011 table. Studies were most often of level 3 (n = 30, 58%) and cross-sectional in design (n = 25, 48 %). Risk of bias scores, level of evidence, and study design of studies are presented in Appendix D1. The risk of bias of the studies considered in examining each one of the influencing factors of the LESS is presented in Appendix D2. Overall, GRADE ratings suggest that the strength of evidence in relation to LESS influential factors explored by meta-analysis is very low (Table 6).

4.3.4 Risk of bias across studies

The Egger's test for funnel plot asymmetry was not significant in any meta-analysis, suggesting that publication bias was not present (Appendix D3). The *p*-values of Egger's test for meta-analysis exploring sex, previous injury, and intervention program were 0.757, 0.914, and 0.072, respectively.

4.3.5 Influencing factors

4.3.5.1 Age

Only Smith et al. (2012a) compared overall LESS scores between different age categories and reported significantly lower overall LESS scores in older college athletes compared to younger high school athletes. Seven studies (DiStefano et al., 2018; DiStefano et al., 2009; Padua et al., 2015; Padua et al., 2012; Parsons et al., 2019;

Parsons et al., 2017; Pryor et al., 2017) tested and reported overall LESS scores for 1,997 participants 15 years or younger; 17 studies (Akbari et al., 2019; Beese et al., 2015; Bell et al., 2014; Distefano et al., 2013a; DiStefano et al., 2013b; Garbenytė-Apolinskienė et al., 2018; Hébert-Losier et al., 2020; James et al., 2016; Kuenze et al., 2018; Lam & McLeod, 2014; O'Malley et al., 2017; Owens et al., 2013; Pfile et al., 2016; Scarborough et al., 2019; Smith et al., 2012a; Theiss et al., 2014; Wesley et al., 2015) for 1,613 participants aged from 15 to 20 years inclusively; and 24 studies (Arslan et al., 2019; Bell et al., 2014; Beutler et al., 2009; Biese et al., 2019; Dar et al., 2019; de la Motte et al., 2016; DiFabio et al., 2018; Everard et al., 2017; Everard et al., 2018; Fox et al., 2017; Gokeler et al., 2014; Herman et al., 2019; Jacobs et al., 2018; John et al., 2019; Kraus et al., 2019; Kuenze et al., 2015; Lepley et al., 2013; Mohammadi et al., 2017; Owens et al., 2013; Scarneo et al., 2017; Stiffler et al., 2015; van Melick et al., 2019; Welling et al., 2016) for 4,566 participants older than 20 years. The weighted mean LESS scores for participants 15 years or younger was 6.1 ± 1.7, for participants aged from 15 to 20 years was 5.5 ± 1.9, and for participant older than 20 years was 5.1 ± 1.8 errors.

4.3.5.2 Sex

Fourteen studies compared LESS scores between males and females (Table 5). Six studies found females to have significantly higher overall LESS scores compared to males (Beutler et al., 2009; de la Motte et al., 2016; Kuenze et al., 2018; Padua et al., 2009; Theiss et al., 2014; Wesley et al., 2015), six studies found no significant difference in overall scores between sexes (Bell et al., 2016; DiStefano et al., 2018; Jacobs et al., 2018; Lam & McLeod, 2014; Smith et al., 2012a; Welling et al., 2016), and the remaining two studies did not specify if the differences were significant (DiStefano et al., 2009; Garbenytė-Apolinskienė et al., 2018). Thirty studies reported overall LESS scores separately for males (n = 3294) and females (n = 1910), with resulting weighted mean scores for males of 5.0 ± 1.8 and 5.6 ± 1.7 errors for females.

Twelve studies testing 2,729 males and 1,656 females reported the results in sufficient detail for meta-analysis (Bell et al., 2016; Beutler et al., 2009; de la Motte et al., 2016; DiStefano et al., 2009; Garbenytė-Apolinskienė et al., 2018; Jacobs et al., 2018; Kuenze et al., 2018; Lam & McLeod, 2014; Smith et al., 2012a; Theiss et al., 2014; Welling et al., 2016; Wesley et al., 2015). A random effect model was used given

the significant and substantial heterogeneity (Q = 21.34, p = 0.030, I^2 = 66%, Figure 16A). Findings from the meta-analysis indicate statistically significant higher LESS scores in females than males ($p < 0.001$), but the mean difference of 0.6 [0.4, 0.8] errors was not clinically meaningful (i.e., less than 1 error, Figure 16A). The quality of evidence was very low according to the GRADE scale (Table 6).

4.3.5.3 Previous injury

Nine studies compared LESS scores between previously injured and control participants (Table 5). Five of these studies (Bell et al., 2014; Gokeler et al., 2014; John et al., 2019; Kuenze et al., 2015; Padua et al., 2015) reported significantly higher LESS scores for the previously injured groups compared with controls. The remaining four studies (James et al., 2016; Lam & McLeod, 2014; Smith et al., 2012a; van Melick et al., 2019) reported no significant difference in scores between previously injured athletes compared with those with no injury history, as well as between athletes who suffered lower-extremity injury during a season compared to those who remained injury free during the same season. Weighted mean LESS scores for all previously injured participants (n = 450) were 5.7 ± 2.3 errors. Weighted mean scores were 5.5 ± 2.3 for ACL injured or reconstructed (n = 338), 5.8 ± 2.4 for other types of injury (n = 110), and 4.4 ± 1.9 errors for uninjured controls (n = 100).

Eight studies were included in the meta-analysis exploring the difference in LESS scores between previously injured and uninjured participants (Bell et al., 2014; James et al., 2016; John et al., 2019; Kuenze et al., 2015; Lam & McLeod, 2014; Padua et al., 2015; Smith et al., 2012a; van Melick et al., 2019), with two studies exploring two subgroups of injuries (James et al., 2016; Lam & McLeod, 2014). The meta-analysis compared the difference in LESS scores from 208 previously injured participants (98 ACL and 110 other injuries) and 1,692 uninjured controls. Given the presence of significant (Q = 16.95, p = 0.031, Figure 16B) moderate (I^2 = 54%, Figure 16B) heterogeneity and two moderators (study-level variables: ACL and other injury), a mixed effect model was used to examine to what extent the type of injury (moderator) influenced the size of the average true effect. The results indicate that participants with a previous ACL injury have statistically significant higher LESS scores (p = 0.004), with a clinically meaningful mean difference of 1.2 [0.4, 2.0] errors. LESS scores of participants with other types of previous injury are similar to those of uninjured controls

($p = 0.441$), Figure 16B. The quality of evidence was very low according to the GRADE criteria (Table 6).

4.3.5.4 Intervention program

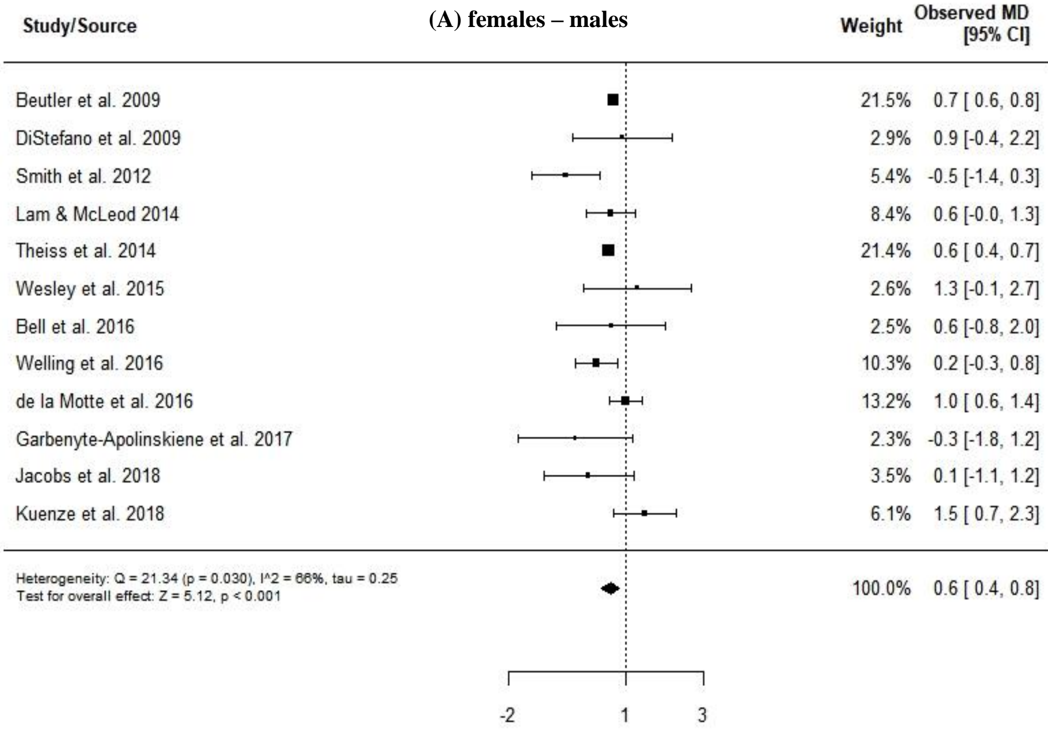
A total of 14 studies explored the influence of intervention programs on LESS (Table 5). The explored interventions included diverse injury prevention, isolated resistance training, weight training, military movement course, aquatic training, static warm up, dynamic warm up, standard warm up, and internal, external, and video instruction programs.

External focus and video instructions had significantly greater potential in decreasing LESS scores compared to internal focus instructions (Welling et al., 2016). Two studies found that participants with poor landing technique improved the most with training (DiStefano et al., 2009; Parsons et al., 2017). Pryor et al. (2017) showed that preventive training programs had a beneficial effect on decreasing LESS scores regardless of coaches and players previous experience with programs.

Four studies examined the persistence of LESS score improvements following intervention programs (DiStefano et al., 2016; Padua et al., 2012; Pfile et al., 2016; Scarneo et al., 2017). DiStefano et al. (2016) reported that even when training programs improved LESS scores, changes were no longer apparent 6 months post-intervention cessation. Padua et al. (2012) compared programs of 3 to 9 months in duration and found that improved scores remained 3 months post-intervention only in the 9-month group. Oppositely, a 6-week neuromuscular training program improved LESS scores, and improvements were sustained 4 (Scarneo et al., 2017) and 9 months (Pfile et al., 2016) post-intervention cessation.

Thirteen studies involving 927 participants and 19 different interventions were included in the meta-analysis exploring the effect of intervention program on LESS scores by comparing differences between pre-intervention and post-intervention scores (Akbari et al., 2019; DiStefano et al., 2013b; DiStefano et al., 2009; Garbenytė-Apolinskienė et al., 2018; O'Malley et al., 2017; Owens et al., 2013; Padua et al., 2012; Parsons et al., 2019; Parsons et al., 2017; Pfile et al., 2016; Pryor et al., 2017; Scarneo et al., 2017; Welling et al., 2016). Note that LESS scores recorded several months post-intervention were not included into the meta-analysis to focus on the more immediate effects of training. Of the participants, 803 completed neuromuscular training programs

with a minimum duration of 6 weeks and 124 completed “other” intervention programs. The 6-week threshold for neuromuscular training programs was selected as evidenced to reduce ACL injury rates (Hewett, Ford, & Myer, 2006a). Given the presence of significant (Q = 49.50, $p < 0.001$, Figure 16C) moderate (I^2 = 53%, Figure 16C) heterogeneity and two moderators (study-level variables: neuromuscular and other intervention program), a mixed effect model was used to determine to what extent the type of intervention program (moderator) influenced the size of the average true effect. Meta-analysis indicated that neuromuscular training programs with minimal duration of 6 weeks significantly and meaningfully decreased LESS scores by 1.2 [0.9, 1.5] error ($p < 0.001$). The “other” training programs significantly improved LESS scores from a statistical perspective ($p = 0.042$), however the 0.5 [0.0, 0.9] error difference was not clinically meaningful, Figure 16C. The quality of evidence was very low according the GRADE criteria (Table 6).



(B) previously injured – uninjured

Study/Source	Weight	Observed MD [95% CI]
Smith et al. 2012	13.6%	0.5 [-0.4, 1.4]
Bell et al. 2014	12.5%	1.1 [0.1, 2.1]
Kuenze et al. 2015	6.9%	3.2 [1.5, 4.9]
Padua et al. 2015	9.5%	1.8 [0.5, 3.1]
van Melick et al. 2019	9.1%	0.0 [-1.4, 1.4]
Lam & McLeod (mild knee injury) 2014	12.3%	-0.1 [-1.1, 0.9]
Lam & McLeod (sever knee injury) 2014	12.8%	0.5 [-0.4, 1.4]
James et al. (history vs nohistory) 2016	6.7%	-0.7 [-2.5, 1.1]
James et al. (injured vs noninjured) 2016	4.0%	-0.3 [-2.8, 2.2]
John et al. 2019	12.6%	1.3 [0.3, 2.3]

Heterogeneity: Q = 16.95 (p = 0.031), I^2 = 54%, tau = 0.66

Others	(Test for overall effect: Z = 0.77, p = 0.441)	**0.3 [-0.5, 1.1]**
ACL	(Test for overall effect: Z = 2.85, p = 0.004)	**1.2 [0.4, 2.0]**

-3 1 5

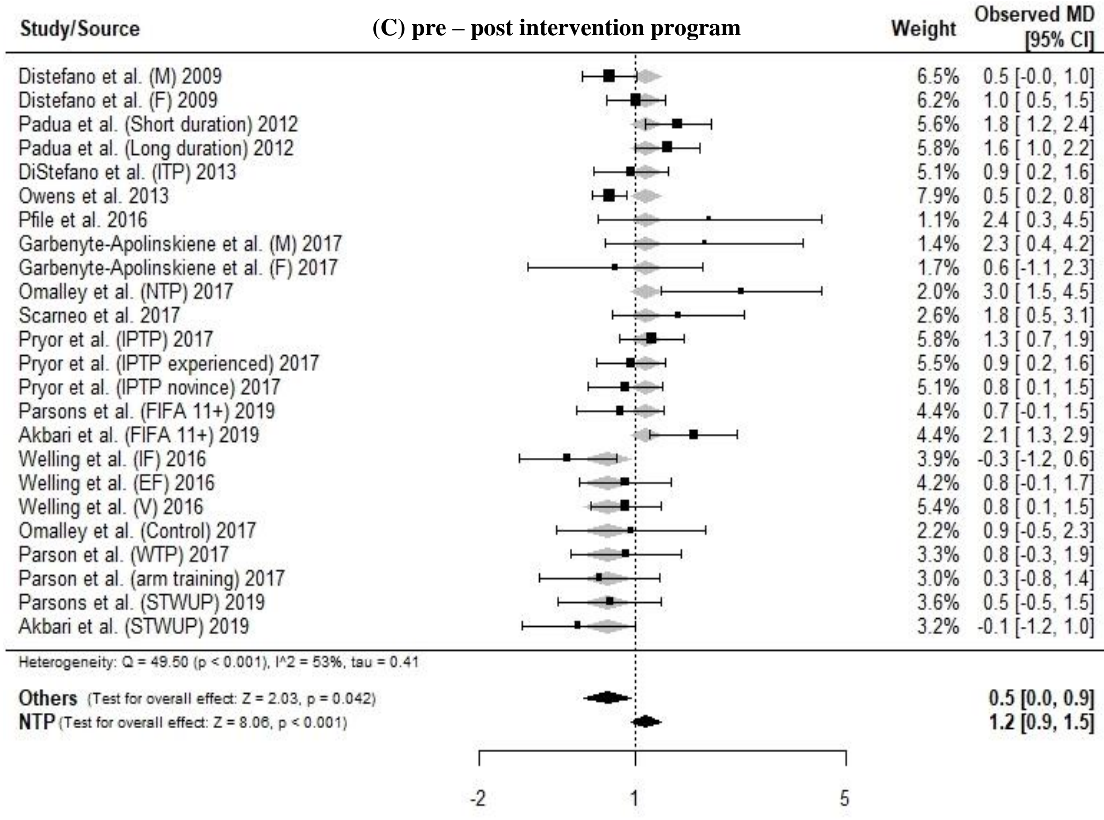


Figure 16. Forest plots comparing mean difference (MD) in Landing Error Scoring System scores between (A) sexes (scores of females minus males), (B) previously injured and uninjured individuals (scores of previously injured minus uninjured), and (C) pre- and post-intervention programmes (scores pre minus post).

Abbreviations: ACL, Anterior Cruciate Ligament injury; CI, Confidential Intervals; EF, external focus instruction; F, females; FIFA, Federation International de Football Association; IF, internal focus instruction; IPTP, injury prevention training programme; ITP, integrated training programme; M, males; NTP, neuromuscular training programme; *Q*, Cochrane *Q*; STWUP, standard warm up; V, video instruction; WTP, weight training programme.

Cochrane *Q* statistical significance set at $p < 0.10$; statistical significance for overall effect set at $p \leq 0.05$; clinical meaningful effect threshold set at one error. Shaded diamonds in the background represent the two moderators.

Table 5. Summary of studies (by year) comparing the influence of sex, previous injury, and training programme on Landing Error Scoring System scores.

Sex						
Study (year)	**Sample size (*n*)**	**Population**	**Age (years)[a]**	**LESS score (errors)[a]**	**Hedge's *g***	**Comparison M vs F**
Beutler et al. (2009)	Total: 2753 M: 1707, F: 1046	Cadets of US military	18 – 24	M: 4.7 ± 1.7 F: 5.3 ± 1.5	0.37	$p < 0.001$
Padua et al. (2009)	Total: 2691 M: 1655, F: 1036	US military freshmen	Not specified	Not specified		Females higher scores than males $p < 0.001$
DiStefano et al. (2009)	Total: 173 M: 90, F: 83	Soccer players	13.0 ± 2.0	M: 4.4 ± 1.7 F: 5.8 ± 1.9	0.78	Not specified
Smith et al. (2012a)	Total: 92 M: 29, F: 63	College and high school athletes	M: 18.5 ± 2.5 F: 18.0 ± 1.7	M: 5.5 ± 2.1[b] F: 5.0 ± 1.9[b]	0.26	Non-significant $p = 0.22$
Lam & McLeod (2014)	Total: 215 M: 116, F: 99	Athletes competing in inter-scholastic sports	M: 19.4 ± 1.5 F: 19.1 ± 1.1	M: 5.1 ± 2.5 F: 5.8 ± 2.3	0.29	Non-significant $p > 0.05$
Theiss et al. (2014)	Total: 277 M: 222, F: 55	Cadets of US military	19.3 ± 0.8	M: 5.1 ± 0.2[b] F: 5.6 ± 0.5[b]	1.75	$p = 0.05$
Wesley et al. (2015)	Total: 36 M: 18, F: 18	Athletes	M: 19.4 ± 1.4 F: 19.2 ± 0.9	M: 5.0 ± 2.3 F: 6.3 ± 1.9	0.70	$p \leq 0.05$

Bell et al. (2016)	Total: 39 M: 20, F: 19	Recreationally active population	M: 20.9 ± 1.2 F: 21.2 ± 1.4	M: 4.7 ± 2.3 F: 5.3 ± 2.1	0.27	Non-significant $p = 0.56$
Welling et al. (2016)	Total: 40 M: 20, F:20	Ball team sport athletes	22.50 ± 1.62	M: 2.8 ± 1.0 [b] F: 3.1 ± 0.7 [b]	0.35	Non-significant $p > 0.05$
de la Motte (2016)	Total: 521 M: 431, F: 90	Military applicants entering US army	M: 20.8 ± 3.0 F: 20.9 ± 3.2	M: 5.5 ± 2.1 F: 6.5 ± 1.8	0.49	$p < 0.001$
Garbenytė-Apolinskienė et al. (2018)	Total: 31 M: 15, F: 16	Basketball players	15.4 ± 0.3[b]	M: 6.9 ± 2.3 F: 6.6 ± 1.8	0.13	Not specified
DiStefano et al. (2018)	Total: 355 M: 122, F: 233	Soccer and basketball players	11.0 ± 2.0	Not specified		Non-significant $p > 0.05$
Jacobs et al. (2018)	Total: 40 M: 20, F: 20	Recreationally active population	M: 24.4 ± 1.8 F: 23.4 ± 2.8	M: 5.1 ± 2.2 F: 5.1 ± 1.5	0.01	Non-significant $p = 0.624$
Kuenze et al. (2018)	Total: 168 M: 41, F: 127	Participants after ACL reconstruction	M: 20 (median) F: 19 (median)	M: 4.6 ± 2.3 F: 6.1 ± 2.3	0.65	$p < 0.001$
Previous injury						
Study (year)	**Sample size (*n*)**	**Population**	**Age (years)[a]**	**LESS score (errors)[a]**	**Hedge's *g***	**Comparison injured vs uninjured**
Smith et al. (2012a)	Total: 92 ACL: 28 Control: 64	College and high school athletes	18.3 ± 2.0	ACL: 5.5 ± 1.9 Control: 5.0 ±2.0	0.25	$p = 0.32$

Lam & McLeod (2014)	Total: 215; Mild knee injury (MI): 31; Severe knee injury (SI): 36; No knee injury (control): 148	Athletes competing in inter-scholastic sports	19.3 ± 1.4[b]	MI: 5.3 ± 2.6 SI: 5.9 ± 2.6 Control: 5.4 ± 2.4	MI vs Control 0.04 SI vs Control 0.20	Non-significant
Bell et al. (2014)	Total: 54 ACLR: 27 Control: 27	Not specified	ACLR: 19.9 ± 1.7 Control: 20.5 ± 1.6	ACLR: 6.7 ± 2.1 Control: 5.6 ± 1.5	0.60	$p = 0.04$
Gokeler et al. (2014)	Total: 20 ACLR: 10 Control: 10	Not specified	ACLR: 27.4 ± 9.6 Control: 21.0 ± 0.8	ACLR: 6.5 Control: 2.5 (median)		Not specified
Kuenze et al. (2015)	Total: 46 ACLR: 22 Control: 24	Not specified	ACLR: 22.5 ± 5.0 Control: 21.7 ± 3.6	ACLR: 6.0 ± 3.6 Control: 2.8 ± 2.2	1.08	$p = 0.002$
Padua et al. (2015)	Total: 1217 ACL: 7 Control: 1210	Soccer players	ACL: 14.9 ± 0.70 Control: 13.9 ± 1.8	ACL: 6.2 ± 1.8 Control: 4.4 ± 1.7	1.06	$p < 0.005$
James et al. (2016)	Total: 34 History of injury (HI): 13 No history of injury (NHI): 21 Injured during study (IDS): 10 Never injured (NI): 11	NCAA division I soccer players	HI: 19.7 ± 1.2 NHI: 19.6 ± 1.3 IDS: 19.6 ± 1.2 NI: 19.6 ± 1.4	HI 4.9 ± 2.4 NHI: 5.6 ± 2.9 IDS 5.5 ± 2.5 NI: 5.8 ± 3.4	HI vs NHI 0.26 IDS vs NI 0.10	HI vs NHI $p = 0.50$ IDS vs NI $p = 0.83$
van Melick et al. (2019)	Total: 33 ACLR: 14 Control: 19	Recreational soccer players	ACLR: 23.2 ± 3.6 Control: 21.3 ± 3.0	ACLR: 4.0 ± 2.0 Control: 4.0 ± 2.0	0.00	Non-significant
John et al. (2019)	Total: 40 CAI: 20 Control: 20	Students	CAI: 23.3 ± 3.3 Control: 25.5 ± 3.4	CAI: 7.4 ± 1.6 Control: 6.1 ± 1.5	0.80	$p = 0.010$

Training programme									
Study (year)	**Sample size (*n*)**	**Population**	**Age (years)[a]**	**Intervention**	**Duration**	**Test times**	**LESS score (errors)[a]**	**Hedge's *g***	**Comparison between groups**
DiStefano et al. (2009)	Total: 173 M: 90, F: 83	Soccer players	13.0 ± 2.0	Stratified and generalised injury prevention TP	10-15 minutes, 3-4 times/week for 3 months	Pre TP Post TP	Males Pre: 4.4 ± 1.7 Post: 3.9 ± 1.8 Females Pre: 5.8 ± 1.9 Post: 4.8 ± 1.7	Males 0.29 Females 0.55	Males vs Females $p = 0.35$
Padua et al. (2012)	Total: 84 M: 20, F: 64 Short duration: 33 Long duration: 51	Soccer players	14.0 ± 2.0	Injury prevention TP short duration (3 months) vs Injury prevention TP long duration (9 months)	10-15 minutes, 3-4 times/week for 3 or 9 months	Pre TP Post TP 3months post TP	Short TP Pre: 5.2 ± 1.5 Post: 3.4 ± 1.1 3 months post: 4.7 ± 1.6 Long TP Pre: 5.7 ± 1.7 Post: 4.1 ± 1.4 3 months post: 4.2 ± 1.3	Short TP pre vs post 1.37 pre vs 3 months post 0.32 Long TP pre vs post 1.03 pre vs 3 months post 0.99	Short and long TP significantly lower scores pre vs post Long TP significantly lower scores 3 months post $p < 0.05$
DiStefano et al. (2013a)	Total: 30 M: 25, F: 5 IRTP: 15 ITP: 15	Participants of weight training course	19.0 ± 1.0	Isolated resistance TP (IRTP) vs Integrated TP (ITP)	45 minutes, 2 times/week for 8 weeks	Pre TP Post TP	IRTP Not specify ITP	ITP 0.9	ITP Pre vs post $p = 0.02$

							Pre: 3.9 ± 1.0 Post: 3.0 ± 1.0		
Owens et al. (2013)	Total: 273 M: 158, F: 115	Participants of Military Movement course	17 to 25	Military Movement course (MMC)	19 sessions of 50 minutes (8 weeks)	Pre MMC Post MMC	Pre MMC: 5.0 ± 1.8 Post MMC: 4.5 ± 2.0	0.26	Pre vs post $p < 0.001$
DiStefano et al. (2016)	Total: 1104 M: 928, F: 176	US military freshmen	17 to 22	Standard warm up vs Dynamic integrated movement enhancement injury prevention TP	10-12 minutes, 2-3 times/week for 6 weeks	Pre TP Post TP 2, 4, 6, 8, months post TP	Not specified		Non-significant group differences in scores at all time point
Pfile et al. (2016)	Total: 11 M: 0, F: 11	Division I basketball players	19.4 ± 1.4	Plyometrics and neuromuscular control TP	18 sessions of 30 min in 6 weeks	Pre TP Post TP 9 months post TP	Pre: 7.3 ± 3.4 Post: 4.9 ± 1.2 9 months post: 5.4 ± 1.8	Pre vs post 0.94 Pre vs 9 months post 0.70	Pre vs post $p = 0.024$ Pre vs 9 months post $p = 0.030$
Welling et al. (2016)	Total: 40 M: 20, F: 20 IF: 10, EF: 10, V: 10, C: 10	Ball team sport athletes	22.5 ± 1.6	4 groups: Internal focus instruction (IF). External focus instruction (EF). Video instruction (V) and Control (C)	1 session	Pre TP Post TP 1 week (1W) post TP	IF Pre: 2.9 ± 1.0 Post: 3.2 ± 1.1 1W post: 3.1 ± 1.5 EF Pre: 3.1 ± 1.0 Post: 2.3 ± 1.0 1W post: 2.3 ± 0.5 V	IF pre vs post 0.29 IF pre vs 1W post 0.16 EF pre vs post 0.8 EF pre vs 1W post 1.01 V pre vs post	Males in V group Pre vs post $p < 0.05$ Pre vs 1W post $p < 0.05$ Female in V and EF group Pre vs post

							Pre: 2.8 ± 0.9 Post: 2.0 ± 0.6 1W post: 2.0 ± 0.6 C Pre: 3.0 ± 0.6 Post: 3.1 ± 0.7 1W post: 2.9 ± 0.5	1.05 V pre vs 1W post 1.05 C pre vs post 0.15 C pre vs 1W post 0.18	$p < 0.05$ Pre vs 1W post $p < 0.05$
O´Malley et al. (2017)	Total: 78 NTP: 41 Control: 37	Gaelic footballers and hurling athletes	18.5	Neuromuscular TP (NTP) vs Usual team training (Control)	15 minutes, 2 times/week for 8 weeks	Pre TP Post TP	NTP Pre: 7.1 ± 3.8 Post: 4.1 ± 3.2 Control Pre: 8.1 ± 3.3 Post: 7.2 ± 2.9	NTP 0.89 Control 0.29	NTP vs control $p < 0.001$
Parson et al. (2017)	Total: 36 M: 0, F: 36 WTP: 19, Control: 17	Athletes	12.3 ± 1.4	Weight TP (WTP) vs Control (arm training)	60 minutes, 2 times/week for 12 weeks	Pre TP Post TP	WTP Pre: 6.8 ± 1.5 Post: 6.0 ± 1.8 Control Pre: 6.4 ± 1.6 Post: 6.1 ± 1.8	WTP 0.48 Control 0.18	WTP vs control Non-significant $p = 0.85$
Scarneo et al. (2017)	Total: 15 M: 0, F: 15	Active population with real-time LESS > 4	21.0 ± 2.0	Aquatic neuromuscular TP	7-10 minutes 3 times/week for 6 weeks	Pre TP Post TP 4 months post TP	Pre: 6.3 ± 1.8 Post: 4.5 ± 1.7 4 months post: 4.2 ± 1.7	Pre vs post 1.03 Pre vs 4 months post 1.20	Pre vs post $p < 0.01$ Pre vs 4 months post $p < 0.01$

Pryor et al. (2017)	Total: 89 M: 41, F: 48 IPTP (experienced): 43 Control (novice): 46	Soccer players	8 to 14	2 stages: Stage 1: Injury prevention IP (IPTP) vs Control Stage 2: group with experience of IPTP vs novice group without experience of IPTP	10-12 minutes 3 times/week for 8 weeks	Pre TP Post TP	Stage 1: IPTP Pre: 6.2 ± 1.0 Post: 4.9 ±1.8 Stage 2: Experienced group Pre: 5.9 ± 1.6 Post: 5.0 ±1.5 Novice group Pre: 6.1 ± 1.6 Post: 5.3 ± 1.9	Stage 1: 1.02 Stage 2: Experienced 0.58 Novice 0.46	Stage 1: IPTP Pre vs post $p = 0.01$ Stage 2: Experienced Pre vs post $p < 0.01$ Novice Pre vs post $p < 0.01$
Garbenytė-Apolinskienė et al. (2018)	Total: 31 M: 15, F: 16	Basketball players	15.4 ± 0.3[b]	Integrated exercise TP	Individual dosage, 5 times/week for 5 months	Pre TP Post TP	Males Pre: 6.9 ± 2.3 Post: 4.6 ± 2.9 Females Pre: 6.6 ± 1.8 Post: 6.0 ±2.9	Males 0.88 Females 0.25	Males pre vs post $p = 0.001$ Females pre vs post Non-significant
Parsons et al. (2019)	Total: 43 M: 0, F: 43 FIFA 11+: 29, Standard warm up: 18	Soccer players	11.1	FIFA 11+ vs standard warm up	10-30 minutes 2 times/week for 5 months	Pre TP Post TP	FIFA 11+ Pre: 6.9 ± 1.6 Post: 6.2 ± 1.6 Warm up Pre: 6.6 ± 1.7 Post: 6.1 ± 1.3	FIFA 11+ 0.42 Warm up 0.31	FIFA 11+ vs Warm up $p = 0.66$

Akbari et al. (2019)	Total: 24 M: 24, F: 0 FIFA 11+: 12, Standard warm up: 12	Elite soccer players	16.8 ± 1.2	FIFA 11+ vs standard warm up	20-25 minutes 3tiems/week for 8 weeks	Pre TP Post TP	FIFA 11+ Pre: 4.4 ± 0.7 Post: 2.3 ± 1.3 Warm up Pre: 4.6 ± 1.3 Post: 4.7 ± 1.4	FIFA 11+ 1.86 Warm up 0.07	FIFA 11+ vs Warm up $p < 0.001$

Abbreviations: ACL, Anterior Cruciate Ligament; ACLR, Anterior Cruciate Ligament reconstruction; CAI, Chronic ankle instability; F, females; FIFA, Federation International de Football Association, LESS, Landing Error Scoring System; M, males; NCAA, National Collegiate Athletic Association; TP, training programme; US, United States.

[a]Mean ± standard deviation values for age (years) and LESS score (errors).

[b]Mean ± standard deviation values weighted based on sample size.

Table 6. Summary of findings regarding influencing factors (sex, previous injury, intervention programme) of the Landing Error Scoring System (LESS).

Outcome	Certainty assessment						Summary of findings		
	Studies (*n*)	**Study design**	**Risk of bias**	**Indirectness**	**Imprecision**	**Publication bias**	**Participants included in meta-analysis (*n*)**	**Results**	**Quality of the evidence (GRADE)**
Sex	12	Observational, randomised and non-randomised interventional studies	Very serious[1]	Serious[2]	Serious[3]	Undetected	Males: 2,729 Females: 1,656	▪Females 0.6 errors higher LESS scores than males	⊕◯◯◯ Very low
Previous injury	8	Observational and non-randomised interventional studies	Very serious[1,4]	Serious[2,5]	Serious[6]	Undetected	Previously injured: 208 Uninjured: 1,692	▪ Participants with ACL injury had 1.2 errors higher LESS scores than uninjured controls ▪ Participants with other types of injury had 0.3 error higher LESS scores than control	⊕◯◯◯ Very low
Intervention programme	13	Randomised and non-randomised interventional studies	Serious[7]	Serious[2,8]	Not serious	Undetected	927	▪Compare to pre-preintervention, LESS score post-intervention decreased by 1.2 error for NTP and by 0.5 errors for other interventions	⊕◯◯◯ Very low

Abbreviations: ACL, Anterior Cruciate Ligament; GRADE, Grading of Recommendations Assessment, Development and Evaluation; NTP, neuromuscular training programme with minimal duration of 6 weeks.

[1] At least a half of observational studies did not justify sample size, describe response rate, blind assessment of outcome, and did not use appropriate statistical tests. At least a half of interventional studies had high or moderate risk of bias due confounding and in selection of the reported results (see Appendix D2).

[2] The heterogeneity may be explained by the varying risk of bias of included studies, different age groups, and population (athletes participating in different sports and different sport levels) explored in the meta-analysis.

[3] Differences in age (pre versus post pubertal) in included studies may seriously affect the results of the meta-analysis.

[4] All observational studies had poor representativeness of the sample and a half of interventional studies had the high risk of bias due to missing data (see Appendix D2).

[5] The heterogeneity may be explained by different types of injuries included in the meta-analysis.

[6] Participants with contact injuries were included into the meta-analysis.

[7] Majority of studies (n = 8) had high or moderate risk of bias due deviations from the intended intervention (adhering to intervention). Five studies had high or moderate risk of bias in selection of the reported results (see Appendix D2).

[8] The heterogeneity may be explained by different intervention programmes with varying duration .

4.4 Discussion

4.4.1 Influencing factors

4.4.1.1 Age

A single study (Smith et al., 2012a) compared overall LESS scores between younger high school and older college athletes, and found significantly better overall scores in the older athletes. When weighted means of LESS scores were calculated for three age groups (under 15, 15 to 20, and over 21 years), scores were seen to decrease with age. Padua et al. (2015) stated that the natural decrease in LESS scores in older athletes could be an effect of maturation or selection in competitive sports that might limit the ability of LESS to predict ACL injury in older athletes. Smith et al. (2012a) who tested older participants (18.3 ± 2.0 years) compared to Padua et al. (2015) (13.9 ± 1.8 years) did not find any predictive values for ACL injury incidence whereas Padua and colleagues (2015) identified 5 errors as optimal cut-off point for distinguishing between athletes with low and high risk.

There is strong evidence showing that females have higher risk of non-contact ACL injury compared to males (Arendt & Dick, 1995). However, there is no strong evidence of this sex difference in injury rate in prepubertal females (Myer, Sugimoto, Thomas, & Hewett, 2013b). Age also significantly influences the effectiveness of ACL injury prevention neuromuscular programmes in females with greater knee injury reduction in those under 18 years compared to older (Myer et al., 2013b). These findings indicate that age is an important injury risk factor. More evidence is needed to conclude whether age influences LESS score and whether the same threshold is suitable to identify athletes at high risk of injury across different age categories.

4.4.1.2 Sex

It is well documented that on average, females have a four to six times higher incidence of knee injury than males participating in the same sport (Arendt & Dick, 1995). Specifically, the risk of non-contact ACL injury is more than double for females compared to males (Arendt & Dick, 1995). Several theories have emerged to explain these sex differences in injury rates that include sex-specific hormonal, anatomical, and neuromuscular abilities differences (Hewett, Myer, & Ford, 2006c). Despite hormonal involvement in injury incidence being a topic of considerable scientific interest, the

overall strength of evidence for hormonal involvement in injury incidence remains still low (Herzberg et al., 2017). Anatomical measures often do not correlate with dynamic injury mechanisms and are difficult to modify (Hewett et al., 2006c). The higher incidence of knee injury seen in female athletes is clearly of multifactorial origin, with specific movement patterns and altered neuromuscular control playing an important role in this increased ACL injury risk (Beutler et al., 2009).

Six studies (Beutler et al., 2009; de la Motte et al., 2016; Kuenze et al., 2018; Padua et al., 2009; Theiss et al., 2014; Wesley et al., 2015) reported statistically significant difference in LESS scores ($p \leq 0.05$) between males and females. These studies together included 6,446 participants overall with a weighted mean age of 20.2 ± 2.2 years (two studies did not specify mean age). The six other studies who reported no significant difference in LESS scores between males and females (Bell et al., 2016; DiStefano et al., 2018; Jacobs et al., 2018; Lam & McLeod, 2014; Smith et al., 2012a; Welling et al., 2016) tested 781 participants altogether with a weighted mean age of 15.9 ± 1.5 years. The different mean age between studies reporting statistically significant and non-significant differences between sexes can be one of the underlying reasons for the discrepancy given that mechanics associated with increased risk of injury in females tend to emerge after the pubertal growth spurt which is commonly between 10 to 16 years (Myer et al., 2009).

The significant differences found in some studies might have been linked to differences in sample sizes; and, albeit being statistically significant, these differences in LESS scores might not have been clinically meaningful. In fact, based on the weighted mean from all studies (mean difference between females and males of 0.6 errors) and results from our meta-analysis (mean difference between females and males of 0.6 errors), the finding of statistically significant higher overall LESS scores in females compared to males is substantiated. However, the difference is not clinically meaningful based on the one error threshold (Padua et al., 2009). The risk of bias was high for a number of domains, and the overall GRADE rating suggests very low strength of evidence.

4.4.1.3 Previous injury

A prior systematic review (McCall et al., 2015) agrees that previous injuries are a strong risk factor of sustaining not only the same, but also another type, of injury. When

dividing previous injury into two subgroups (ACL and others), our meta-analysis identified the ACL group as having meaningfully higher LESS scores from a clinical perspective (mean difference of 1.2 errors) than the control group. The LESS scores of the group with other types of injuries than ACL were not significantly different from control group ($p = 0.441$). One explanation for these findings may be that the LESS was developed to screen for risk of ACL injury, and therefore targets movements linked with this type of injury. That said, knee valgus and stiff landing are movement patterns linked with various non-contact lower-extremity injuries (Decker et al., 2003), suggesting that the LESS should be a useful screening tool for a range of injuries other than ACL. Two out of three studies exploring the effect of other types of previous injury on LESS (James et al., 2016; Lam & McLeod, 2014) did not differentiate between contact and non-contact mechanisms of injury (e.g., contusion was recorded as an injury), which could also explain why the meta-analysis identified no significant difference in LESS scores between the other injury and control groups. Furthermore, injures were self-reported in these two studies (James et al., 2016; Lam & McLeod, 2014). Research shows that only 61% of athletes accurately recall their 12 months injury history (Gabbe, Finch, Bennell, & Wajswelner, 2003), which highlights the difficulty of using self-reported data in research. On the other hand, John et al. (2019) concluded that individuals with chronical ankle instability have significantly higher LESS scores compared to a healthy controls with a meaningful difference of 1.3 errors between groups, suggesting that LESS may be a useful tool for identifying movement patterns linked with injury risk in individuals with ankle instability. Nonetheless, the strength of the evidence regarding the influence of injury on LESS scores was considered very low based on the GRADE scale, and there was high risk of bias in several domains.

4.4.1.4 Intervention programme

The meta-analysis of meta-analyses provide evidence for the effectiveness of neuromuscular training in reducing the incidence of ACL injury (Webster & Hewett, 2018). It is therefore logical to expect that intervention programmes influence LESS scores. Fourteen studies (Akbari et al., 2019; DiStefano et al., 2013b; DiStefano et al., 2016; DiStefano et al., 2009; Garbenytė-Apolinskienė et al., 2018; O'Malley et al., 2017; Owens et al., 2013; Padua, DiStefano, DiStefano, Beutler, & Marshall, 2011b; Padua et al., 2012; Parsons et al., 2019; Parsons et al., 2017; Pfile et al., 2016; Pryor et

al., 2017; Root, Beltz, Martinez, Scarneo, & DiStefano, 2016; Scarneo et al., 2017) together tested 2,031 participants and explored the influence of a variety of intervention programmes on LESS scores. Seven training programmes (Akbari et al., 2019; Garbenytė-Apolinskienė et al., 2018; O'Malley et al., 2017; Padua et al., 2012; Pfile et al., 2016; Pryor et al., 2017; Scarneo et al., 2017) meaningfully improved LESS scores (change ≥ 1 error), all of which implemented injury prevention training programmes with neuromuscular components. O'Malley et al. (2017) concluded that injury prevention training programmes involving strength, core stability, balance, movement control, plyometric, and agility exercises are statistically significantly superior in decreasing LESS scores compared to usual training methods that do not emphasise neuromuscular control. Training programmes with meaningful decreased in LESS scores (Akbari et al., 2019; Garbenytė-Apolinskienė et al., 2018; O'Malley et al., 2017; Padua et al., 2012; Pfile et al., 2016; Pryor et al., 2017; Scarneo et al., 2017) were implemented in diverse cohort groups, including males and females from 8 (Pryor et al., 2017) to 21 (Scarneo et al., 2017) years of age; soccer (Akbari et al., 2019; Padua et al., 2012; Pryor et al., 2017), basketball (Garbenytė-Apolinskienė et al., 2018; Pfile et al., 2016), Gaelic football (O'Malley et al., 2017), and hurling (O'Malley et al., 2017) players; and recreational (Scarneo et al., 2017) to elite (Akbari et al., 2019) level of sport participation. Given this diversity, it is difficult to ascertain whether sex, age, sport, or sport level also contributed to LESS score improvements following these intervention programmes.

From all programmes tested, the most effective in improving LESS scores were: (1) plyometric and neuromuscular training programmes [decreased scores by 2.4 errors (Pfile et al., 2016)], and (2) neuromuscular training programmes with strength, core stability, movement control, plyometric, and agility exercises [decreased scores by 3 errors (O'Malley et al., 2017)]. Both training (O'Malley et al., 2017; Pfile et al., 2016) programmes emphasised landing technique, with only one having controls completing their usual training programme for comparison (O'Malley et al., 2017). The programmes consisted of 2 to 3 session per week over 6 to 8 weeks, each lasting approximately 15 to 30 minutes. Meta-analysis exploring the effect of intervention on ACL injury incidence (Hewett et al., 2006a) highlighted the importance of plyometrics and technique feedback in intervention programmes. Both of these components were present in the most effective training programmes in improving LESS scores (O'Malley

et al., 2017; Pfile et al., 2016). Noteworthy is that both studies involved cohorts with some of the highest pre-intervention mean LESS score [7.3 ± 3.4 (Pfile et al., 2016) and 7.1± 3.8 (O'Malley et al., 2017) errors], which could have contributed to their higher relative LESS improvements given research indicating that individuals with the poorest landing technique improve the most with training (DiStefano et al., 2009; Parsons et al., 2017).

The results from our meta-analysis showed that neuromuscular training programs with a minimum duration of 6 weeks meaningfully reduced LESS scores (mean difference: 1.2 errors, $p < 0.001$). Different interventions or training programmes with a shorter duration than 6 weeks did significantly reduce LESS scores ($p = 0.042$), but the mean difference of 0.5 error was not clinically meaningful. These finding are in agreement with meta-analysis showing 6 weeks as a minimum duration of intervention programmes that can assist in reducing ACL injury incidence (Hewett et al., 2006a). Based on our results, there is evidence that neuromuscular training programmes with a minimum duration of 6 weeks can meaningfully influence LESS scores. However, studies disagree in regard to the persistence of the effect once the intervention programme stops (e.g., improvements persist up to 9-months versus improvements no longer present at 3-months or 6-months) and the training duration required (e.g., 3-week, 3-month, 9-month programmes) for the most optimal and long-term effect (DiStefano et al., 2016; Padua et al., 2012; Pfile et al., 2016; Scarneo et al., 2017). Furthermore, the strength of the evidence was considered very low based on GRADE and high risk of bias was present, notably in relation to adherence, confounding factors, and selection of reported results.

4.4.2 Limitations

This systematic review with meta-analysis explored the influence of age, sex, previous injury, and intervention programmes on LESS scores. The main limitations of this review and associated findings are the varied study designs and heterogeneity between studies, risk of bias of the included studies, indirectness and imprecision of outcomes which resulted in very low quality of evidence according to the GRADE scale (Table 6). We included all studies exploring LESS as a main outcome measure regardless of study design, population tested, or risk of bias to systematically review and analyse all the scientific literature available on the topic. However, the results and corresponding

interpretations may differ if only randomised control trials with low risk of bias studies were included. Another limitation is the use of the NOS as a risk of bias assessment tool given that there are no specific tools to assess risk of bias in cross-sectional observation studies. Furthermore, the testing protocols [e.g., sampling frequency of the cameras (Hébert-Losier et al., 2020; Kuenze et al., 2018), landing distance (Distefano et al., 2013a), and landing surface (Jacobs et al., 2018)] and calculations of total LESS score [mean of three jumps (Padua et al., 2012) versus the best jump (Garbenytė-Apolinskienė et al., 2018)] varied across studies, which can influence LESS scores (Hanzlíková, Athens, & Hébert-Losier, 2020).

Based on this review of the literature, there is indication that the influence of sex on LESS scores may vary in different age groups (pre versus post puberty). Therefore, it is probable that multiple influencing factors interact with each other. For example, females in puberty age with a history of ACL injury who do not participate in injury prevention programmes may have the greatest LESS scores, and males older than 20 years with no previous injury and who have adhered to a neuromuscular training programme lasting over 6 weeks potentially exhibit the lowest LESS scores. However, we did not explore this assumption specifically, hence, it is not possible to make conclusions regarding interactions between influencing factors and specifically regarding the influence of sex on LESS scores across different age groups. Moreover, studies that did not differentiate between contact and non-contact mechanisms of injury were included into the meta-analysis, which could explain the lack of significant difference in LESS scores between the other injury and control groups. Given the limited number of studies exploring other injury in this meta-analysis (n = 3), we did not explore how the results would change if we excluded those studies involving contact injuries (n = 2). Besides sex, age, previous injury, and intervention programme, other factors [e.g., fatigue (Bell et al., 2016; Gokeler et al., 2014; Wesley et al., 2015), sport and competition level (DiStefano et al., 2018; Kraus et al., 2019; Theiss et al., 2014), and strength levels (Beutler et al., 2009; Lepley et al., 2013; Mohammadi et al., 2017)] may also influence LESS scores; however, these factors were not explored in this review.

4.5 Conclusion

The goal of this literature review was to critically appraise and summarise research addressing age, sex, previous injury, and intervention programme as factors potentially influencing LESS scores. The meta-analysis results provide evidence that sex, previous ACL injury, and training programmes significantly influence LESS scores. However, only previous ACL injury and neuromuscular training programmes with a minimal duration of 6 weeks were associated with a clinically meaningful change of one error. Our qualitative analysis of the reviewed studies suggests that LESS scores may be influenced by age; however, more evidence is needed to confirm the potential influence of age on LESS scores. These findings, however, should be interpreted cautiously considering the very low GRADE rating of the evidence. Further research is required to enhance our certainty regarding which factors influence LESS scores.

Summary of Section 1

To summarise the key findings from Section 1, the LESS is a reliable screening tool and useful in clinical and research settings for quantifying landing mechanics through visual observations. However, further work is needed to improve the validity of some LESS items against 3D motion capture and determine its predictive validity for ACL and other non-contact lower-extremity injuries. The clinical construct of the LESS is to screen for ACL injury risk; therefore, ascertaining its predictive ability is crucial. The evidence available indicates that age may influence LESS scores in a clinically meaningful manner, suggesting that age-specific thresholds to define injury risk may be required or should at least be considered when using the LESS. Females had significantly higher LESS scores compared to males, however, the difference was not clinically meaningful. This finding justifies the recruitment of both females and males to participate in the following cross-sectional studies presented in the thesis. History of ACL injury meaningfully increased LESS scores likely due to residual long-term deficits in movement control and strategy of these individuals. Undertaking neuromuscular training programme for a minimum of six weeks meaningfully altered LESS scores. Based on the systematic review, neuromuscular training programmes completed for at least six weeks and incorporating landing technique feedback and plyometric exercises appear to be the most effective in reducing LESS scores. These findings, however, should be interpreted cautiously considering the very low GRADE rating of the evidence.

Section 1 systematically reviewed 53 studies that used the LESS as a main outcome measure, substantiating its frequent use in the scientific literature. During the reviewing process, the authors observed differences in the LESS methodological procedures reported between the studies. These variations in methodological procedures may also affect the LESS outcomes and the interpretation of findings, and are therefore explored further.

SECTION 2

Influence of Landing Error Scoring System methodological procedures on outcomes

Prelude: Section 1 systematically appraised and summarised the literature concerning the psychometric properties of the Landing Error Scoring System (LESS) and influencing factors on LESS outcomes. One of the limitations highlighted in both systematic reviews was the differences in the LESS methodological procedures reported between the included studies. It is essential in both research and practice that outcomes from assessments are reproducible and comparable between studies to improve healthcare management and scientific inference. Therefore, the aim of the following three chapters is to explore whether differences in the methodological procedures of the LESS reported between studies influence LESS outcomes, namely final LESS score calculation methods, jump-landing distance, and participants' knowledge of scoring criteria and their prior performance.

CHAPTER 5

Clinical implications of Landing Error Scoring System calculation methods

Hanzlíková, I., Athens, J., & Hébert-Losier, K. (2020). Clinical implications of Landing Error Scoring System calculation methods. *Physical Therapy in Sport, 44*, 61-66. (Appendix A3)

Prelude: Three jump-landings are typically assessed during the Landing Error Scoring System (LESS); however, the original paper did not specify explicitly how to allocate a final LESS score to an individual from the three jump-landings. As a result, five different final LESS score calculation methods are present in the literature. Therefore, the aim of Chapter 5 is to explore the effect of the final LESS score calculation methods on the LESS scores and risk categorisations.

5.1 Introduction

The LESS is a clinical-based screening tool developed by Padua et al. (2009) used to identify individuals at risk of suffering a non-contact Anterior Cruciate Ligament (ACL) injury through the evaluation of potentially high-risk biomechanical movement patterns. The LESS relies on the use of two standard video cameras to capture motion in the frontal and sagittal planes during three trials of a double-leg jump-landing (DLJL) task. When compared to three-dimensional motion capture systems, which is considered the "gold standard" tool for quantifying human movement, standard two-dimensional video cameras require considerably less financial outlay as well as preparatory time and space to perform the analysis. Therefore, the LESS is more practical for large-scale screening initiatives. To score the LESS, an investigator visually evaluates lower-extremity and trunk kinematics during landing from the video recordings, noting the number of 'movement errors' using a 17-item scoring sheet (Padua et al., 2009). LESS scores range from 0 to 17 errors, where higher scores indicate a greater number of landing errors.

The LESS has been shown to be a reliable screening tool (Hanzlíková & Hébert-Losier, 2020b). Although the concurrent validity of the LESS against three-dimensional motion capture data has been shown to be strictly item dependent; the items representing the key risk factors for ACL showed moderate to excellent concurrent validity (Hanzlíková & Hébert-Losier, 2020b; Onate et al., 2010). Therefore, LESS is a useful tool for clinicians and researchers to visually assess jump-landing movement patterns and differentiate between participants presenting high risk biomechanics (Padua et al., 2009). Padua et al. (2015) evaluated ACL risk in elite youth soccer players in a prospective study and concluded that LESS scoring exhibited good sensitivity (86%) and acceptable specificity (64%) to identify risk of non-contact ACL injury when implementing a 5-error cut-off defining high injury risk. More specifically, the relative risk of sustaining an ACL injury was 10.7 times greater in individuals with a LESS score of 5 or more (high risk) compared to less than 5 (low risk). In contrast, Smith et al. (2012a) did not find any significant relationship between LESS and ACL injury incidence. Differences in sampled populations in terms of age, main sporting event, and previous injury status, as well as lack of statistical power in both studies (Padua et al., 2015; Smith et al., 2012a), are potential underlying factors to the diverging findings on the predictive value of the LESS.

Padua et al. (2009) provided operational definitions and scoring details for each item of the LESS on conception, but the authors did not explicitly specify how to compute the final LESS score from the recommended DLJL trials (e.g., whether to use the mean or the best trial). In the footnotes of online Appendix that presented how frequent positive scores were in their population, Padua et al. (2009) stated: "For items 1 to 15, a positive score was defined as an error on at least 2 of the 3 trials. For item 16 and 17, a positive score was defined as Average on at least 2 of 3 trials or Poor/Stiff on at least 1 of 3 trials." These footnotes infer that final LESS scores derived from items where errors were present in at least 2 of 3 trials, but this computational approach was never clearly stated in the methods. Furthermore, in subsequent articles from the same group of authors, the mean score of 3 DLJL trials was used to allocate the final LESS score to individuals (Padua et al., 2015; Padua et al., 2012).

In scientific literature, most studies using the LESS as an outcome measure calculate the final LESS score for an individual as a mean of 3 DLJL trials (Beese et al., 2015; Beutler et al., 2009; DiStefano et al., 2018; DiStefano et al., 2009; Kuenze et al., 2015; Mohammadi et al., 2017; Padua et al., 2015; Padua et al., 2012; Pfile et al., 2016; Scarneo et al., 2017; Smith et al., 2012a; Theiss et al., 2014; Welling et al., 2016; Wesley et al., 2015), although some studies have used the LESS score of the 1st jump (Onate et al., 2010), 3rd jump (O'Malley et al., 2017), or best jump (Garbenytė-Apolinskienė et al., 2018; Kraus et al., 2019) for analysis. Additionally, two studies scored an error if the participant demonstrated the specific error in at least 2 of the 3 DLJL trials (Bell et al., 2014; Pryor et al., 2017). Only a few authors justified their selected calculation methods: Onate et al. (2010) scored the 1st jump only to reduce possible biases between the two raters scoring each participant; whereas Bell et al. (2014) and Pryor et al. (2017) selected the sum of errors present in at least 2 jumps method to analyse the frequency of individual LESS item errors. There is a lack of knowledge on the effect of computational method on the final LESS score and risk categorisation of individuals.

It is essential in both research and practice that outcomes from assessments are reproducible and comparable between studies to improve healthcare management and scientific inference. Therefore, our aim was to explore whether final LESS scores significantly differ between calculation methods used in the scientific literature. We hypothesised that the calculation method would significantly influence the estimated

group mean LESS score, group-level risk categorisation, and individual-level risk categorisation, anticipating lower scores and lesser individuals categorised at high risk using the LESS score from the best trial versus the mean of 3 DLJL trials. On the other hand, we expected similar scores between methods based on the mean score from 3 DLJL trials and sum of errors present in at least 2 trials.

5.2 Methods

5.2.1 Sample size calculation

The sample size calculation for this study was based on data from the two methods we assumed would demonstrate the smallest mean difference; [i.e., mean of 3 jumps (Root, Trojian, Martinez, Kraemer, & DiStefano, 2015) and sum of errors present in at least 2 jumps (Pryor et al., 2017)]. Sample size requirements were calculated using a customisable statistical spreadsheet (Hopkins, 2006) from standard two-tailed hypothesis equations using an 90% power ($\beta = 0.10$), 5% significance level ($\alpha = 0.05$), critical values of the *t* distribution, and data from previous studies (Pryor et al., 2017; Root et al., 2015) on similar cohorts (i.e., healthy young individuals). These equations indicated that we needed 273 participants to identify group differences in mean LESS scores between these two calculation methods. To account for 20% of potential withdrawals and missing data, we recruited 328 participants.

5.2.2 Participants

A sample of 328 participants (167 males and 159 females) volunteered to participate. Age, height, mass, and body mass index (mean ± standard deviation) for males were 18.3 ± 4.0 years (range 15 to 42 years), 180.9 ± 7.9 cm, 86.7 ± 16.4 kg, and 26.5 ± 4.7 kg/m^2; and for females were 17.8 ± 4.6 years (range 12 to 41 years), 168.9 ± 6.2 cm, 67.9 ± 12.1 kg, and 23.8 ± 4.0 kg/m^2. All participants were involved in physical activity: On average three times per week, six hours a week. The majority of participants (90%) participated in team sports (53% rugby, 21% netball, 7% soccer, 5% field hockey, and 4% other team sports). Participants had to be free from injury, pain, or any other issue limiting physical activity participation at the time of study participation. Previous injuries were not an exclusion criterion. The study protocol was approved by our Human Research Ethics Committee [HREC(Health)#41] and adhered to the Declaration of Helsinki. All participants and their legal guardian when younger than 16

years of age signed a written informed consent document that explained the potential risks associated with testing.

5.2.3 Testing procedure

The testing procedure we used was identical to that described by the developers of the LESS (Padua et al., 2009). For the DLJL, we asked participants to jump horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately rebound for a maximal vertical height. The successful trial was defined as jumping off the box with both feet, landing in front of the designated line, jumping as high as possible straight up in the air upon landing from the box, and completing the task in a fluid motion. We did not provide any feedback on participants landing technique unless they were performing the task incorrectly. Participants used their own sport footwear for testing.

After providing instructions and allowing practice jumps for familiarisation (typically 1), each participant performed three successful trials of DLJL in front of two standard video cameras capturing at 120 Hz (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm). We mounted the cameras on tripods placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m. We allowed participants to rest until they felt ready to perform the task again to limit fatigue. The total testing time was typically 2 minutes per participant.

A qualified physiotherapist who completed over 400 LESS evaluations prior to this study replayed the videos using the Kinovea software (version 0.8.15, www.kinovea.org) and scored all trials using the 17-item LESS scoring sheet (Padua et al., 2009). The physiotherapist used the video analysis software as proposed as a mean to improve the psychometric properties of the LESS (Onate et al., 2010). The average scoring time was typically four minutes per one DLJL. The final LESS score was calculated for every participant according to the five methods reported in the scientific literature: 1) mean of 3 jumps, 2) 1st jump score, 3) 3rd jump score, 4) best jump score, and 5) sum of errors present in at least 2 jumps. The overall LESS score demonstrates good to excellent intra-rater (ICC = 0.82 to 0.99) and inter-rater (ICC = 0.83 to 0.92; Hanzlíková & Hébert-Losier, 2020b).

5.2.4 Statistical analyses

From our data, we assessed the effect of calculation method on: 1) estimated group mean LESS score, 2) group-level risk categorisation [proportion of participants categorise at high (LESS ≥ 5) and low (LESS < 5) injury risk], and 3) individual-level risk categorisation (consistency of high and low injury risk category and odds of being at high risk for individual participants). The mean of 3 jumps method is the most common (Beese et al., 2015; Beutler et al., 2009; DiStefano et al., 2018; DiStefano et al., 2009; Kuenze et al., 2015; Mohammadi et al., 2017; Padua et al., 2015; Padua et al., 2012; Pfile et al., 2016; Scarneo et al., 2017; Smith et al., 2012a; Theiss et al., 2014; Welling et al., 2016; Wesley et al., 2015); therefore, we set the mean of 3 jumps as the reference method in all analyses and compared other methods to the reference method. Note that comparisons between all methods are presented in Appendix E1–E4.

The influence of the calculation method on group mean LESS score and group-level risk categorisation was estimated using a Generalised Estimating Equation (GEE) (Liang & Zeger, 1986). We selected the GEE approach as estimates consider the variation within individuals in presence of multiple observations. The GEE approach provides an estimate with its 95% confidence interval [lower, upper] of the average effect in a population, applying robust standard errors to account for within-individual correlations.

We used the GEE model with a Gaussian (normal) distribution to explore the influence of the final LESS score calculation method on the group mean LESS score. It is common in studies using a single trial for the final LESS score calculation to report LESS scores as continuous data; i.e., mean and standard deviation (Garbenytė-Apolinskienė et al., 2018; Kraus et al., 2019; O'Malley et al., 2017) despite the data being ordinal in nature. This approach is fundamentally flawed; however, to be able to compare group mean LESS scores between different calculation methods, we made the assumption that the continuous outcome of the reference method (mean of three jumps) was comparable to the ordinal outcomes of the other methods. We used a GEE model with a binominal distribution to explore the influence of calculation method on group-level risk categorisation, estimating the odds ratio of being at high risk of injury for a given method compared to the reference method. Both GEE models applied an exchangeable correlation structure, which assumes that all observations have the same

amount of correlation over time. To have more certainty that differences between methods were not due to multiple comparisons, we decided a priori to adjust the 95% confidence intervals and p-values using the Bonferroni method in post-hoc analysis.

To explore the individual-level risk categorisation, we assessed the agreement (n and %) in risk categorisation with regards to the reference method using odds ratio and McNemar's tests. The odds ratio shows which one of the two methods is more likely to score individuals at high injury risk; i.e., the number of participants at high risk exclusively for a given method divided by the number of participants at high risk exclusively for the reference method. McNemar's test compares two proportions; in our case, whether the proportion of participants at high injury risk for a particular calculation method significantly differs from that of the reference method.

We set a significance level of $p \leq 0.05$ for all analysis. The statistics were computed using Microsoft® Excel for Office 365 MSO and RStudio® version 1.1.463 with R version 3.5.2. All participants finished the study, and we analysed the complete data set.

5.3 Results

The group mean ± standard deviation (minimum to maximum) LESS score was: 6.07 ± 1.71 errors (0.67 to 11.67 errors) for the reference method; 5.87 ± 1.87 errors (0 to11 errors) for the 1st jump method; 6.10 ± 2.00 errors (1 to13 errors) for 3rd jump method; 5.13 ± 1.75 errors (0 to 11 errors) for best jump score method; and 6.02 ±1.90 errors (1 to 13 errors) for sum of errors present in at least 2 jumps method.

5.3.1 Estimated group mean Landing Error Scoring System score

From our data, the GEE model estimated a group mean LESS score of 5.91 [5.73 to 6.10] errors for the reference method. The GEE group mean LESS score estimated from the best jump method was significantly lower than the reference method ($p < 0.001$; Table 7). Comparisons of estimated group mean LESS scores between all methods are presented in Appendix E1 and E2.

Table 7. Comparison of the group mean Landing Error Scoring System score between other methods versus reference method using Generalised Estimating Equations.

Method	Mean difference in LESS scores* (error) [95% CI]	p – value*
1st jump score	-0.16 [-0.55 to 0.24]	1.000
3rd jump score	0.07 [-0.34 to 0.48]	1.000
Best jump score	-0.92 [-1.30 to -0.54]	< 0.001
Error present in at least 2 jumps	-0.01 [-0.41 to 0.38]	1.000

Mean of 3 jumps was set as the reference method. Abbreviations: LESS, Landing Error Scoring System; CI, confidence interval. * difference versus reference method using the Bonferroni correction.

5.3.2 Group-level risk categorisation

Table 8 presents the number of individuals categorised at high and low risk of injury for each method. At a group-level, odds of high-risk categorisation were significantly lower in the best jump score method compared to the reference method based on GEE analyses (odds ratio 0.50, $p < 0.001$, Table 8). Comparisons of odds ratios between all methods are presented in Appendix E3 and E4.

Table 8. Number of participants at high and low risk and Generalised Estimating Equation of the group-level risk categorisation.

Method	Participants at high risk	Participants at low risk	Odds ratio* [95% CI]	p – value*
Reference method	76% (n = 249)	24% (n = 79)	--	--
1st jump score	77% (n = 251)	23% (n = 77)	1.03 [0.75 to 1.43]	1.000
3rd jump score	80% (n = 261)	20% (n = 67)	1.24 [0.90 to 1.69]	0.569
Best jump score	61% (n = 201)	39% (n = 127)	0.50 [0.39 to 0.65]	< 0.001
Error present in at least 2 jumps	79% (n = 260)	21% (n = 68)	1.21 [0.94 to 1.57]	0.333

Mean of 3 jumps was set as a reference method. Abbreviations: CI, confidence interval. Odds ration greater than 1.00 indicate higher odds of high injury risk category for given method compared to the reference method. *comparing other methods with reference method using the Bonferroni correction.

5.3.3 Individual-level risk categorisation

At an individual-level, inconsistency in risk categorisation compared to the reference method ranged from 8 to 15% across methods (Table 9). The individual-level risk

categorisation was significantly different for the best jump score compared to the reference method ($p < 0.001$, Table 9), with a greater number of individuals exclusively at high risk for the reference method.

Table 9. Individual-level risk categorisation. Four calculation methods are compared to the reference method (mean of 3 jumps).

Method	Consistent[a]	Inconsistent[a]	High risk given method[b]	High risk reference method[b]	Odds ratio[c] [95% CI]	McNemar's test *p* – value*
1st jump score	85% (n = 280)	15% (n = 48)	n = 25	n = 23	1.09 [0.62 to 1.92]	0.885
3rd jump score	88% (n = 288)	12% (n = 40)	n = 26	n = 14	1.86 [0.97 to 3.56]	0.081
Best jump score	85% (n = 280)	15% (n = 48)	n = 0	n = 48	--	< 0.001
Error present in at least 2 jumps	92% (n = 301)	8% (n = 27)	n = 19	n = 8	2.38 [1.04 to 5.43]	0.052

Abbreviations: CI, confidence interval. **p*-value: difference in individual-level risk categorisation versus reference method.

[a] Participants categorised consistently/inconsistently versus the reference method.

[b] Participants categorised at high risk exclusively for a given/reference method.

[c] The number of participants at high risk exclusively for a given method divided by the number of participants at high risk exclusively for the reference method.

5.4 Discussion

The use of clinical tools such as the LESS to assess injury risk is common in sport science and clinical practice (Dallinga et al., 2012; McCall et al., 2015). It is essential that clinical tools provide outcomes that are reproducible and comparable between practitioners and studies to improve healthcare management and scientific inference. The authors who introduced the LESS to the scientific community did not explicitly specify the method used to calculate the final LESS score (Padua et al., 2009). As a

result, five different calculation methods have been reported in the literature. This paper explored the influence of these five calculation methods on estimated group mean LESS scores, group-level risk categorisation, and individual-level risk categorisation. We provide clinically meaningful evidence that the LESS calculation method can affect clinical outcomes and their interpretation and result in altering injury risk classification of participants and affecting injury prevention efforts.

LESS data are commonly averaged and compared between (e.g., males versus females, injured versus uninjured) or within (e.g., pre versus post-intervention) groups to make clinical inferences (DiStefano et al., 2018; Pryor et al., 2017; Smith et al., 2012a). When we compared estimated group mean LESS scores using different calculation methods, we found that the best jump method led to lower LESS score estimates (0.92 errors, $p < 0.001$) compared to the reference method. According to a literature review exploring the psychometric properties of the LESS (Hanzlíková & Hébert-Losier, 2020b), the standard error of measurement (SEM) for intra-rater reliability is 0.19–0.52, inter-rater reliability is 0.71, and test-retest reliability is 0.81. These SEM values indicate that the magnitude of the difference in estimated group mean LESS score between the best jump and reference calculation methods is clinically meaningful. According to Padua et al. (2009), poor LESS scores are associated with decreased peak knee and hip flexion angles, and increased peak knee valgus angles and moments, all of which have been associated with high injury risk landing strategies (Hewett et al., 2005). Basing the final LESS score of individuals on their best jump (i.e., the trial with the lowest number of errors) may mask their innate risk of injury and habitual movement patterns. The greatest similarity with the reference method was the 3rd jump score and score with an error present in at least 2 jumps. To score only the 3rd jump rather than all three jumps could be beneficial for large-scale screening initiatives, as it would decrease the total scoring time and associated costs, yet still reflect typical group-level performance according to our analyses.

On the other hand, when the group-level risk categorisation (number of participants at high and low injury risk) is of interest, the odds of being categorised at high risk of injury was significantly lower using the best jump score method compared to the reference one (odds ratio 0.50, $p < 0.001$). This significant difference in risk classification between methods could lead to different interpretations of clinical and research outcomes. The 1st jump score calculation method was the most comparable to

the reference method in terms of risk categorisation at a group-level (odds ratio 1.03). The 1st jump score method could be suitable for use when the proportion of participants at high and low injury risk is of interest, and when the time available for testing and scoring is limited as it only requires completing of a single DLJL instead of three. Although not as similar in magnitude to the reference method in terms of group mean LESS scores compared to the 3rd jump score method (see Table 7), using the 1st jump score might offer the best compromise in terms of reflecting LESS data from three trials and risk categorisation at a group level.

Previous literature reviews and meta-analyses provide evidence for the effectiveness of neuromuscular training programmes in reducing the incidence of sport injuries (Hübscher et al., 2010; Yoo et al., 2010), including ACL. For injury prevention programmes to be cost-effective and efficient, identifying individuals at high injury risk is important. In individual-level risk categorisation, the method most consistent (92%) with the reference method was that of scoring errors present in at least 2 jumps, although participants were more likely to be categorised at high risk of injury exclusively for this method (19 participants) compared to exclusively for the reference method (8 participants). The advantage of the errors present in at least 2 jumps method is that it reflects the typical errors of an individual. Practitioners can use this information to target these faulty movement patterns in individual preventative programmes. The other calculation methods had a 12 to 15% inconsistency in risk categorisation compared to the reference method, reaching statistical significance for the best jump score method ($p < 0.001$). The odds ratio for the best jump score compared to the reference method is infinity, as the best jump score (jump with the lowest number of errors) will always have a similar or lower number of participants at risk when compared to the reference method (mean of 3 jumps).

Scoring a single trial may sometimes be needed when resources (time or finance) are constrained or to answer a specific question, such as to determine the best possible performance of a person. However, it is important to note limitations in the use of a single trial to encapsulate an individual's movement patterns. Given that variability is present in all human movement, using a single trial may result in a poor representation of an individual's inherent movement variability. More specifically, a single trial protocol may by chance represent a typical performance, but also an atypical one. Using a single trial has been proposed invalid and unreliable for testing human

movement (Bates, Dufek, & Davis, 1992). Previous studies have concluded that averaging a minimum of four trials is needed to achieve stability in ground reaction force variables during double-leg landing (James, Herman, Dufek, & Bates, 2007); eight to thirteen trials for stable mean ankle, knee, and hip kinetic values during double-leg jumping (Rodano & Squadrone, 2002); and twenty strides for stable kinematic and spatiotemporal values whilst running on a treadmill (Riazati, Caplan, & Hayes, 2019). Hence, the LESS calculation method using the mean of the 3 trials or sum of errors present in at least two jumps are recommended over single trial methods to represent typical movement patterns.

The main limitation of this study is that group-level and individual-level risk categorisation were based on a threshold of 5 errors per Padua et al. (2015). This threshold derives from a population of young (13.9 ± 1.8 years) elite male and female soccer players and might not be appropriate for our population of predominantly young physically active adults (18.1 ± 4.3 years). Another limitation is that we set the mean of 3 jumps as a reference method given its frequent use (Beese et al., 2015; Beutler et al., 2009; DiStefano et al., 2018; DiStefano et al., 2009; Kuenze et al., 2015; Mohammadi et al., 2017; Padua et al., 2015; Padua et al., 2012; Pfile et al., 2016; Scarneo et al., 2017; Smith et al., 2012a; Theiss et al., 2014; Welling et al., 2016; Wesley et al., 2015) even though this method is not necessarily a "gold standard" method. It is important to note that our study assessed the difference between LESS computational methods on scores and risk categorisation of individual. Our study did not assess which scoring method has the greatest predictive ability, with only the mean of 3 jumps method used for this purpose to date (Padua et al., 2015; Smith et al., 2012a). Moreover, the Bonferroni method used to adjust 95% confidence intervals and *p*-values during post-hoc comparisons is a conservative method and could inflate Type II error. However, the interpretation of our results would not be altered by changing the adjusting method given how far away our *p*-values were from the set significance level of $p \leq 0.05$.

5.5 Conclusion

This paper found that final LESS score calculation methods can influence estimated group mean LESS scores, group-level risk categorisation, and individual-level risk categorisation to various extents. In line with our expectations, the best jump method

exhibited the greatest difference in group mean LESS score from the reference method. The significant difference of 0.92 errors in LESS score between methods is clinically meaningful based on reported psychometric properties across the scientific literature (Hanzlíková & Hébert-Losier, 2020b); and therefore, interpreting results from studies or clinical practices using the best jump computational method in relation to the reference method should be done with caution. Using the mean score from the 3 DLJL trials is the most common in the scientific literature and the only one with demonstrated predictive ability (Padua et al., 2015), and hence, is recommended. However, when there are time or financial restrictions, scoring the 3rd jump offers a suitable option when mean group score is of interest, whereas scoring the 1st jump is a viable option when the group-level risk categorisation is of interest. When both are of interest, the former option offers the best compromise. Clinicians should bear in mind that human movement is variable and that scoring a single trial only may not represent the typical performance of an individual. Selecting the mean of 3 trials or sum of errors present in at least 2 trials methods reflects typical LESS performance and individual movement errors than single trial methods. The different LESS calculation methods provide different information, outcomes, and clinical interpretations that need consideration in research and practice.

CHAPTER 6

Clinical implications of landing distance on Landing Error Scoring System scores

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Prelude: Authors have reported using different landing distances when administering the Landing Error Scoring System (LESS). The original LESS protocol required individuals to jump forward from a 30-cm box to 50% of their body height (Padua et al., 2009); however, some authors use different landing distances during the LESS assessment (Distefano et al., 2013a; Onate et al., 2010). The effect of altering landing distance on LESS scores is currently unknown. If the LESS outcomes remain unaffected by landing distance, testing of large cohorts would be facilitated and less time-consuming as it would be unnecessary to adjust the landing distance to match 50% of an individual's height. Therefore, the aim of this chapter is to explore the influence of landing distance on LESS scores and risk categorisation.

6.1 Introduction

The LESS is a clinical assessment tool that examines the presence of biomechanical "errors" that have been linked to non-contact Anterior Cruciate Ligament (ACL) injury during jump-landing task (Padua et al., 2009). Clinicians evaluate frontal and sagittal plane videos of jump-landing and visually evaluate aberrant lower-extremity and trunk kinematics at initial ground contact and peak knee flexion instances. A subjective assessment of the quality of movement between initial ground contact and peak knee flexion is also considered during LESS scoring. The scientific literature and clinical community use a range of terminology to describe the jump-landing task used to score the LESS, including jump-landing (DiStefano et al., 2018; Distefano et al., 2013a; Everard et al., 2017; Hanzlíková & Hébert-Losier, 2020b), drop-jump (Onate et al., 2010), drop-landing (Kuenze et al., 2015), and drop-vertical jump (Fox et al., 2016; Read et al., 2019; Smith et al., 2012a). Given that the jump-landing task of the original LESS is fundamentally active in nature; i.e., requires an individual to jump forward (Padua et al., 2009), in contrast to the more passive nature of the drop-jump task, the term jump-landing will be used to reference the jump-landing task of the LESS.

The LESS scores range from 0 to 17 errors, where a greater score indicates a greater number of landing errors, poorer landing biomechanics, and greater risk of sustaining non-contact ACL injury. A recent systematic review concluded that the LESS is a reliable screening tool, however the predictive value of the LESS for ACL injury remains uncertain based on current scientific evidence (Hanzlíková & Hébert-Losier, 2020b). More specifically, Padua et al. (2015) evaluated ACL injury risk in elite-youth soccer players in a prospective study and concluded that LESS scoring has a good sensitivity (86%) and acceptable specificity (64%) in identifying risk of non-contact ACL injury. The relative risk was 10.7 times greater when LESS scores were ≥ 5 errors compared to lower than 5 errors. In contrast, Smith et al. (2012a) found no significant relationship between LESS and ACL injury incidence. Differences in sampled populations in terms of age, main sporting event, and previous injury status, as well as lack of statistical power in both studies (Padua et al., 2015; Smith et al., 2012a), are potential underlying factors to the diverging findings on the predictive value of the LESS. Despite these diverging findings in terms of the predictive value of the LESS, this assessment is commonly used in research and practice to evaluate faulty movement patterns, the effect of interventions on neuromuscular control, and

rehabilitation outcomes (Hanzlíková & Hébert-Losier, 2020b; Padua et al., 2015; Smith et al., 2012a). Furthermore, from the existing field-based injury screening methods, the LESS is often the one that is the most recommended for use based on reviews of the literature (Fox et al., 2016; Read et al., 2019).

The jump-landing task used during LESS assessment involves jumping forward from a 30-cm high box to a distance of 50% of an individual's body height, and immediately jumping upwards for maximal vertical height (Padua et al., 2009). Although the majority of the scientific studies using LESS set the jump distance according to the original protocol (Everard et al., 2017; Kuenze et al., 2015; Padua et al., 2009; Smith et al., 2012a), variations exist. For instance, Onate et al. (2010) standardised landing distance to 30 cm from the box and Distefano et al. (2013a) implemented a landing distance equal to 25% of participant's body height, although no rational was provided. Moreover, anecdotal observations and discussions with clinicians and practitioners in health and sports indicate that landing distance is often not set when using the LESS, and rather the more passive "dropping down" rather than active "jumping from" the box method is used to reflect the strength and conditioning drop-jump approach to assess mechanical outputs of the lower-extremity (Bobbert & Huijing, 1987). Changes in clinical tests and protocols can exert non trivial effects on outcomes and their interpretation (Hébert-Losier, 2017).

It is essential in both research and practice that outcomes from assessments are reproducible and comparable between studies to improve healthcare management and scientific inference. If LESS scores and risk categorisation remain unaffected by landing distance, testing of large cohorts would be facilitated and less time-consuming as removing the need to adjust the landing distance to match 50% of an individual's height. We aimed to explore whether the landing distance influenced LESS scores and risk categorisation. We assumed the null hypothesis in that landing distance would exert no significant effect on mean LESS score, group-level risk categorisation, and individual-level risk categorisation.

6.2 Methods

6.2.1 Sample size calculation

The sample size calculation for this study was based on data from two previous studies using the LESS, one according to the original protocol; i.e., 50% body height (Smith et al., 2012a) and the second using a modified protocol; i.e., 25% body height (Distefano et al., 2013a). Both studies involved similar cohorts (29 and 20 physically active males, age 18.5 ± 2.5 and 20 ± 2.0 years, respectively). We used standard two-tailed hypothesis equations, 95% power ($\beta = 0.05$), 5% significance level ($\alpha = 0.05$), critical values of the *t* distribution, and data from these previous studies (Distefano et al., 2013a; Smith et al., 2012a) to calculate sample size requirements. These equations indicated that 64 participants were needed to identify group differences in mean LESS scores between these two jump distances. To account for 10% of potential withdrawals and missing data, we recruited 70 participants.

6.2.2 Participants

Participants had to be 16 to 30 years old, regularly engaged in physical activity (at least once a week) at any level, and free from injury, pain, or any other issue that would limit physical activity participation. Both genders (males and females) were included. Previous injuries were not an exclusion criterion. The study protocol was approved by our institution's health research ethics committee [HREC(Health)#41] and adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks associated with testing.

6.2.3 Testing procedure

The testing procedure we used was identical to that described by the developers of the LESS (Padua et al., 2009) in both experimental conditions with the exception of landing distance from the box. During the jump-landing task, we required participants to jump from a 30-cm high box under two landing conditions: (1) set distance of 50% of their body height ($d_{50\%}$), and (2) self-selected distance (d_{ss}) where landing distance was not set. We instructed participants to immediately jump upwards for maximal vertical height upon landing. We placed an emphasis on actively jumping (not dropping) off the box with both feet, jumping as high as possible straight up once they landed from the box, and completing the task in a fluid motion. We did not provide any feedback on

participants landing technique unless they were performing the task incorrectly. After task instructions and practice jumps for familiarisation (typically 1), each participant performed three successful jump-landing trials under each landing condition. The order of the two landing conditions was randomised. We allowed participants to rest until they felt ready to perform the task between trials within conditions to limit fatigue (typically 1 minute), with at least 15 minutes of seated rest between conditions. All tests were completed in a single experimental session.

Two standard video cameras capturing at 120 Hz (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm) recorded the jump-landing tasks. We mounted the cameras on tripods placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m. A qualified physiotherapist who completed over 400 LESS evaluations replayed the videos using the Kinovea software (version 0.8.15, www.kinovea.org) and scored all 6 trials using the 17-item LESS scoring sheet (Padua et al., 2009). The mean LESS score from the three trials completed under each condition was used for statistical analysis. The physiotherapist could not be blinded to the landing condition due to the visibility of the landing distance on the videos; however, the assessor was blinded to the participants' scores under the alternate condition. The physiotherapist used the Kinovea video analysis software also to measure the length of the jump (distance from the box to the heel closest to the box during landing) for each trial subsequent video calibration to a 1-m ruler.

6.2.4 Statistical analyses

From our data, we assessed the effect of landing condition on 1) group mean LESS score, 2) group-level risk categorisation [proportion of participants categorise at high (LESS ≥ 5 errors) and low (LESS < 5 errors) injury risk], and 3) individual-level risk categorisation (consistency of high and low injury risk category). The landing distance (in cm and expressed as percentage of body height) and the proportion of specific LESS errors between the two conditions were also compared.

The influence of the landing condition on group mean LESS score, group-level risk categorisation, and landing distance was estimated using a Generalised Estimating Equation (GEE) (Liang & Zeger, 1986). The GEE approach provides an estimate of the average effect in a population, applying robust standard errors to account for within-

individual correlations. We used the GEE model with a Gaussian (normal) distribution to explore the influence of the landing condition ($d_{50\%}$ vs d_{SS}) on the group mean LESS score and landing distance. We applied a binominal distribution to explore the influence of landing condition on group-level risk categorisation to estimate the odds ratio (OR) of being categorised at high injury risk in the d_{SS} compared the $d_{50\%}$ condition. Both GEE models applied an exchangeable correlation structure.

To explore the individual-level risk categorisation, we assessed the agreement (*n* and %) in risk categorisation between the two landing conditions using OR and two-tailed McNemar's tests. The OR indicates whether a landing condition is more likely to categorise individuals at high injury risk; specifically, the number of participants at high risk exclusively for the $d_{50\%}$ condition divided by the number of participants at high risk exclusively for the d_{SS} condition. McNemar's test compares two proportions; in our case, whether the proportion of participants at high risk significantly differs between conditions. McNemar's tests were also used to compare the proportion of specific LESS movement errors for LESS items 1 to 15 (scored 1 – error present, 0 – error absent) between conditions. Due to different scoring of items 16 and 17 (0 to 2 errors), we used the two-sided Wilcoxon signed rank test to compare these items between conditions.

We set the significance level at $p \leq 0.05$ for all analyses. The statistics were computed using Microsoft® Excel for Office 365 MSO and RStudio® (version 1.1.463) in R (version 3.5.2). All participants finished the study, and the complete data set was analysed.

6.3 Results

A sample of 70 young adults (34 males, 36 females) participated in this study voluntarily. Age, height, and mass (mean ± standard deviation) for males were 18.9 ± 0.8 years (range: 18 to 21 years), 180.3 ± 6.7 cm, and 80.1 ± 14.4 kg; and for females were 19.6 ± 2.4 years (range: 17 to 26 years), 169.0 ± 6.9 cm, and 64.5 ± 7.1 kg. All participants were involved in physical activity on average 3.7 times per week, 6.8 hours a week, and for at least 2 years. The participants' levels of engagement with sport were 51% club level, 20% school level, 19% national level, and 10% recreational.

Participants landed at the prescribed 50% of body height under $d_{50\%}$ and significantly closer to the box under the d_{SS} condition ($p < 0.001$, Table 10). The group mean ± standard deviation LESS score was 5.58 ± 1.79 errors (range: 1.67 to 11.00 errors) for $d_{50\%}$ and 5.57 ± 1.74 errors (range: 1.30 to 10.7 errors) for d_{SS} conditions, with 66% and 64% of participants categorised at high risk of injury based on the threshold of LESS ≥ 5 errors (Table10). Based on GEE estimates, group mean LESS scores ($p = 0.969$) and odds of being classified at high injury risk at a group-level (OR: 0.94 [0.47 to 1.88], $p = 0.859$) were similar between conditions (Table 10).

Table 10. Comparison of landing distances, Landing Error Scoring System scores, and group-level risk categorisation between two landing conditions using Generalised Estimating Equations.

	Conditions		**Difference**	
Variables	$d_{50\%}$ [95% CI]	d_{SS} [95% CI]	Mean [95% CI]	*p*-value
Landing distance (cm)[a]	86.19 [82.98 to 89.40]	45.42 [40.87 to 49.97]	-40.77 [-45.32 to -36.32]	< 0.001
Landing distance (% height)[a]	49.39% [47.57 to 51.21]	26.11% [23.54 to 28.67]	-23.28% [-20.73 to -25.81]	< 0.001
LESS (errors)	5.58 [5.17 to 5.99]	5.57 [4.98 to 6.16]	-0.01 [-0.59 to 0.57]	0.969
% at high risk (*n*)[b]	65.71% (46)	64.29% (45)	0.94[c] [0.47 to 1.88]	0.859

Abbreviations: CI, confidence interval; $d_{50\%}$, distance of 50% body height; d_{SS}, self-selected distance.

[a] Distance between box and heel landing closer to the box.

[b] LESS score ≥ 5 errors.

[c] Odds ratio, values lower than 1.00 indicate lower odds of high injury risk compared to $d_{50\%}$.

At an individual-level, risk categorisation was inconsistent for 33% ($n = 23$) of participants between the two conditions (Figure 17). Twelve participants were categorised at high risk of injury exclusively for $d_{50\%}$ (Figure 17). Their mean difference in LESS scores was 1.85 errors between the two conditions. In contrast, eleven participants were categorised at high risk of injury exclusively for d_{SS} (Figure 17). Their mean difference in LESS scores was 1.82 errors between conditions. The difference in the proportion of participants at high and low injury risk was not significant between two landing conditions (McNemar's test $p = 1.000$), with slightly greater odds of being

at high injury risk (OR: 1.09 [0.48 to 2.47]) in the $d_{50\%}$ condition (Figure 17). The proportion of specific LESS errors was significantly different for ankle plantar flexion at initial contact ($d_{50\%} > d_{SS}$, $p = 0.004$), knee valgus at initial contact ($d_{50\%} < d_{SS}$, $p < 0.001$), narrow stance width ($d_{50\%} < d_{SS}$, $p = 0.002$), toe-out foot position ($d_{50\%} > d_{SS}$, $p = 0.008$), and knee valgus displacement ($d_{50\%} > d_{SS}$, $p = 0.001$, Table 11).

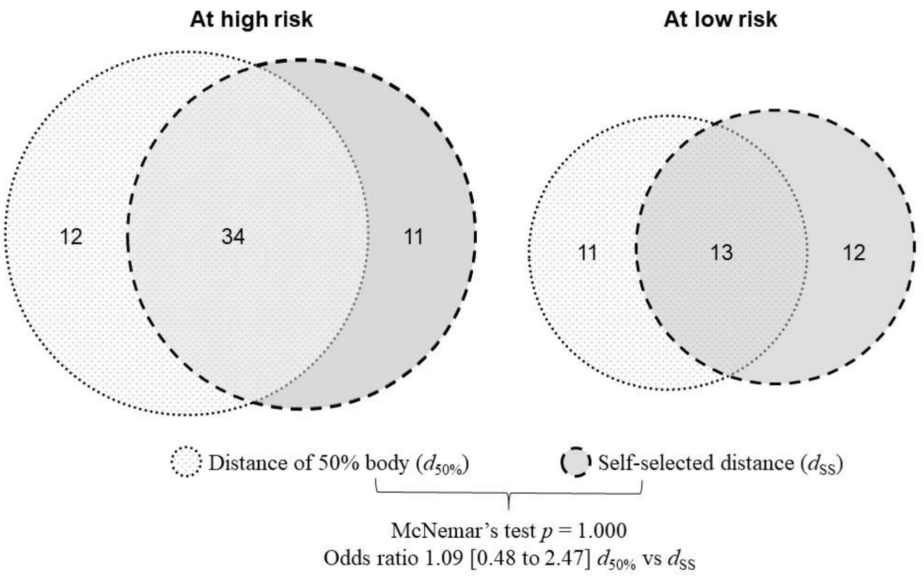


Figure 17. Number of participants at high (LESS ≥ 5 errors) and low (LESS < 5 errors) risk of injury for each landing distance condition. LESS, Landing Error Scoring System.

Table 11. Landing Error Scoring System (LESS) specific errors (n = 210 jump-landing tasks).

No	Items	Number of errors		p-value[a]
		$d_{50\%}$	d_{SS}	
1.	Knee flexion at initial contact	142	141	1.000
2.	Hip flexion at initial contact	0	0	1.000
3.	Trunk flexion at initial contact	2	1	1.000
4.	Ankle plantar flexion at initial contact	16	4	0.004*
5.	Knee valgus at initial contact	13	42	< 0.001*
6.	Lateral trunk flexion at initial contact	140	121	0.070

7.	Stance width (wide)	16	23	0.092
8.	Stance width (narrow)	108	132	0.002*
9.	Foot position (toe-in)	1	0	1.000
10.	Foot position (toe-out)	53	38	0.008*
11.	Symmetric foot contact at initial contact	147	157	0.314
12.	Knee flexion displacement	12	19	0.167
13.	Hip flexion at maximal knee flexion	6	4	0.754
14.	Trunk flexion at maximal knee flexion	47	38	0.122
15.	Knee valgus displacement	103	82	0.001*
16.	Joint displacement	116	116	1.000
17.	Overall impression	237	236	0.871

Abbreviations: $d_{50\%}$, distance of 50% body height; d_{SS}, self-selected distance.

* Significantly different between conditions ($p < 0.05$).

[a] McNemar's test *p*-values comparing proportion of specific errors scored for LESS items 1 to 15 and Wilcoxon signed rank test *p*-values for LESS items 16 and 17 between conditions.

6.4 Discussion

Our study explored the influence of landing to a distance of 50% of body height as prescribed in the original LESS protocol (Padua et al., 2009) versus a self-selected distance as typically prescribed by strength and condition, athletic trainers, and physiotherapists on mean LESS score, group-level risk categorisation, individual-level risk categorisation, and occurrence of specific LESS errors. Landing distance did not significantly influence the mean LESS score, or the proportion of participants categorised at high (LESS ≥ 5 errors) and low (LESS < 5 errors) injury risk; however, occurrence of specific LESS errors and individual-level risk categorisation were inconsistent between the two landing conditions. Based on these results, researchers can consider using d_{SS} to facilitate testing of large cohorts when only group mean LESS score or the proportion of participants at high and low injury risk in a given population is of interest, with the caveat that the injury risk threshold of 5 errors set for LESS has not been validated for d_{SS} (Padua et al., 2015). However, in clinical and sport environments, the specific movement errors and injury risk categorisations are of primary interest and using d_{SS} during LESS assessment might lead to different LESS errors and risk categorisation at an individual level compared to $d_{50\%}$. Given that LESS

with $d_{50\%}$ is the protocol that has shown some predictive value of ACL injury risk at an individual-level (Padua et al., 2015), this protocol should be used in a first instance in clinical and sport settings until the predictive ability of LESS applied to d_{ss} is prospectively examined. In any circumstance, explicit documentation of landing distance is encouraged to ensure the reproducibility of protocols and outcomes.

The original LESS requires individuals to perform a jump-landing task from a 30-cm box to $d_{50\%}$ (Padua et al., 2009). However, scientists have implemented various landing distances for LESS assessment (Distefano et al., 2013a; Onate et al., 2010) than the $d_{50\%}$ originally described by Padua et al. (2009) with no prior knowledge on how variations in protocol influence outcomes. Moreover, anecdotal observations and discussions with clinicians and practitioners in health and sports indicate that landing distance is often not set when using the LESS. On average, $d_{50\%}$ equated to a landing distance of 86.19 cm in our study. In contrast, when individuals self-selected their landing distance, they landed at a distance equalling 26.11% of their body height, the equivalent of 45.42 cm, close to the 25% used in a study by Distefano et al. (2013a) For us, this landing distance was approximately 40 cm closer to the box than $d_{50\%}$.

The mean LESS scores and group-level risk categorisation were similar between the two landing distances. Changing the landing distance of jumps has been shown to alter landing biomechanics significantly (Sell, Akins, Opp, & Lephart, 2014; Simpson & Kanter, 1997; Simpson & Pettit, 1997). With increasing jump distance from 20 to 80% (35.2 to 140.7 cm) of body height (Sell et al., 2014) during the double-leg stop-jump task and from 30 to 90% (42 to 163 cm) of maximal jump distance during a travelling jump in dancers (Simpson & Kanter, 1997; Simpson & Pettit, 1997); anterior tibia shear force, peak forward acceleration of the tibia, peak posterior ground reaction shear force, and vertical ground reaction force (GRF) have been reported to increase. These biomechanical variables have been associated with a superior ACL strain and are considered important risk factors for non-contact ACL injury (Bakker et al., 2016; Shimokochi & Shultz, 2008; Yu & Garrett, 2007). As such, one would expect increased ACL strain and worse LESS scores under $d_{50\%}$ compared to d_{SS} due to the increased landing distance, which we did not observe. However, the number of specific LESS movement errors changed between conditions. Specifically, from the 210 jump-landing tasks (70 participants x 3 tasks) scored, 12 more errors for ankle plantar flexion at initial contact (item 4), 18 more errors for toe-out foot position (item 10), and 21 more errors

for knee valgus displacement (item 15) were scored under $d_{50\%}$ compared to d_{SS} condition (Table 11). On the other hand, 29 more errors for knee valgus at initial contact (item 5) and 24 more errors for narrow stance width (item 8) were scored under d_{SS} compared to $d_{50\%}$ condition (Table 11). All of these mentioned LESS movement errors have been shown to have 80 to 100% intra-rater agreement (Onate et al., 2010); hence, it is not probable that these differences between landing distances would be due to poor intra-rater reliability of individual LESS items. The change in the occurrence of specific LESS errors confirm that altering jump distance affects gross movement patterns during LESS assessment. However, given that the change in movement errors was distributed quasi-equally between the two landing distances (i.e., certain errors increased, and others decreased), mean LESS scores and group-level risk categorisation were not affected.

Other than landing distance (Dufek & Bates, 1989, 1990, 1991), box height (Dufek & Bates, 1989, 1990, 1991; Huston, Vibert, Ashton-Miller, & Wojtys, 2001; McNitt-Gray, 1989), footwear (Dufek & Bates, 1991), instructions (Dufek & Bates, 1989, 1990), subsequent movement (Bates, Ford, Myer, & Hewett, 2013), and history of ACL rupture (Hébert-Losier, Schelin, Tengman, Strong, & Häger, 2018) can all affect jump-landing biomechanics and neuromuscular control. For instance, the vertical GRF was 1.1 times body weight when barefoot compared to shod during netball landings (Dufek & Bates, 1991) and increasing the heights of boxes from 32 to 72 to 128 cm (Dufek & Bates, 1991; McNitt-Gray, 1989) increased the vertical GRF of landing from 3.9 to 6.3 to 11 times body weight, respectively. When vertical GRF increases, individuals are more prone to land with greater knee flexion displacement to moderate forces and protect the body against high impact loads (Huston et al., 2001). Huston et al. (2001) showed that the knee angle at initial contact increased from 7 to 12° and maximum knee flexion angle increased from 88 to 104° when landing height increased from 20 to 60 cm during drop-jump tasks. The “softness” of landing (item 16, Table 11), knee flexion angle at initial contact (item 1, Table 11), and knee flexion displacement (item 12, Table 11) during the jump-landing task are items scored during the LESS (Padua et al., 2009). It is likely that changes in box height would influence LESS scores to a greater extent than changes in landing distance. Certain studies have used a 40 cm rather than a 30-cm box (Kraus et al., 2019) and tested participants barefoot (O'Malley et al., 2017) during the LESS, with no indications of the clinical

implications of this alteration in box height and footwear compared to the original protocol (Padua et al., 2009).

Whereas the odds of being classified at high injury risk were similar between $d_{50\%}$ and d_{SS} conditions at a group-level (p = 0.859) based on the established cut-off score of 5 errors (Padua et al., 2009), only a subset of individuals (n = 34, 49%) were categorised at high risk under both conditions. The difference in landing biomechanics and related difference in number of specific LESS errors between conditions is the most probable source of inconsistency in risk categorisation. The mean difference in LESS scores between conditions for participants scored at high-risk category exclusively for $d_{50\%}$ and d_{SS} was 1.85 and 1.82 errors, respectively. According to studies exploring the psychometric properties of the LESS, the standard error of measurement (SEM) for intra-rater reliability is 0.19 to 0.52, inter-rater reliability is 0.71, and test-retest reliability is 0.81 errors (Hanzlíková & Hébert-Losier, 2020b). These SEM values indicate that the magnitude of the difference in LESS score between participants categorised at high risk exclusively for a given landing condition is clinically meaningful. Therefore, we caution against using d_{SS} when individual errors and individual-level risk categorisation is of interest.

The main limitation of this study is that group-level and individual-level risk categorisation were set at 5 errors based on a prospective study from Padua et al. (2015) Research on other functional movement screens, i.e., YBT and FMS, indicate that injury risk thresholds should consider sex, sport, and age (Lehr et al., 2013). The threshold of 5 errors derives from a population of young (13.9 ± 1.8 years) elite soccer players (Padua et al., 2015) and might not be appropriate for our population of young physically active adults (19.3 ± 1.8 years). However, no other population-specific cut-off score has been established to date for the LESS. Furthermore, it is important to note that the predictive ability of the LESS for non-contact ACL injury is uncertain based on current evidence (Padua et al., 2015; Smith et al., 2012a). We also caution that our sampled population of 70 active young individuals may limit the generalisability of our findings to younger and older athletic populations or less active groups.

6.5 Conclusion

Group mean LESS scores and the proportion of participants categorised at high and low risk of injury based on a threshold of 5 errors are similar between landing to a distance

of 50% of an individual's height compared to landing to a self-selected distance. In research, the LESS data are commonly averaged and compared between groups (e.g., males versus females, injured versus uninjured) or within (e.g., pre versus post-intervention) to make clinical inferences (DiStefano et al., 2018; Pryor et al., 2017; Smith et al., 2012a). In such cases, using d_{SS} could facilitate testing of large cohorts as removing the need to individualise landing distances to 50% of body height. On the other hand, the change in the occurrence of specific LESS errors confirm that altering jump distance affects gross movement patterns during LESS scoring. Injury risk thresholds for d_{SS} have not been validated and might provide inconsistent and inaccurate comparisons at an individual level against LESS findings using $d_{50\%}$. In clinical and sport settings, specific movement errors and injury risk categorisations are of primary interest. Therefore, using the validated protocol of $d_{50\%}$ is recommended until psychometric properties of LESS at d_{SS} have been established given that our data showed inconsistency in individual-level risk category in 33% of participants and significant differences regarding the occurrence of specific LESS errors between d_{SS} and $d_{50\%}$ protocols.

CHAPTER 7

Landing Error Scoring System scores change with knowledge of scoring criteria and prior performance

Hanzlíková, I., & Hébert-Losier, K. (2020). Landing Error Scoring System scores change with knowledge of scoring criteria and prior performance. *Physical Therapy in Sport 46*, 155-161. (Appendix A4)

Prelude: It is common in clinical practice to explain Landing Error Scoring System (LESS) items and give feedback on an individual's landing technique after the LESS test, even when there is an intention to use the test to assess changes due to an intervention or monitor risk factors over time. This provision of feedback may alter performance during the LESS assessment and potentially compromise the value of the LESS as a screening tool. The aim of Chapter 7 is to compare LESS outcomes before and after the provision of individuals' scores and LESS scoring criteria to determine whether providing this information affects an individual's performance.

7.1 Introduction

Lower-extremity injuries are common in sport and are associated with health burden and socioeconomic costs (Knowles et al., 2007). Biomechanical and neuromuscular factors play an important role in non-contact lower-extremity injuries and are potentially modifiable through preventive programmes (Emery et al., 2015; Webster & Hewett, 2018). Therefore, several movement screens have been developed and are used daily to help clinicians identify individuals at high risk of non-contact injuries and inform injury prevention efforts (Cook, Burton, & Hoogenboom, 2006; Dos'Santos et al., 2019; Myer, Ford, & Hewett, 2008a; Padua et al., 2009; Plisky et al., 2009).

The LESS is a movement-based injury risk screening tool that is easy to administer, suitable for testing large cohorts, and can be used both in clinics and in the field without expensive laboratory equipment (Padua et al., 2009). The LESS involves the performance of a double-leg jump-landing task and relies on the use of two standard video cameras, one placed to capture frontal plane motion and the other to capture sagittal plane motion. Using the video recordings to score the LESS, an examiner visually evaluates movement patterns and notes the number of "movement errors" using a 17-item scoring sheet (Table 12). The movement errors are aberrant lower-extremity and trunk movement patterns that have been suggested as factors contributing to non-contact lower-extremity and Anterior Cruciate Ligament (ACL) injuries (Hewett et al., 2010). For instance, several LESS items (items: 1 to 4, 12 to 14, and 16, Table 12) are linked to a stiff landing technique, which results in increased ground reaction forces and loading of joint structures (Laughlin et al., 2011). The magnitude of ground reaction forces has been associated with increased lower-extremity injury risk, including to the ACL (de Noronha et al., 2006; Leppänen et al., 2017). Furthermore, knee valgus angle (items 5 and 15, Table 12) and lateral trunk flexion angle (item 6, Table 12) have been identified as strong predictors of knee ligament injuries in prospective studies (Hewett et al., 2005; Zazulak et al., 2007). The remaining items (items 7 to 11, Table 12) are hypothesised to contribute to ACL injury; however, stronger evidence is still needed. LESS scores range from 0 to 17 errors, where greater scores indicate more movement errors and poorer landing biomechanics (Padua et al., 2015). A prospective study has identified a 10.7 times greater relative risk of sustaining a non-contact ACL injury in presence of a LESS score ≥ 5 errors versus < 5 errors (Padua et al., 2015).

A recent systematic review of the literature concluded that the overall LESS score has good to excellent intra-rater (intraclass correlation coefficient [ICC], 0.82-0.99), inter-rater (ICC, 0.83-0.92), and inter-session (ICC, 0.81) reliability (Hanzlíková & Hébert-Losier, 2020b). Validity of the overall LESS score against three-dimensional (3D) jump-landing biomechanics was good when individuals were divided into four quartiles based on LESS scores, although the validity of the individual LESS items was item dependent (Onate et al., 2010; Padua et al., 2009). However, most of the items addressing key risk factors for ACL showed moderate-to-excellent validity versus 3D motion capture data (Onate et al., 2010). Padua et al. (2015) identified 5 errors as an optimal cut-off point for non-contact ACL injury in a prospective investigation, yielding a sensitivity of 86%, specificity of 64%, and 10.7 times greater relative risk. However, two studies (James et al., 2016; Smith et al., 2012a) did not find any associations between LESS scores and ACL or other sport-related injuries; therefore, the predictive validity of the LESS cannot be ascertained based on current evidence.

For any clinical assessment, it is essential that testing methods provide outcomes that are valid and that changes in scores reflect meaningful changes in function of individuals and identify individuals with differing abilities. Previous studies showed that knowledge of scoring criteria can potentially compromise the clinical utility of the injury risk screening tool (Bryson, Arthur, & Easton, 2018; Frost, Beach, Callaghan, & McGill, 2015). Frost et al. (2015) demonstrated that professional firefighters could significantly improve their performance on the Functional Movement Screen™ (FMS) once provided with information regarding the scoring criteria. Bryson, Arthur, and Easton (2018) confirmed Frost et al. (2015) findings employing a randomised control trial design involving male professional soccer players. The FMS evaluates imbalances in mobility and stability during seven fundamental movement patterns, which are rather slow and controlled movements in nature compared to the more dynamic jump-landing task employed during the LESS.

Besides knowledge of scoring criteria, feedback on performance is able to alter movement patterns (Myer et al., 2013a). A meta-analysis exploring the effect of intervention on ACL injury incidence (Sugimoto et al., 2016) highlighted the importance of plyometrics and technique feedback in intervention programmes. Therefore, jump-landing technique feedback is commonly used in clinical practice and research and is also emphasised in injury prevention programmes which meaningfully

improved LESS scores by 2.4 to 3 errors (O'Malley et al., 2017; Pfile et al., 2016). Examples of instructions used to improve jump-landing technique include: land softly, on your toes and your knees bend; bend hips, knees, and ankles slightly and lean upper body forward; do not let your knee buckle inward; keep upper body stable (O'Malley et al., 2017; Pfile et al., 2016). All these instructions closely correspond with items assessed during LESS scoring (Table 12).

It is common in clinical practice and sport settings to explain LESS items and give feedback on individual's landing technique after the LESS test. Furthermore, jump-landing technique feedback has been shown to meaningfully improve LESS scores when integrated as part of injury prevention programmes (O'Malley et al., 2017; Pfile et al., 2016). It may be that feedback on prior performance may instantly improve LESS scores regardless of adhering to a specific injury prevention programme. Similar to the FMS, it is possible that participants are able to alter performance during the LESS with knowledge of scoring criteria albeit being more dynamic in nature than the FMS tasks. Therefore, our aims were to compare LESS scores, risk categorisation, and specific LESS errors before and after the provision of the LESS scoring criteria and information on individuals' performance. We hypothesised that knowing the scoring criteria and individuals' movement errors would lead to lower LESS scores, a lower number of participants being classified at high risk of injury and alter the proportion of specific errors on the LESS.

7.2 Methods

7.2.1 Sample size calculation

Sample size requirements were calculated using a G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007) from paired *t*-test two-tailed hypothesis equations using an 80% power ($\beta = 0.20$), 5% significance level ($\alpha = 0.05$), critical values of the *t* distribution, and the data from previous studies (Hanzlíková & Hébert-Losier, 2020b; Padua et al., 2009). These studies indicated one error as a clinically meaningful difference in LESS scores (Padua et al., 2009) and 1.7 errors as the typical LESS standard deviation (Hanzlíková & Hébert-Losier, 2020b). The equations indicated that we needed 25 individuals to identify clinically meaningful differences in LESS score before and after the provision of the scoring criteria and information on an individual's

own performance. To account for 20% of potential withdrawals and missing data, we recruited 30 participants.

7.2.2 Participants

Thirty young adults (15 males, 15 females) volunteered to participate in the study. Age, height, and mass (mean ± standard deviation) for males were 21.8 ± 4.8 years (range 19 to 39 years), 179.4 ± 6.5 cm, and 81.3 ± 14.4 kg; and for females were 21.3 ± 3.7 years (range 19 to 32 years), 168.7 ± 7.0 cm, and 68.6 ± 9.4 kg. All participants were involved in physical activity on average 3.4 ± 3.1 times per week for 6.7 ± 6.3 hours a week. Participants had to be free from injury, pain, or any other issues that would limit physical activity participation. Previous injuries were not an exclusion criterion. The study protocol was approved by our institution's health research ethics committee [HREC(Health)#41] and adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks associated with testing.

7.2.3 Testing procedure

We used a repeated measure study design to examine whether individuals' awareness of the LESS scoring criteria and performance would alter LESS scores, risk categorisation, and specific LESS errors. Thirty participants performed 3 x 30-cm double-leg jump-landing tasks (DLJL) for LESS scoring at *Baseline.* A qualified physiotherapist (IH) who completed over 400 LESS evaluations replayed the videos using the Kinovea software (version 0.8.15, www.kinovea.org) and scored all three trials using the 17-item LESS scoring sheet (Table 12). One week later, the participants performed three DLJL again, once *Pre* information and once *Post* information. Following the *Pre* condition, all 17 items used for scoring (Table 12) were explained to participants with pictures showing errors for each item. The participants were also given their individual LESS scores from *Baseline* testing that specified their own movement errors for each one of the three *Baseline* jumps. After the 20-minute education session, participants performed three DLJL to obtain LESS scores *Post* information. The identical verbal instructions were given to participants in all three session, i.e., participants were not specifically instructed to change their landing technique based on their individual's errors. The same assessor (IH) collected data and scored LESS trials in all three instances. A random subsample of 10 jump-landings was scored three times

by the assessor to determine the intra-rater reliability. Assessments were separated by a minimum of one week, with the assessor blinded to the previous assessment scores. The intraclass correlation coefficient was 0.96 and the standard error of the measurement was 0.23 error. The assessor was blinded to participants *Baseline* scores, and the *Pre* and *Post* time points were presented to the assessor in a random fashion.

The original LESS protocol and scoring per Padua et al. (2009) were used in all three instances (*Baseline*, *Pre*, and *Post*). Participants jumped horizontally from a 30-cm box to a line placed at 50% of their body height, and immediately jumped upward for maximal vertical height. Participants were instructed to jump off the box with both feet, land in front of the designated line, jump as high as possible upward upon landing, and complete the task in fluid motion. No feedback on landing technique was provided unless participants were performing the task incorrectly. Participants were given as many practice trials as needed to become comfortable with the task (typically one) and were allowed to rest between trials until they felt ready to perform the DLJL again to limit fatigue. In all instances, the DLJL were recorded by two standard video cameras capturing at 120 Hz (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm). We mounted the cameras on tripods placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m.

7.2.4 Statistical analyses

The mean LESS score from the three DLJL trials, number of individuals categorised at high (LESS ≥ 5 errors) and low (LESS < 5 errors) injury risk (Padua et al., 2015), and number of specific LESS errors were used for statistical analysis. Group mean LESS scores between *Pre* and *Post* conditions were compared using mean differences (MD) with 95% confidence intervals [lower, upper], two-tailed paired t-tests, and corresponding effect sizes (Hedge's g) with 95% confidence intervals. Thresholds for interpreting the magnitude of Hedge's g were set at 0.2, 0.5, and 0.8 for small, medium, and large effects (Lakens, 2013). Effect sizes < 0.2 were considered trivial (Lakens, 2013).

McNemar's tests were used to compare the proportion of participants categorised at high and low injury risk between *Pre* and *Post* conditions. McNemar's test compares proportions; in our case, the proportion of participants at high risk

exclusively for one condition compared to the proportion of participants at high risk exclusively for a second condition. McNemar’s tests were also used to compare the proportion of specific LESS movement errors between *Pre* and *Post* conditions. For LESS items 1 to 15 (Table 12), an error was marked as present when the specific LESS error was present in at least 2 of 3 trials. For items 16 and 17 (Table 12), error was marked as present when the “*Average*” rating was present in at least 2 of 3 trials or “*Poor/Stiff*” rating in at least 1 of 3 trials (Padua et al., 2009).

Statistical significance level was set at $\alpha \leq 0.05$. Given the number of statistical comparisons used to compare the proportion of specific LESS movement errors between conditions ($n = 17$), the Bonferroni-corrected *p*-value ($p \leq 0.003$) was used to infer statistical significance in this analysis to reduce the likelihood of type 1 errors. The statistics were computed using Microsoft Excel® for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2.

7.3 Results

All participants finished the study, and the complete data set was analysed. The mean LESS scores of individuals ranged from 1.7 to 11.0 errors. *Post* information mean LESS scores were significantly lower than *Pre,* with a mean difference of -1.9 [-2.9 to -1.0] errors ($p < 0.001$, Figure 18). The effect of condition on mean LESS scores was large (Hedge’s g 1.2 [0.5 to 1.9]). The number of participants at high injury risk was significantly lower *Post* information compared to *Pre* information condition (McNemar’s test $p < 0.001$, Figure 19). *Post* information, 17 (57%) participants changed their injury risk categorisation from high to low, 11 (37%) participants remained in the same category, and 2 (6%) participants went from low to high injury risk compared to the *Pre* information condition. Table 12 presents the proportion of specific LESS errors during the *Pre* and *Post* information conditions. Proportion was significantly lower for item 16: Joint displacement *Pre* compared to *Post* condition ($p < 0.001$).

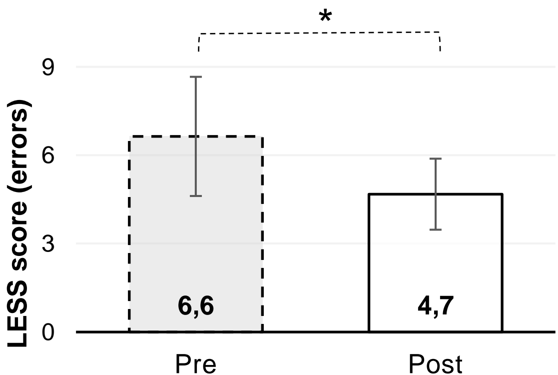


Figure 18. Group mean Landing Error Scoring System (LESS) scores. Error bars represent standard deviations. * Indicate paired t-test p < 0.001.

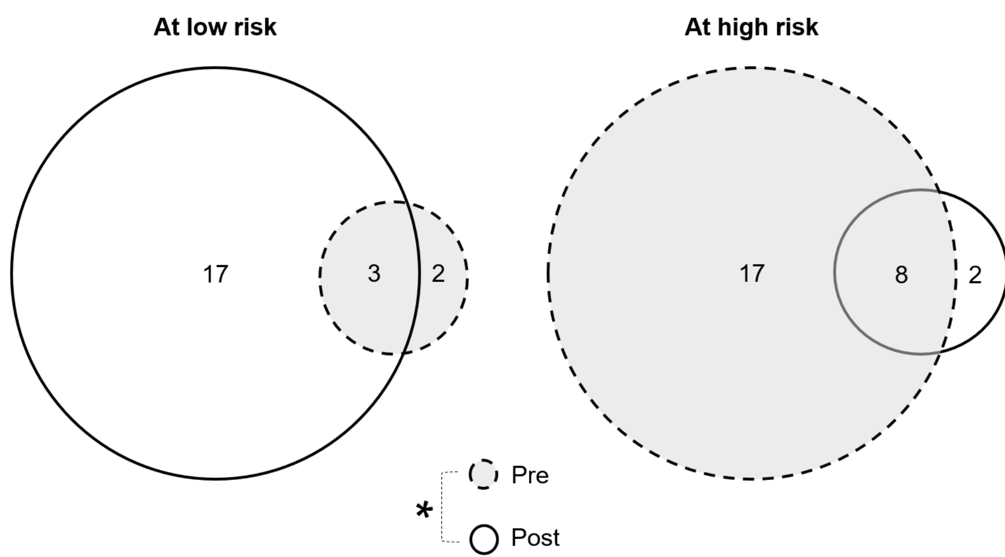


Figure 19. Venn diagrams representing the number of participants at high (LESS ≥ 5 errors) and low (LESS < 5 errors) injury risk for each condition. The sum of all values within one circle represents the number of participants categorised at high/low injury risk for given condition. Overlapping circles show the number of participants consistently scored at high/low risk within both conditions. LESS, Landing Error Scoring System. * Indicate McNemar's test $p < 0.001$.

Table 12. Landing Error Scoring System (LESS) specific errors.

No	Item	Definition of error	Number (percentage) of errors[a]		*p*-value[b]
			Pre	***Post***	
1	Knee flexion at IC	Knee flexion < 30°	11 (37%)	13 (43%)	0.791
2	Hip flexion at IC	Thigh is in line with the trunk (hips not flexed)	0 (0%)	0 (0%)	1.000
3	Trunk flexion at IC	Trunk is vertical or extended at the hips (i.e., not flexed)	0 (0%)	0 (0%)	1.000
4	Ankle plantar flexion at IC	Heel-to-toe or flat foot landing at initial contact	8 (27%)	3 (10%)	0.125
5	Knee valgus at IC	Centre of the patella is medial to the midfoot at initial contact.	10 (33%)	14 (47%)	0.289
6	Lateral trunk flexion at IC	Midline of the trunk is flexed to the left or the right side of the body at initial contact	11 (37%)	14 (47%)	0.607
7	Stance width (wide)	Feet are positioned greater than shoulder width apart (acromion processes) at initial contact	7 (23%)	14 (47%)	0.065
8	Stance width (narrow)	Feet are positioned less than shoulder width apart (acromion processes) at initial contact	10 (33%)	5 (17%)	0.125
9	Foot position (toe-in)	Foot is externally rotated more than 30° between initial contact and maximum knee flexion	0 (0%)	0 (0%)	1.000
10	Foot position (toe-out)	Foot is internally rotated more than 30° between initial contact and maximum knee flexion	12 (40%)	9 (30%)	0.065
11	Symmetric foot contact at IC	One foot lands before the other foot or 1 foot lands heel to toe and the other foot lands toe to heel	21 (70%)	12 (40%)	0.064
12	Knee flexion displacement	Knee flexes less than 45° between initial contact and maximum knee flexion	5 (17%)	0 (0%)	0.063
13	Hip flexion at MKF	Thigh does not flex more on the trunk between initial contact and maximum knee flexion	1 (3%)	0 (0%)	1.000

14	Trunk flexion at MKF	Trunk does not flex more between initial contact and maximum knee flexion	9 (30%)	0 (0%)	0.004
15	Knee valgus displacement	At the point of maximum medial knee position, the center of the patella is medial to the midfoot	16 (53%)	9 (30%)	0.065
16	Joint displacement	Joint displacement: *Soft, Average, Stiff*	25 (83%)	7 (23%)	<0.001*
17	Overall impression	Overall impression: *Excellent, Average, Poor*	30 (100%)	30 (100%)	1.000

Abbreviations: IC, initial contact; MKF, maximum knee flexion

[a] Number (percentage) of participants scored error on specific LESS item. For items 1 to 15, error was marked as present when the specific LESS error was present in at least 2 of 3 trials. For items 16 and 17, error was marked as present when the "*Average*" rating was present in at least 2 of 3 trials or "*Poor/Stiff*" rating in at least 1 of 3 trials (Padua et al., 2009).

7.4 Discussion

The LESS is a clinical screening tool used to identify high injury risk movement patterns from a jump-landing task. Individuals can alter their performance on movement screens with prior knowledge of scoring criteria (Bryson et al., 2018; Frost et al., 2015) or feedback on their performance (Myer et al., 2013a). Our results confirm that individuals can improve their LESS scores, alter their risk category, and affect specific LESS errors after being provided with scoring criteria and information regarding their own prior performance. These results highlight how knowledge of scoring criteria and feedback can affect changes in movement patterns acutely and might be a useful training tool to raise awareness and encourage lower-risk movement patterns. However, if the innate jump-landing movement patterns and injury risk of individuals are of interest, it is recommended to abstain from providing individuals with their individualised item scores following LESS testing or explaining LESS scoring criteria for a valid assessment of high injury risk movement patterns.

Post information mean LESS scores were 1.9 errors lower than Pre information. This 1.9-error difference is clinically meaningful based on Padua et al. (2009) who identified one error change in total LESS score to be clinically meaningful as associated with moderate to large differences in biomechanical variables previously linked to ACL injury. Our results are supported by previous research showing meaningful improvements in kinetic and kinematic variables after training focusing on correct technique feedback (Storberget, Grødahl, Snodgrass, van Vliet, & Heneghan, 2017). Previous literature reviews have emphasised the importance of incorporating technique feedback in ACL injury prevention programmes (Sugimoto et al., 2016) and in the rehabilitation of musculoskeletal lower-extremity injuries (Storberget et al., 2017). Technique feedback has been shown effective in improving jump-landing biomechanics in a manner that would reduce ACL injury risk (Nyman & Armstrong, 2015; Storberget et al., 2017). Furthermore, Myer et al. (2013a) concluded that augmented feedback targeting deficits during the tuck jump assessment was effective in improving biomechanics during a different drop vertical jump task, which supports a transfer of skills and movement pattens across tasks after provision of feedback. Altogether, these studies indicate that technique feedback is a useful tool in prevention and rehabilitation of injuries.

Within one education session, our participants were able to decrease LESS scores to a greater extent than following neuromuscular training programmes for several weeks (Owens et al., 2013; Padua et al., 2012; Pryor et al., 2017). In a study conducted by Root et al. (2015), participants improved their LESS scores by 0.5 error after a single 10 to 12-minute injury prevention session; however, no improvements were found after static or dynamic warm up sessions of the same duration. Compared to static and dynamic warm up programmes, the injury prevention programme included balance and plyometric exercises and concentrated on proper technique using cues, such as "land softly", "bend your knees and hips", "keep your toes facing forwards", and "keep your knees over your toes" (Root et al., 2015). These findings highlight the powerful impact of short interventions on changing movement patterns acutely when interventions focus on awareness of low-risk movement mechanics and feedback. It appears that explaining scoring criteria representing low and high-risk biomechanics and specific feedback on participant's prior performance used in our study is superior to improve LESS scores in the short term compared to real-time feedback provided during injury prevention programmes, such as used in Root et al. (2015). However, further targeted research is needed to confirm these speculations.

Individuals may perform better on clinical tests with knowledge of test scores and grading criteria without any long-lasting neuromuscular or physiological adaptations from training or rehabilitation and therefore reducing the screen's ability to identify individuals presenting high-risk movement patterns during jump-landing tasks. Previous study findings regarding the effect of internal and external focus instructions on the LESS indicated that instructions can significantly improve LESS scores immediately after a training session, and that improvements can persist in some – but not all – individuals one week post testing (Welling et al., 2016). It is questionable whether one education session focusing on knowledge of scoring criteria and technique feedback is able to change innate movement patterns and injury risk factors, or whether participants are simply more aware of movement biomechanics needed to perform well during this particular injury risk screening task. Examining the performance of participants at a later date (e.g., 4 to 8 weeks) would have provided insight into the persistence of learnings or reversion to innate movements. Padua et al. (2012) compared the effectiveness of 3 and 9-month injury prevention programmes that included landing technique feedback and concluded that improved LESS scores remained 3 months post-

intervention only in the 9-month programme group. Therefore, it seems that long-lasting intervention programmes specifically designed to change movement patterns are needed to alter LESS scores in the long term. To date, there is no evidence to our knowledge that links improvements in LESS scores with changes in the innate movement patterns of individuals or changes in high-injury risk sport-specific movement patterns, such as cutting or pivoting.

When seeking to identify individuals with high injury risk movement patterns, there is arguably more value in assessing innate movement behaviour as opposed to immediate movement behaviour influenced by knowledge of scoring criteria or prior performance. Therefore, before more evidence is available on persistence of LESS score improvements after one technique feedback session, we recommend clinicians abstain from providing individuals with their individualised item scores following LESS or from explaining LESS scoring criteria if the test is to be used to capture habitual jump-landing patterns to assess innate injury risk, monitor rehabilitation, or assess the effects of a preventive programme.

Over half of our sample were reclassified from high to low injury risk categories between Pre and Post information conditions. It is interesting to consider that two participants changed injury risk categorisation from low to high between *Pre* and *Post* information conditions. For certain individuals, a greater amount of feedback can lead to maladaptive short-term responses and changes in movement patterns in part due to over-intellectualisation of the task (Lee, Swinnen, & Serrien, 1994). Motor control literature has shown that certain individuals demonstrate a propensity to consciously control and correct their movement patterns more than others (Maxwell et al., 2006). Consciously controlling and monitoring one's own movement can constrain or inhibit more effective automatic control processes and lead to greater movement disruption (Masters & Maxwell, 2008). How individuals respond to feedback or consciously control their movements may explain why some participants worsen their LESS scores after being provided with feedback. Furthermore, it could be that those individuals who are unable to improve their LESS scores and remain at high risk of injury have a lesser ability to modify their movement patterns and are in fact at the greatest risk of injury and in most need of preventative programmes. However, prospective studies with large cohorts are needed to confirm these speculations.

When considering the number and percentage of specific LESS errors *Post* vs *Pre* condition, most participants improved their LESS scores mostly via sagittal plane movement errors, with a significant reduction in the number of errors for item 16: Joint displacement ($p < 0.001$, Table 12). Our finding are supported by a systematic literature review showing that jump-landing training interventions combined with verbal or visual technique feedback were useful in reducing ACL injury parameters related to sagittal plane, but had little effect on frontal plane biomechanics (Neilson, Ward, Hume, Lewis, & McDaid, 2019). Externally focused instructions have been shown to impact movement behaviours to a greater extent than internally focus ones (Peh, Chow, & Davids, 2011). The LESS item number 16: Joint displacement is graded as: soft landing = 0 error, average landing = 1 error, and stiff landing = 2 errors. This item elicits a more external focused attention from individuals attempting to improve their scores. In comparison, certain items elicit more internal focus from individuals; for example, an error upon lateral trunk flexion (item 6) is attributed when the midline of the trunk is flexed to the left or to the right side of the body. It is possible that after explaining the scoring criteria, participants were more successful in using external focused cues and concentrated on overall landing more softly, which is associated with item 16: Joint displacement and also with other LESS errors in the sagittal plane. This assumption is in agreement with studies showing that participants were more successful in reducing the vertical ground reaction force during landing using instructions with an external focus; i.e., sound associated with foot impact compared to internal focus; i.e., lower-extremity kinematics (McNair, Prapavessis, & Callender, 2000; Onate, Guskiewicz, & Sullivan, 2001). Similarly, individuals have been shown to jump higher with external focus instructions compared to internal focus instructions or no instruction (Abdollahipour, Psotta, & Land, 2016). The only sagittal plane item that did not demonstrate a lower occurrence after education was item 1: Knee flexion at initial contact. This finding agrees with a recent meta-analysis (Lopes et al., 2018) indicating no effect of injury prevention programmes on increasing knee flexion angles at initial contact during landing task.

In the studies of Frost et al. (2015) and Bryson et al. (2018), participants were explained FMS scoring criteria after the first FMS testing session; however, unlike our study, participants were not aware of their specific scores, and still improved their FMS scores by 12.4%. Altogether, these studies indicate that merely knowing the screen's

objectives or scoring criteria can modify results and performance. During the LESS assessment, individuals are asked to jump as high as possible after the first landing (Padua et al., 2009). This instruction is important to shift participants' focus to performance rather than landing mechanics and resemble sporting demands where performance is of primary interest. It has been shown that the verbal instructions have the ability to acutely alter the drop vertical jump biomechanics variables and influence assessment of athletic performance and injury risk (Khuu, Musalem, & Beach, 2015). Therefore, it is recommended to emphasise the maximisation of jump height during LESS testing to shift attention to performance. Furthermore, clinicians could perhaps report jump height as metric to participants and address jump-landing movement errors detected by the LESS though training interventions. This solution would minimise impact of individual's awareness of the screening purpose on outcomes and improve the ability of clinicians to monitor the impact of their intervention strategy to elicit safe landing patterns.

7.5 Conclusion

The LESS is clinical tool used to screen for risk of non-contact lower-extremity and ACL injuries. The knowledge of scoring criteria and performance meaningfully improved LESS scores, altered risk categorisation, and changed proportions of specific LESS errors. These findings confirm the potential for feedback to acutely affect movement patterns. However, knowledge of scoring criteria and individual performance may potentially compromise the clinical utility of the LESS to assess the habitual movement patterns of individuals during the jump-landing task and identify individuals at risk of injury in practice and research. Given that it is not clear whether a single feedback session may change habitual movement behaviour in the long-term, we caution against explaining the scoring criteria and individual movement errors to tested individuals when there is an intention to use the screening tool to assess innate movement patterns or use the tool again to monitor progress over time. Given that it is likely that the screening task may lose its utility to evaluate injury risk when the individual is aware of the purpose of testing, we recommend that clinicians focus on maximising jump height after the first landing to shift an individual's attention to performance rather than landing technique. These directives are more likely to reveal innate movement patterns that have been linked with a higher risk of sustaining non-

contact lower-extremity and ACL injuries. On the other hand, providing feedback on LESS performance or information regarding scoring criteria may be a useful training tool to encourage lower injury risk movement patterns during jump-landing if employed on a regular basis. In this case, the ability of the LESS to screen for innate risk of injury in athletes may be compromised and transference to sport-specific tasks are not guaranteed.

Summary of Section 2

To summarise the key findings from Section 2, the final LESS score calculation method, landing distance, and knowledge of scoring criteria and prior performance altered LESS scores. Therefore, using the original LESS testing protocol when feasible in a first instance and clearly documenting the methodology of testing are recommended to scientists and practitioners for reproducible, and comparable outcomes. Furthermore, we caution against explaining the scoring criteria and individual movement errors to tested individuals for valid assessment of innate jump-landing movement patterns.

Sections 1 and 2 of this thesis addressed several aspects of the Landing Error Scoring System (LESS) and identified key areas that may compromise its clinical utility or ensure reproducible and comparable outcomes. The last aspect of the LESS which may compromise its clinical utility explored in the thesis is the double-leg jump-landing task used during the LESS test.

SECTION 3

Sport and injury-specific jump-landing task

Prelude: Section 3 aims to explore the ecological validity of the LESS screening task in greater detail, as it is not representative of common sports movements associated with Anterior Cruciate Ligament (ACL) injury mechanisms (Hootman et al., 2007). Indeed, several authors have criticised the double-leg jump-landing task used in the LESS (Fox et al., 2017; Krosshaug et al., 2016; Mørtvedt, Krosshaug, Bahr, & Petushek, 2020; Smith et al., 2012a), stating that it is not fully reflective of common sport movements and injury situations, not challenging enough, and poor for predicting ACL injury. There is a need to base lower-extremity injury screening methods on more sport and injury-specific tasks, whilst keeping the task viable for large-scale screening. Therefore, the premise of Section 3 is to identify a more ecologically valid task than the double-leg jump-landing, which could be used to screen for risk of sport-related injuries in a clinical and on-field setting. Using a more ecologically valid screening task would potentially yield a greater predictive ability than the LESS for sport-related injuries; the latter being currently unclear based on the results from Chapter 3.

CHAPTER 8

Which jump-landing task best represents lower extremity and trunk kinematics of unanticipated cutting manoeuvre?

Hanzlíková, I., Richards, J., Athens, J., & Hébert-Losier, K. (2021). Which jump-landing task best represents lower extremity and trunk kinematics of unanticipated cutting manoeuvre? *Gait & Posture, 85,* 171-177. (Appendix A5)

Prelude: Side-step cutting manoeuvres are frequently performed movements in numerous field and court based sports, such as soccer, handball, netball, basketball, rugby, and American football (Hootman et al., 2007). Given that side-step cutting has a propensity for generating large knee valgus and rotation moments, cutting manoeuvres are frequently associated with non-contact Anterior Cruciate Ligament (ACL) injuries (Kristianslund et al., 2014). Therefore, the aim of this chapter is to investigate and compare the level of associations between four jump-landing tasks to a sport and injury-specific unanticipated side-step cutting manoeuvre.

8.1 Introduction

The double-leg jump-landing (DLJL) task is commonly used to evaluate landing biomechanics in research and clinics (Hewett et al., 2005; Krosshaug et al., 2016; Mørtvedt et al., 2020; Padua et al., 2015; Smith et al., 2012a), and can be implemented for movement screening in large cohorts. However, the DLJL has limitations, including that it does not fully represent movements associated with high risk of injury in a sporting context. Athletes frequently land on one leg and injuries often involve complex movements, such as side-cutting, pivoting, or cross-cutting (Hootman et al., 2007). Krosshaug et al. (2016) criticised using the DLJL as a screening task to predict ACL injury in sports, given that it is not challenging enough or reflective of common sport movements. Moreover, it has been shown that sport medicine and coaching professionals are unable to correctly identify athletes who subsequently sustain an ACL injury through visual assessment of DLJL kinematics (Mørtvedt et al., 2020).

The Landing Error Screening System (LESS) is a popular injury risk screening tool that uses the DLJL (Hanzlíková & Hébert-Losier, 2020b; Padua et al., 2009). Reliability of the LESS has been established, but its predictive validity is unclear (Hanzlíková & Hébert-Losier, 2020b; Padua et al., 2015; Smith et al., 2012a). The inconsistent findings relating to its predictive value may be due to the non-sport specific nature of the LESS task, supporting the view that the DLJL task is not challenging enough to unveil 'risky' movement patterns (Smith et al., 2012a). In examining the efficiency of the LESS to identify high-risk lower-extremity mechanics during a sport-specific landing task associated with ACL injury in netball, Fox et al. (2017) concluded that the LESS might have low applicability in identifying netballers at high injury risk.

In recent years, other ACL injury risk clinical screening tools have been proposed, including the Cutting Movement Assessment Score (CMAS) (Dos'Santos et al., 2019). This tool identifies potentially high-risk movement patterns linked with greater knee valgus moments during side-step cutting (Dos'Santos et al., 2019). The CMAS has been shown reliable and valid against three-dimensional (3D) motion capture (Dos'Santos et al., 2019). However, its predictive value for injury has not been established, and the space and time requirements for testing are greater compared to the LESS, and may therefore be less suitable for large-scale screening (Dos'Santos et al., 2019).

There is a need for injury screening methods based on more sport-related and injury-related tasks, whilst keeping the screening task viable for large-scale screening initiatives. Incorporating single-leg landing and rotational movements within injury screening models may offer an appealing alternative to DLJL. Non-contact lower-extremity injuries, including to the ACL, result from poor whole-body movement control in all three planes of motion, rather than dysfunction or altered movement in a single joint or plane of motion (Hewett et al., 2010). Therefore, rather than considering discrete kinematic measures at specific joints, our aim was to compare the level of association between whole-body kinematics of four jump-landing tasks to a sport-specific and injury-specific unanticipated side-step cutting manoeuvre. The jump-landing task demonstrating the strongest association with cutting manoeuvre may be suitable for large-scale injury-risk screening in sports that involve cutting (e.g., soccer, field hockey) or a mix of cutting and jump-landing (e.g., netball, handball) tasks. Additionally, subjective ratings of the difficulty of each task were examined. We hypothesised that single-leg jump-landing (SLJL) would show the strongest correlations to the side-step cutting manoeuvre, and that $SLJL_{rot}$ would be rated as the most difficult.

8.2 Methods

8.2.1 Sample size calculation

A two-tailed hypothesis using an 80% power ($\beta = 0.20$), 5% significance level ($\alpha = 0.05$), critical values of the *t*-distribution, and data from previous studies using a similar 3D motion capture set-up and marker set were used to determine the sample size (Hanzlíková et al., 2016; Sinclair, Vincent, & Richards, 2017). Given the absence of correlation data for sample size estimations, values reporting knee flexion at initial contact (IC), coronal plane knee range of motion, and transverse plane knee range of motion were compared between the SLJL and side-step cutting tasks. It was anticipated that detecting differences between these two tasks would require the largest sample size. This analysis indicated that 33 participants were needed to identify differences between these two tasks. To account for 25% withdrawals or missing data, 42 participants were recruited.

8.2.2 Participants

Inclusion criteria were: age between 16 and 35 years, free from any injury or illness that prohibited or limited physical activity participation, and regular participation in a team sport that involved cutting. A history of injury or surgery was not an exclusion criterion given that injury risk screening is relevant to previously injured athletes. A Health Research Ethics Committee approved the study protocol [HREC(Health)2018#27], which adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks before participating.

8.2.3 Testing procedure

Participants were familiarised with the experimental protocol and all testing was completed in one session. After completing a baseline questionnaire and the International Physical Activity Questionnaire (Craig et al., 2003), participants performed five tasks: 1) double-leg jump-landing (DLJL); 2) rotated double-leg jump-landing ($DLJL_{rot}$); 3) single-leg jump-landing (SLJL); 4) rotated single-leg jump-landing ($SLJL_{rot}$); and 5) unanticipated side-step cutting. The DLJL followed the LESS protocol (Padua et al., 2009), requiring participants to jump forward from a 30-cm high box with both feet, landing to a distance equal to half of their body height, and then immediately jump upwards to their maximum height. For $DLJL_{rot}$, the protocol was similar to DLJL, but participants rotated 90° in the air before landing on both legs (Figure 20). For SLJL, the protocol was similar to DLJL, but landing was on one leg (Figure 20). For $SLJL_{rot}$, the protocol was similar to $DLJL_{rot}$, but landing was on one leg (Figure 20). To begin SLJL and $SLJL_{rot}$ tasks, participants stood on one leg. Due to the difficulty of these tasks, the landing distance was reduced to 25% of body height.

For the unanticipated side-step cutting, participants started five meters from the target cutting area. When participants moved within the target area, timing gates (Swift Performance SpeedLight™) triggered one of two pairs of lights to signal the cutting direction. During cutting, participants were required to remain between two lines taped to the floor, indicating a cutting angle of 60° to 90°. A minimum approach speed of 3.5 m/s at the penultimate foot contact was required based on previous studies to mimic a typical game setting (Saunders, 2006). Any trials performed at slower speeds were disregarded and repeated.

The testing order was randomised for task and then direction (i.e., left or right). After a familiarisation period of typically two attempts per task, each participant completed three successful repetitions. With the exception of DLJL, all tasks were performed three times to the left and three times to the right. The Perceived Recovery Status Scale (Laurent et al., 2011) was used to ensure sufficient subjective recovery between trials and tasks, with participants needing to self-report ratings ≥ 7 before proceeding to the next trial or task. On average, time between trials was 30 seconds, and between tasks was 3 minutes. Furthermore, after each task, participants were asked to evaluate the level of difficulty of the task using the following 5-point Likert scale: 1– very difficult, 2 – difficult, 3 – neutral, 4 – easy, 5 – very easy.

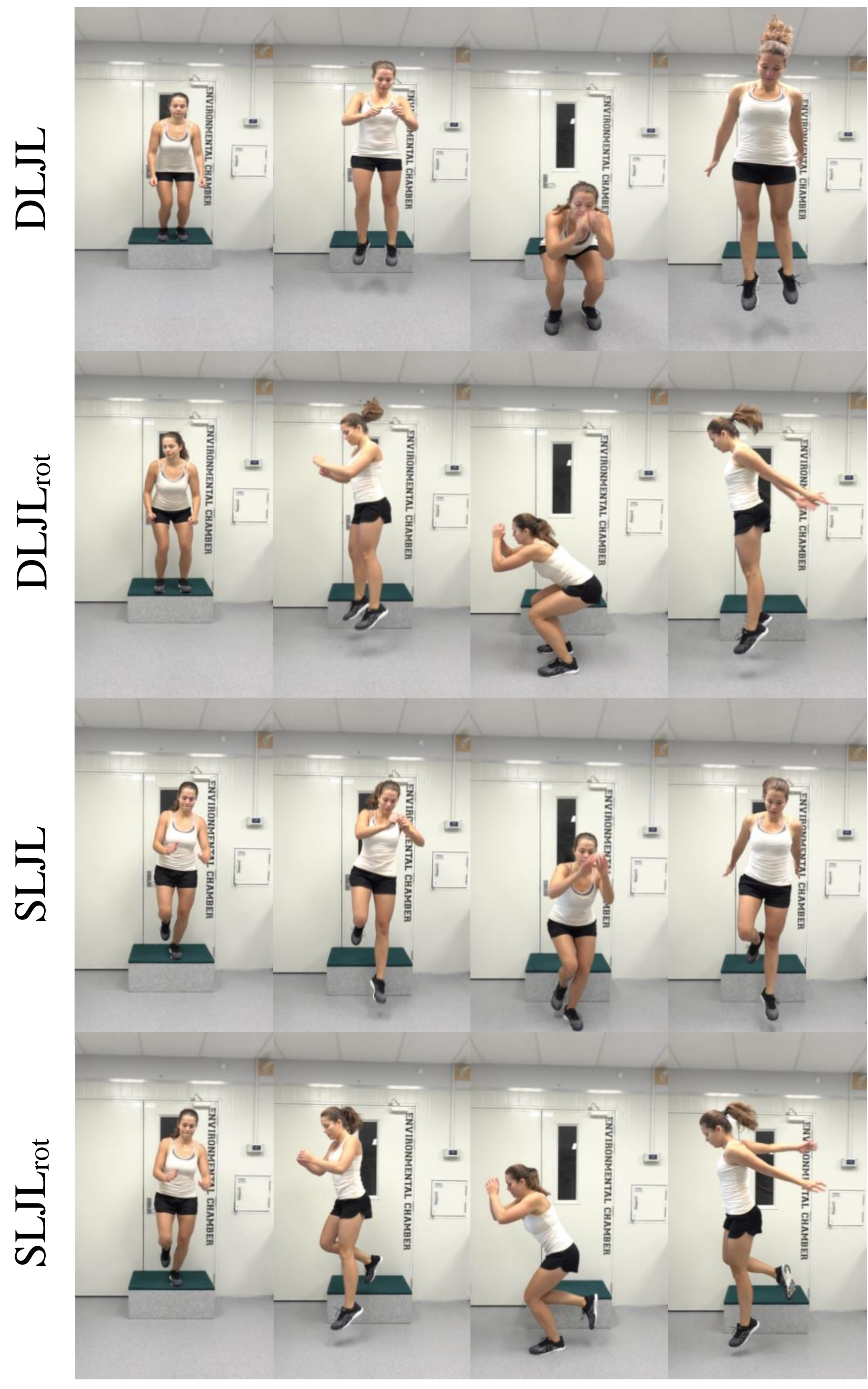


Figure 20. Jump-landing task variations.

Abbreviations: DLJL, double-leg jump-landing; $DLJL_{rot}$, rotated double-leg jump-landing; SLJL, single-leg jump-landing; $SLJL_{rot}$, rotated single-leg jump-landing.

8.2.4 Instrumentation

Whole-body motion was recorded at 200 Hz during all five tasks using an 8-camera 3D motion capture system (Oqus 700+ cameras) and software (Qualisys Track Manager v.2019.1, Qualisys AB, Gothenburg, Sweden). Forty-two 12.5-mm retroreflective markers and five clusters were taped onto the skin and shoes, which were modelled using the Calibrated Anatomical System Technique (Cappozzo, Catani, Della Croce, & Leardini, 1995). An additional cluster was placed on the right side of the pelvis to improve segment tracking (Figure 21). Three inertial measurement unit (IMU) sensors (Delsys Trigno IM sensors, Delsys Inc., MA, USA) sampling at 148 Hz were synchronised with the 3D motion capture system to assist with event determination in the absence of force plates. Two sensors were placed bilaterally 4 cm above the lateral malleoli, and one attached over the sacrum.

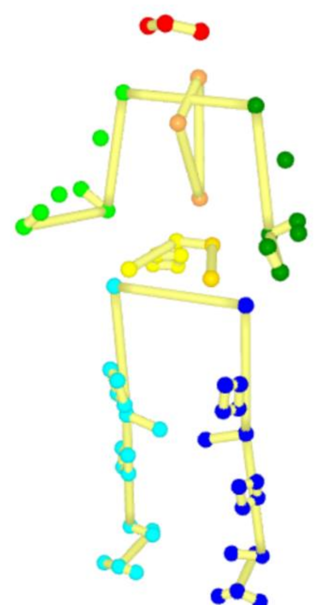


Figure 21. Marker set.

8.2.5 Data processing

Data were exported to .c3d format and processed using Visual3D Professional™ (v.6.01.36, C-Motion Inc., Germantown, Maryland, USA). A 13 rigid segment biomechanical model with six degrees of freedom at each joint was constructed. The local coordinates of all segments were derived from a static trial captured prior to the dynamic trials. Any marker data gaps less than 10 frames were interpolated using a

third order polynomial fit algorithm. A fourth order low-pass Butterworth filter with a cut-off frequency of 15 Hz was then applied to the marker data (Hanzlíková, Richards, Hébert-Losier, & Smékal, 2019). IMU data were visually assessed using a range of cut-off frequencies (15 to 100 Hz), and 80 Hz was confirmed as the best at preserving all high-frequency signal characteristics, while also removing noise. The sacrum IMU acceleration data were corrected based on the pelvis angle in all three planes.

Kinematic parameters were calculated using an XYZ cardan sequence, equivalent to the joint coordinate system (Grood & Suntay, 1983). Ankle, knee, hip, pelvis, and trunk angles and angular velocities, and pelvic linear accelerations were considered between IC and 100 milliseconds after IC, and the minimum, maximum, and range of values were extracted. Additionally, foot-ground angles in all three planes were extracted one frame before IC to explore pre-landing strategies (Harry, Silvernail, Mercer, & Dufek, 2017). IC was defined based on the peak vertical acceleration from IMU sensors placed above the lateral malleoli for jump-landing tasks, and as the instance when the cutting-leg foot centre of gravity acceleration in the vertical plane (i.e., plane perpendicular to the floor) of the lab coordinate system (z) reached a maximum value for the cutting task. The 100-millisecond timeframe was chosen as ACL injuries have been reported to occur within this period (Koga et al., 2010). For DLJL, data from the pelvis, trunk, and both extremities were extracted. For $DLJL_{rot}$, data from the pelvis, trunk, and the extremity furthest away from the box were extracted. For single-leg tasks, data from the pelvis and trunk from the landing extremities were extracted. The directionality and interpretation of joint movements are presented in Table 13. Furthermore, the pelvis centre of gravity velocity at IC and cutting angle during the cutting manoeuvre were extracted to quantify cutting performance.

Table 13. Directionality of joint kinematic variables in all three planes.

	Sagittal plane (X)		**Coronal plane (Y)**		**Transverse plane (Z)**	
	Negative	**Positive**	**Negative**	**Positive**	**Negative**	**Positive**
Foot[a]	Toe landing	Heel landing	Eversion	Inversion	External rot	Internal rot
Ankle	Plantar flexion	Dorsiflexion	Abduction	Adduction	External rot	Internal rot

Knee	Extension	Flexion	Valgus	Varus	External rot	Internal rot
Hip	Extension	Flexion	Abduction	Adduction	External rot	Internal rot
Pelvis	Anteversion	Retroversion	Pelvis drop on SL	Pelvis drop on CL	Rot towards SL	Rot away from SL
Trunk	Extension	Flexion	Lateral flexion away from SL	Lateral flexion towards SL	Rot towards SL	Rot away from SL

Abbreviations: SL, stance leg; CL, contralateral leg; rot, rotation.

[a] Foot-ground angle one frame before initial contact.

8.2.6 Statistical analyses

Joint angle, angular velocity, and IMU data from the three trials of each task were averaged for statistical analyses. To determine which jump-landing task was the most reflective of the sport-specific unanticipated cutting manoeuvre, the association between the kinematic variables extracted (n = 72, Supplementary data) during cutting and each of the jump-landing tasks was quantified using single measurement, consistency agreement, two-way random effect intraclass correlation coefficients (ICCs) for each participant (Koo & Li, 2016). Both dominant and non-dominant lower extremities were included in the analysis to derive the ICC for each participant.

Subsequently, Friedman tests with Wilcoxon signed-rank tests during post-hoc comparisons were used to compare the strength of the associations of the kinematic variables from the different jump-landing tasks to the cutting task at IC (including pre-landing foot-ground angles) and during the 100 milliseconds after IC (Table 13). Friedman tests were used due to violated assumptions for parametric testing. Subjective ratings regarding task difficulty were described using median, mode, and frequency indicators, and compared between tasks using the Friedman test with Wilcoxon signed-rank tests during post-hoc comparisons. The significance level was set at $p \leq 0.05$ for all analyses, which were performed using Microsoft® Excel (Office 365 MSO) and RStudio® (version 1.1.463) with R (version 3.5.2).

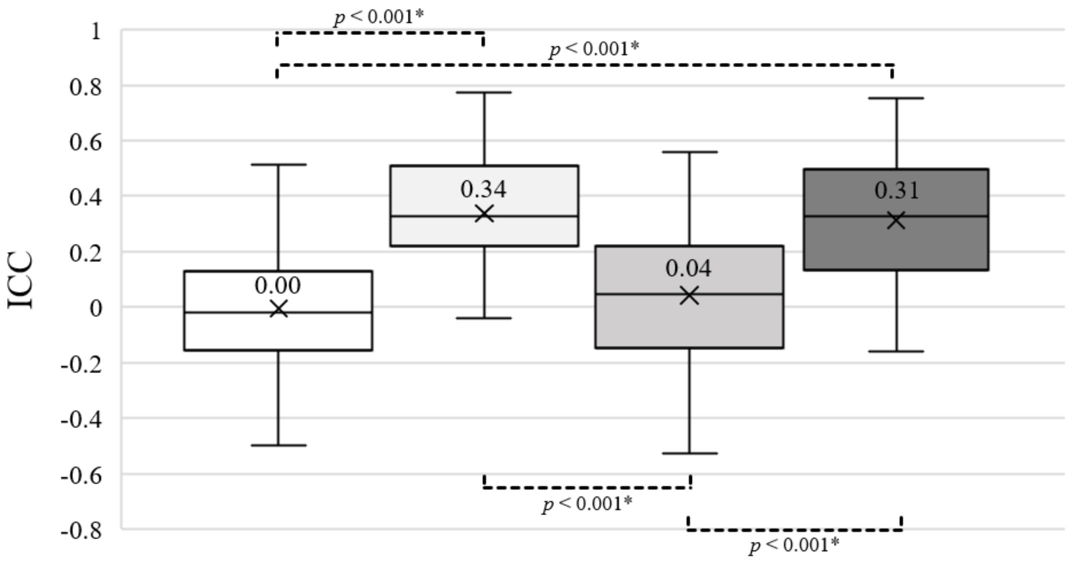
8.3 Results

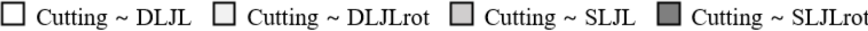
Forty-two participants (25 males and 17 females) volunteered. Age, height, and mass (mean ± standard deviation) for males were 23.6 ± 4.1 years (range 17 to 32 years), 182.2 ± 6.4 cm, and 85.0 ± 11.9 kg; and for females were 22.2 ± 5.7 years (range 16 to 35 years), 169.1 ± 6.0 cm, and 63.7 ± 6.8 kg. Ninety-three percent of participants were right-leg dominant based on the preferred leg to kick a ball. The International Physical Activity Questionnaire indicated that activity levels were high, moderate, and low in

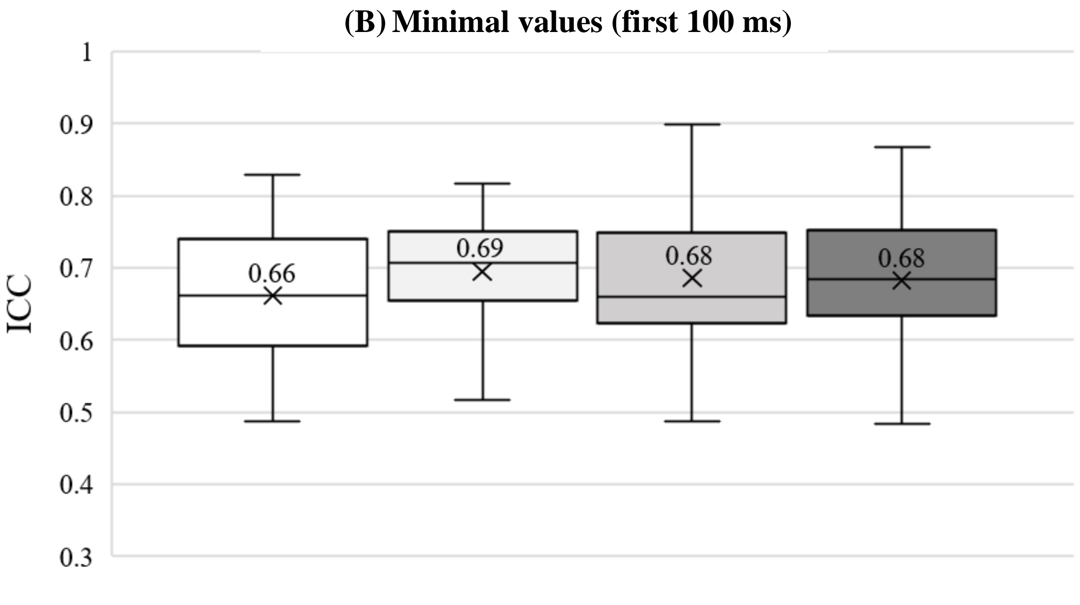
60%, 38%, and 2% of participants, respectively. Thirty-one percent of participants played soccer, 26% rugby, 17% ultimate-Frisbee, 14% netball, 7% basketball, and 5% field hockey. Participants' level of engagement with sport was 55% club level, 21% recreational, 17% national level, and 7% school level. Participants were involved in physical activity 3 times per week (median) for on average 6.7 ± 4.4 hours weekly. On average, our sample had participated in physical activity on a regular basis for 10.5 ± 6.2 years. In all analyses, there were no missing data.

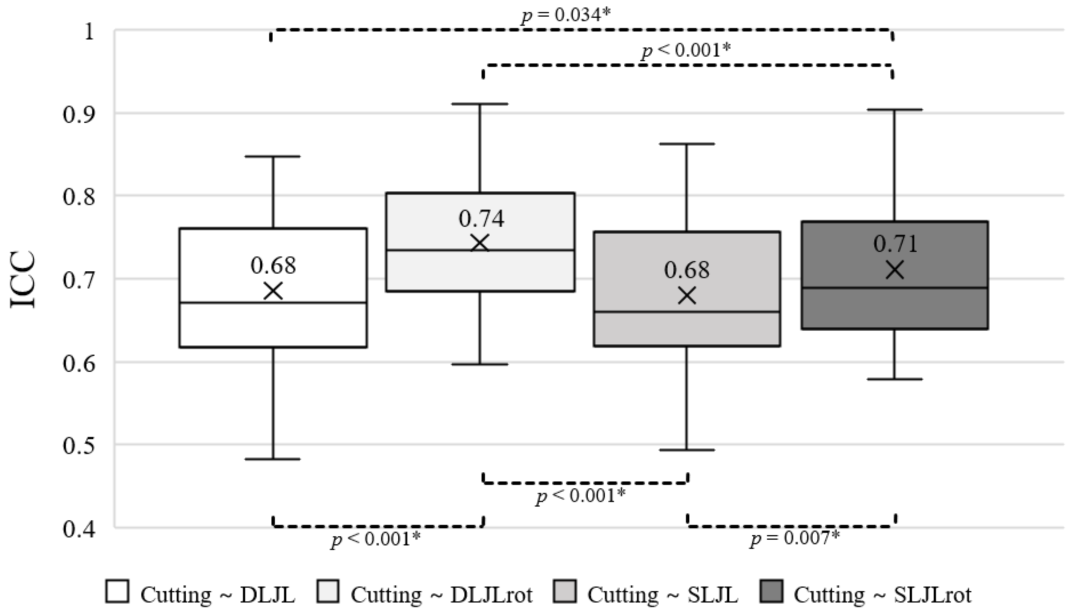
Mean values and standard deviations of all extracted variables are presented as Appendix F1. The mean waveform diagrams of ankle, knee and hip angles between IC and maximal knee flexion for each task and plane of movement are presented in Appendix F2. Overall, the mean cutting angle was 58.3 ± 9.8° and cutting speed at IC was 3.4 ± 0.5 m/s. At IC, rotated tasks were more strongly ($p < 0.001$) associated with cutting kinematics than non-rotated tasks based on ICCs (Figure 22A). The minimum values of the explored variables during all jump-landing tasks showed similar levels of associations to those of cutting, with mean ICC values ≥ 0.66 for all tasks (Figure 22B). The maximum values of the kinematic variables during the $DLJL_{rot}$ was the most strongly associated with cutting compared to all other jump-landing tasks (ICC 0.74, $p < 0.001$), and DLJL and SLJL the least associated (Figure 22C). The range of motion in all jump-landing tasks showed similar levels of association to those of cutting, with mean ICC values ≥ 0.80 for all tasks (Figure 22D). Overall, when considering ICC values across the events of interest, the DLJL kinematics appeared to be the least associated with cutting, and $DLJL_{rot}$ the most followed by $SLJL_{rot}$.

Additionally, subjective ratings relating to task difficulty significantly differed between tasks ($p < 0.022$), expect for between cutting and SLJL ($p = 1.000$), cutting and $SLJL_{rot}$ ($p = 0.103$), and SLJL and $SLJL_{rot}$ ($p = 0.052$). Participants rated the DLJL as the easiest task to perform (median = "easy", mode = "very easy"), and the $SLJL_{rot}$ as the most difficult (median = "neutral", mode = "neutral"). Five percent of participants rated the $SLJL_{rot}$ as "very difficult" and 31% as "difficult" (Figure 23).


(A) Initial contact
ICC
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
p < 0.001*
p < 0.001*
p < 0.001*
p < 0.001*
0.00
0.34
0.04
0.31


Cutting ~ DLJL
Cutting ~ DLJLrot
Cutting ~ SLJL
Cutting ~ SLJLrot


(B) Minimal values (first 100 ms)
ICC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.66
0.69
0.68
0.68
Cutting ~ DLJL
Cutting ~ DLJLrot
Cutting ~ SLJL
Cutting ~ SLJLrot



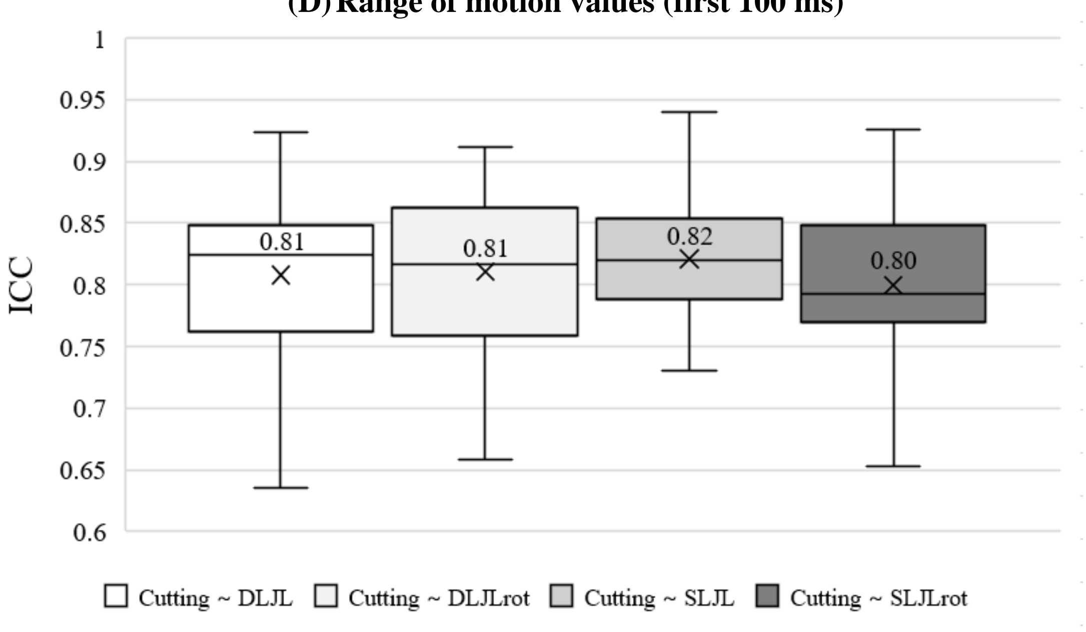


Figure 22. Comparison of intraclass correlation coefficients (ICC) associating (A) values at initial contact (IC), (B) minimal values in the 100 milliseconds (ms) after IC, (C) maximal values in the 100 ms after IC, and (D) range of motion values in the 100 ms after IC of biomechanical variables between unanticipated side-step cutting manoeuvre and jump-landing tasks.

Abbreviations: DLJL, double-leg jump-landing; $DLJL_{rot}$, rotated double-leg jump-landing; SLJL, single-leg jump-landing; $SLJL_{rot}$, rotated single-leg jump-landing.

Cross indicates the mean value. Horizontal line indicates the median. Error bars represent minimal and maximal values within the sample.

* Indicates significant differences between tasks based on pairwise comparison from Friedman test.

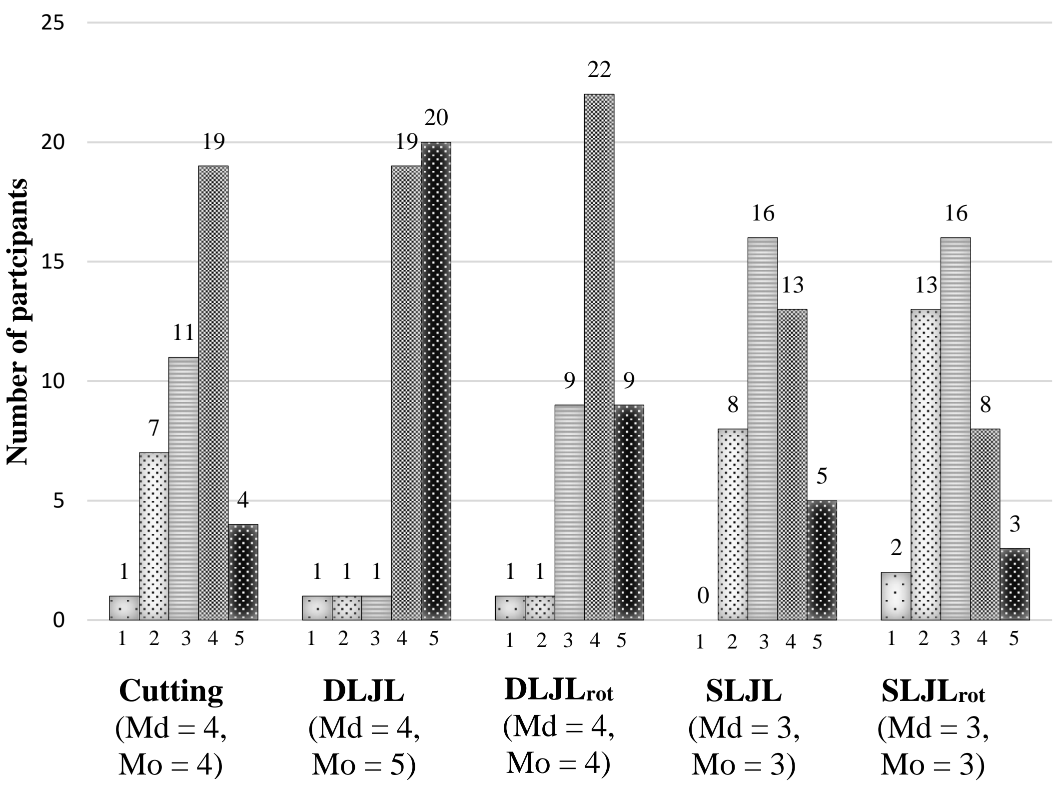


Figure 23. Subjective ratings of the difficulty of each task.

Ratings: 1, very difficult; 2, difficult; 3, neutral; 4, easy; 5, very easy

Abbreviations: DLJL, double-leg jump-landing; $DLJL_{rot}$, rotated double-leg jump-landing; SLJL, single-leg jump-landing; $SLJL_{rot}$, rotated single-leg jump-landing; Md, median; Mo, mode.

8.4 Discussion

Almost two decades ago, Hewett et al. (2005) suggested the DLJL could be used to screen for risk of ACL injury. The DLJL has become commonplace in the assessment of landing biomechanics. However, several studies have criticised the DLJL task, stating it is not reflective of common sport movements and injurious situations, not challenging enough, and poor for predicting ACL injury (Fox et al., 2017; Krosshaug et al., 2016; Mørtvedt et al., 2020; Smith et al., 2012a). Our results support these statements and indicate the lowest association between DLJL and sport-specific cutting kinematics when compared to other jump-landing tasks. Furthermore, according to the subjective ratings, DLJL was rated as easy (*n* = 19, 45%) and very easy (*n* = 20, 48%), reflecting the low perceived challenge of this task. From the tasks tested, the $DLJL_{rot}$ showed the greatest biomechanical similarities to cutting based on ICC values, followed

by $SLJL_{rot}$. Furthermore, single-leg landing tasks had a similar perceived challenge than cutting, with $SLJL_{rot}$ subjectively rated as the most difficult. Therefore, the two rotated jump-landing tasks ($DLJL_{rot}$ and $SLJL_{rot}$) may be more appropriate than the DLJL to reveal risky movement patterns that are more sport-specific and challenging.

Overall, single-leg landings are biomechanically more challenging for the knee than double-leg landings, with lower knee flexion at IC, lower sagittal plane knee displacement, greater frontal plane knee displacement, and greater knee abduction moments (Yeow, Lee, & Goh, 2011). Single-leg landings are also more common in sports and during injury situations than double-leg landings (Koga et al., 2010; Olsen et al., 2004). Most athletic movements involve unilateral propulsion or stabilisation (e.g., running, kicking, jumping). Video analysis of injury situations during games show that up to 80% of non-contact ACL injuries occur during single-leg landings or cuttings (Koga et al., 2010; Olsen et al., 2004). Moreover, high injury risk movement patterns may become more apparent during single-leg landings due to greater lower-extremity loadings, smaller bases of support, and greater motor control challenges to stabilise the pelvis and trunk (Russell, Palmieri, Zinder, & Ingersoll, 2006). All of these variables probably contributed to the greater perceived challenge of single-leg tasks in our study. Altogether, our findings suggest that single-leg tasks may more accurately reflect the challenge associated with unanticipated cutting. However, compared to SLJL, $SLJL_{rot}$ showed stronger associations with cutting biomechanics and was rated as the most difficult task to perform. Hence, compared to SLJL, $SLJL_{rot}$ may be better suited to reveal movement patterns present during more challenging sport situations and, in turn, have a greater association with injury risk profiles specific to ACL injuries.

Due to their subjectively-rated difficulty levels and biomechanical association with cutting movements, both $DLJL_{rot}$ and $SLJL_{rot}$ may be more appropriate screening tasks for landing (e.g., volleyball and basketball) and cutting (e.g., soccer, netball, field hockey, handball, American football, and rugby) sports than the traditional DLJL. Given that two-dimensional video assessments of double-leg and single-leg landings have been used to identify athletes with increased risk of non-contact knee injuries (Dingenen et al., 2015; Padua et al., 2015) and both tasks require minimal space requirements, they could be useful for large-scale screening initiatives. However, establishing what specific parameters from the $DLJL_{rot}$ or $SLJL_{rot}$ may be useful in the

clinical assessment of injury risk requires further research, and prospective studies are needed to confirm the psychometric properties and predictive value of these tasks.

Noteworthy is that our study examined the association between kinematic variables, and not their comparability. The concept of kinetic chains stipulates that each joint movement and underlying muscle contraction are coupled with movements and muscle contractions in other joints (Karandikar & Vargas, 2011). For example, trunk control is closely related to the ability of the hip and pelvis to adequately respond to unexpected movements and forces generated by distal body segments (Hewett & Myer, 2011). For instance, weak hip abductors lead to contralateral pelvis drop (Trendelenburg position); to compensate for a Trendelenburg position, the trunk inclines laterally towards the stance leg and produces a greater lateral lever arm relative to the knee joint centre and increases the knee valgus moment and ACL strain (Hewett & Myer, 2011). Hence, every joint movement in each plane may contribute to non-contact lower-extremity injuries, supporting that whole-body movement patterns and control should be considered when screening for injury risk. Therefore, rather than comparing specific angles in given joints or planes of motion, this study examined the association between whole-body movement patterns during cutting and different jump-landing variations. Given that cutting was used as the sport-specific task to determine the relevance of various jump-landing movements to screen for potential risk of ACL injuries, our results might be of greater relevance for athletes and sports that involve cutting (e.g., soccer, field hockey) or cutting and jump-landing (e.g., netball, handball) rather than predominantly jump-landing (e.g., volleyball). Moreover, due to absence of force plates, we were unable to compute joint moments through inverse dynamics, which could have provided further insight into the biomechanical associations between the tasks tested.

8.5 Conclusion

Within the tasks explored, whole-body kinematics of $DLJL_{rot}$ were the most strongly and consistently associated with cutting kinematics, followed by $SLJL_{rot}$. The $SLJL_{rot}$ task was rated as the most difficult to perform and had similar self-reported difficulty levels to cutting. Therefore, rotated jump-landing tasks may be more appropriate than the DLJL to reveal risky movement patterns present during rapid changes of direction

and landing, which could be implemented in large-scale screening as an alternative to DLJL.

Summary of Section 3

To summarise Section 3, there is a need to base sport-related injury risk screening methods on more sport and injury-specific tasks than the double-leg jump-landing task, whilst keeping the screening task viable for large-scale screening initiatives. According to our results, rotated jump-landing tasks may fulfil these requirements and could be viable options for screening for high-risk movement patterns across a range of sports. Based on the results from Section 3, $SLJL_{rot}$ may offer greater representation of the movement patterns present during more challenging sport situations. Therefore, $SLJL_{rot}$ may be a good alternative to the DLJL used in the LESS assessment and may improve upon the screen's ability to predict sport-related injuries.

It is worth acknowledging that there are several statistical approaches that can be used to deal with time-series and waveform data, such as statistical parametric mapping and other functional data analysis methods (Hébert-Losier et al., 2015; Hébert-Losier et al., 2018). Such approaches could have been used to analyse the data from Section 3. However, we decided to explore the association between a series of key biomechanical variables between cutting and each jump-landing variations using ICCs at several time events (minimal values, maximal values, initial contact, range of motion) given that these time points are important in scoring LESS. The results of this study were used to develop Modified LESS (Appendix G).

The first three sections of this thesis explored the LESS with a premise to inform screening practices and inform development of a more effective clinical screening tool for sport-related injury risks. In the upcoming section (Section 4), other clinically assessable injury risk factors and their influence on dynamic movements are explored.

SECTION 4

Clinically assessable injury risk factors

Prelude: Previous sections explored and addressed several aspects of the Landing Error Scoring System (LESS). Besides the LESS, other clinically friendly tests have been associated with greater injury risk in the scientific literature. Generalised joint hypermobility is a risk factor for knee injuries and is easily diagnosed using the Beighton score (Pacey et al., 2010). Propensity for conscious control of movement (i.e., reinvestment) is one psychological factor that can influence human movements and is assessable using a self-administered questionnaire (Masters & Maxwell, 2008). Ankle range of motion is relatively straightforward to test in clinical and sport environments and plays a prominent role in landing biomechanics (Fong et al., 2011). All these clinically assessable factors may contribute to greater risk of sport-related injuries; however, their association with dynamic movement patterns has not been fully explored. Therefore, the aim of Section 4 is to explore the influence of these factors on jump-landing and/or side-step cutting biomechanics to inform clinicians and guide prevention efforts.

Despite the limitations of the LESS stated in previous Chapters, the LESS was used to quantify jump-landing biomechanics in Chapters 9 and 11 using a clinically applicable tool. Although the LESS predictive value for non-contact sport-specific injuries cannot be ascertained based on current evidence, the LESS has a good ability to assess movement patterns linked to ACL injury (Onate et al., 2010; Padua et al., 2009). Furthermore, undertaking neuromuscular training programmes can meaningfully alter LESS scores and jump-landing biomechanics (O'Malley et al., 2017; Pfile et al., 2016), indicating that it is able to detect change in performance and functional abilities. Although assessing landing biomechanics using a more challenging task than the double-leg jump-landing from the LESS could offer a better representation of sport-related injury risk and movement mechanics (e.g., single-leg rotated jump), there are no validated clinical alternatives. For both Chapters 9 and 11, the recommendations from Section 2 regarding LESS testing protocols were implemented.

The original LESS protocol described by Padua et al. (2009) demonstrating predictive value was followed, and the final LESS score was calculated as the mean of three trials.

CHAPTER 9

Do asymptomatic generalised hypermobility and knee hyperextension influence jump-landing biomechanics?

Hanzlíková, I., & Hébert-Losier, K. (2020). Do asymptomatic generalised hypermobility and knee hyperextension influence jump landing biomechanics? *European Journal of Physiotherapy*. Advance online publication. https://doi.org/10.1080/21679169.2020.1769721

Prelude: The scientific literature has identified generalised hypermobility and knee hyperextension as important risk factors for knee injuries, including Anterior Cruciate Ligament (ACL) injuries (Dallinga et al., 2012; Donaldson, 2012; Pacey et al., 2010). One of the proposed mechanisms that may place hypermobile individuals at greater risk of injury compared to non-hypermobile populations is their altered movement patterns, as identified in the literature (Fatoye et al., 2011; Galli et al., 2011; Luder et al., 2015; Rombaut et al., 2011; Simonsen et al., 2012). However, most published studies have explored movement patterns of symptomatic hypermobile individuals, or individuals with well-defined disorders associated with hypermobility, during slow, controlled movements. Given that asymptomatic hypermobile individuals participate in sporting activities, exploring their dynamic movement patterns is warranted to assess their sport-related injury risk. Therefore, Chapter 9 aims to explore whether asymptomatic hypermobile individuals present with greater injury risk during the dynamic jump-landing task used in the Landing Error Scoring System (LESS) compared to non-hypermobile individuals. Despite its limitation, the LESS was used given that this test is currently the only reliable and valid screening tool easily administered in a clinical setting to assess jump-landing biomechanics.

9.1 Introduction

Joint hypermobility is characterised by increased joint movement beyond normal ranges expected in a given population (Castori et al., 2017). The term generalised joint hypermobility is used when multiple joints (usually five or more) are affected (Castori et al., 2017). Unlike joint hypermobility, generalised joint hypermobility is usually a congenital inherited disorder (Castori et al., 2017; Malfait et al., 2017), but may be acquire by inflammation, degenerative, and endocrine processes (Castori et al., 2017). Overall, the prevalence of generalised hypermobility reported to exist in the general population ranges from 2 (Klemp, Williams, & Stansfield, 2002) to 57% (Birrell, Adebajo, Hazleman, & Silman, 1994), with most studies reporting a prevalence from 10 to 20% (Remvig et al., 2007b) with females and children more often affected (Larsson, Baum, Mudholkar, & Srivastava, 1993). A recent framework for the classification of joint hypermobility (Castori et al., 2017) suggests dividing hypermobile individuals into three groups: individuals with asymptomatic joint hypermobility, individuals with a well-defined syndrome associated with joint hypermobility, and individuals with symptomatic joint hypermobility.

Generalised hypermobility has been associated with a range of musculoskeletal disorders in literature reviews (Dallinga et al., 2012; Hakim & Grahame, 2003; Pacey et al., 2010; Remvig et al., 2007b), including arthralgia, joint dislocation, joint synovitis, chondromalacia patellae, ligament, muscle, and meniscus tear, tendinopathy, and osteoarthrosis. The scientific literature has identified generalised hypermobility as an important risk factor for knee injury (Dallinga et al., 2012; Donaldson, 2012; Pacey et al., 2010), including ACL injury (Goshima et al., 2014; Sundemo et al., 2019). Two prospective studies have demonstrated increased risk of ACL injury with increased hypermobility of the knee joint specifically (Hewett et al., 2006b; Myer et al., 2008b). When greater knee abduction moments and angles during a drop vertical jump task were combined with the presence of knee hyperextension, the likelihood ratio of ACL injury increased significantly from 15.5 to 23.3 (Hewett et al., 2006b). Furthermore, generalised hypermobility appears to compromise dynamic stability and neuromuscular control. In most people, joint hypermobility is coupled with reduced proprioception in selected joints (Smith et al., 2013), muscle weakness (Rombaut et al., 2012; Scheper et

al., 2016), and altered movement patterns (Fatoye et al., 2011; Galli et al., 2011; Rombaut et al., 2011; Simonsen et al., 2012).

The LESS is a 17-item clinical assessment tool that identifies potentially high injury risk movement patterns during a jump-landing task (Table 1, p. 5; Padua et al., 2009). The examiner scores lower-extremity and trunk motion during landing from a 30-cm box from initial ground contact until maximal knee flexion. The minimum (best) score is 0 and maximal (worse) score is 17 errors. Higher LESS scores indicate poorer jump-landing mechanics (Onate et al., 2010; Padua et al., 2009). Padua et al. (2015) concluded that 5 errors was the optimal cut-off score for determining increased risk of non-contact ACL injury incidence from a prospective investigation, with a risk ratio of sustaining a non-contact ACL injury of 10.7 with a LESS score of 5 or greater compared to lower than 5 errors. However, two other studies (James et al., 2016; Smith et al., 2012a) did not find any association between LESS scores and ACL or other non-contact lower extremity injury.

Most published studies explored movement patterns in symptomatic hypermobile individuals or individuals with inherited well-defined disorders and used laboratory-based tests rather than clinical tests (Fatoye et al., 2011; Galli et al., 2011; Rombaut et al., 2011). Furthermore, the studies did not explore more dynamic and demanding tasks associated with higher injury risk (Wetters et al., 2016). The LESS is an easy-to-use reliable clinical test assessing landing biomechanics in physically active individuals (Padua et al., 2009). Thus, the LESS may be useful to identify potentially high-risk movement patterns in asymptomatic hypermobile individuals, confirming that this population is at higher risk of injury risk and inform preventive efforts. Therefore, the aim of this paper was to explore the relationship between LESS and Beighton scores in young active individuals, as well as to compare LESS scores and proportions of participants at high injury risk (LESS ≥ 5 errors) between non-hypermobile participants and participants with asymptomatic generalised hypermobility, as well as between participants with non-hyperextended and hyperextended knees (passive knee extension < 10° and ≥ 10°, respectively). We hypothesised that hypermobile participants and participants with hyperextended knees would exhibit greater LESS scores than non-hypermobile and non-hyperextended participants.

9.2 Methods

9.2.1 Sample size calculation

Given that no published data exist regarding the association between LESS and Beighton scores, we calculated sample size requirements based on the ability to detect a correlation of low magnitude, i.e., 0.30 (Mukaka, 2012). Based on sample size calculations using a customisable statistical spreadsheet (Hopkins, 2006) from standard two-tailed hypothesis equations using an 80% power ($\beta = 0.20$) and 5% significance level ($\alpha = 0.05$), we required 85 participants to detect a low correlation between measures.

9.2.2 Participants

Eighty-five (37 females, 48 males) 16 to 41 years old physically active individuals volunteered to participate (Table 14). Participants had to be free from injury or medical conditions that would limit physical activity participation at the time of study participation. Only asymptomatic hypermobile or non-hypermobile participants were eligible, therefore participants with known diagnosis of medical syndromes associated with joint hypermobility (e.g., Ehlers-Danlos syndrome and Marfan syndrome) or participants with symptomatic joint hypermobility were excluded. Participants were recruited through word-of-month and research contacts. The study protocol was approved by our institution's health research ethics committee [HREC(Health)#27] and adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks associated with testing.

9.2.3 Testing procedure

All tests were completed in a single session with half of the participants completing the LESS protocol first followed by the Beighton diagnostic test for hypermobility, and the other half performing the tests in the opposite order. The concurrent validity studies of the LESS against three-dimensional (3D) motion capture indicate the test is able to estimate jump-landing movement patterns and identify individuals presenting with high injury risk biomechanics (Onate et al., 2010; Padua et al., 2009). According to recent systematic reviews, LESS has good to excellent intra-rater (intraclass correlation coefficient [ICC], 0.82-0.99), inter-rater (ICC, 0.83-0.92), and inter-session reliability (ICC, 0.81; Hanzlíková & Hébert-Losier, 2020b), and can meaningfully change when

undertaking at least 6 weeks of neuromuscular training (Hanzlíková, Athens, & Hébert-Losier, 2021).

The Beighton score is a major criterion used in diagnosing joint hypermobility syndrome, and is a valid and reliable diagnostic tool for joint hypermobility (Remvig, Jensen, & Ward, 2007a). In this study, sex and age-specific cut-off scores based on Singh et al. (2017) were used. The cut-off score of ≥ 5 points was used for females and ≥ 4 for males in our sample.

The LESS testing procedure used was identical to the one described by Padua et al. (2009). Participants jumped horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately jumped upward for maximal vertical height. Participants were instructed to jump off the box with both feet, land in front of the designated line, and jump as high as possible upward upon landing. We provided no feedback on landing technique unless participants were performing the task incorrectly. Participants were given as many practice trials as needed to become comfortable with the task (typically one). Each participant performed three trials of the double-leg jump-landing task in their own footwear and were allowed to rest until they felt ready to perform the task again to limit fatigue. Two digital cameras (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm) placed on tripods captured the task at 60 Hz. The cameras were placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m to capture frontal and sagittal plane motion. One experienced investigator who completed over 400 LESS evaluations replayed the videos using the open-source Kinovea video analysis software (version 0.8.15, www.kinovea.org) and scored all three trials using the 17-item LESS scoring criteria (Table 1, p. 5). An experienced physiotherapist recorded the Beighton scores consisting of five components: (1) passive dorsiflexion and hyperextension of the fifth metacarpal joints (little fingers) beyond 90°, (2) passive apposition of the thumbs to the flexor aspects of the forearms, (3) passive hyperextension of the elbows beyond 10°, (4) passive hyperextension of the knees beyond 10°, and (5) active forward flexion of the trunk with the knees fully extended so that the palms of the hands rest flat on the floor following standard protocols and using a hand-held goniometer (Smits-Engelsman, Klerks, & Kirby, 2011). Note here that the first four elements can be given a maximum score of 2 points because they are performed bilaterally (1 point for each hypermobile

joint), and the last element has a maximum of 1 point. The fourth component of the Beighton score encapsulates hypermobility of the knee joint and was used to identify individuals presenting with knee hyperextension.

9.2.4 Statistical analyses

Mean ± standard deviation, median (interquartile range), and range (minimum to maximum) values were calculated to describe variables based on variable type. Independent *t*-tests with unequal variance and Mann-Whitney U tests were carried out to investigate differences in demographic characteristic of the subgroups analysed. To investigate the relationship between LESS and Beighton scores, Spearman rank correlation coefficient (ρ) was calculated. The correlation coefficient values were interpreted using thresholds of 0.30, 0.50, 0.70, and 0.90 to indicate low, moderate, high, and very high correlations (Mukaka, 2012). Correlations < 0.30 were considered negligible. Note that the mean LESS score from the three trials completed by each participant was used for statistical analysis.

Independent *t*-tests with unequal variance were carried out to investigate differences in LESS scores between non-hypermobile and hypermobile (Beighton score ≥ 5 points for females and ≥ 4 points for males) participants, and between participants with non-hyperextended (passive knee extension < 10°) and hyperextended (passive knee extension ≥ 10°) knees. Participants were classified into the hyperextended group when one or both knees extended ≥ 10°. Mean differences and 95% confidence intervals [upper, lower] in LESS scores between groups (non-hypermobile versus hypermobile, and non-hyperextended versus hyperextended) and corresponding effect sizes (Hedge's *g*) with 95% confidence intervals were calculated. Thresholds for interpreting the magnitude of Hedge's *g* were 0.20, 0.50, and 0.80 for small, medium, and large effects (Lakens, 2013). Effect sizes < 0.20 were considered trivial. The proportions of participants at high injury risk (LESS ≥ 5 errors) between non-hypermobile and hypermobile, and non-hyperextended and hyperextended groups were tested using two-proportion *z*-tests. Statistical significance level was set at α ≤ 0.05 for all analyses. The statistics were computed using Microsoft® Excel® for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2. Data from all 85 participants were analysed (i.e., no missing data).

9.3 Results

The mean LESS score for all participants was 5.4 ± 1.4 errors (range: 1.7 to 8.3). The median and interquartile range of Beighton score was 2 (4) points (range: 0 to 9, Table 14). Twenty-six participants (31%) were considered hypermobile (13 females and 13 males) and 59 participants (69%) non-hypermobile (24 females and 35 males). Twenty-two participants (26%) demonstrated knee hyperextension (13 females and 9 males), whereas 63 (74%) did not (24 females and 39 males). The demographic characteristics between the groups compared are presented in Table 14

There was a negligible non-significant relationship between LESS and Beighton scores ($\rho = -0.08$, $p = 0.490$). There was no significant difference in LESS scores between non-hypermobile and asymptomatic hypermobile participants with trivial effect of grouping on LESS scores (Table 15). The LESS scores between participants with non-hyperextended and hyperextended knees were similar (Table 15). The proportions of high injury risk participants between non-hypermobile and hypermobile and non-hyperextended and hyperextended groups were similar ($p = 0.395$ and $p = 0.424$, respectively, Table 15).

Table 14. Participant characteristics. Values are mean ± standard deviation and median (interquartile range).

	All females (n = 37)	All males (n = 48)	Non-hypermobile [a] (n = 59)	Hypermobile [a] (n = 26)	p-value [c]	Non-hyperextended [b] (n = 63)	Hyperextended [b] (n = 22)	p-value [c]
Age (years)	22.6 ± 5.9	24.0 ± 5.7	23.6 ± 5.6	23.0 ± 6.2	0.637	23.8 ± 5.7	22.3 ± 6.1	0.317
Height (cm)	168.9 ± 6.1	180.2 ± 6.8	176.2 ± 8.7	173.5 ± 8.1	0.171	176.7 ± 8.3	171.7 ± 8.3	0.022*
Mass (kg)	66.0 ± 8.2	84.0 ± 12.2	77.3 ± 13.9	73.9 ± 13.8	0.300	78.2 ± 13.4	70.9 ± 14.2	0.040*
BMI (kg/m^2)	23.2 ± 2.8	25.8 ± 3.0	24.8 ± 3.1	24.4 ± 3.4	0.669	24.9 ± 2.3	23.9 ± 3.6	0.250
Physical activity (times per week)	3 (3)	4 (3)	3 (3)	3.5 (3)	0.667	3 (2)	4 (3)	0.201
Beighton (points)	3 (5)	2 (4)	2 (2)	6 (3)	< 0.001*	2 (3)	7 (3)	< 0.001*

Abbreviations: BMI, body mass index

[a] Hypermobile, participants with asymptomatic hypermobility and Beighton score ≥ 5 points for females and ≥ 4 points for males; non-hypermobile, participants with Beighton score < 5 points for females and < 4 point for males.

[b] Hyperextended, passive knee extension ≥ 10°; non-hyperextended, passive knee extension < 10°.

[c] *t*-test *p*-values comparing age, height, mass, and BMI. Mann-Whitney U test *p*-values comparing physical activity and Beighton scores.

* Significantly different between subgroups ($p \leq 0.05$)

Table 15. Comparison of LESS scores between groups in the sampled cohort (n = 85).

	n	*n* at risk (%) [c]	LESS scores (error)	MD [95% CI]	*t*-test	Hedge's *g* [95% CI]
Non-hypermobile [a]	59	40 (67.8%)	5.3 ± 1.5	-0.1 [-0.7 to 0.7]	0.949	0.02 [-0.45 to 0.48]
Hypermobile [a]	26	20 (76.9%)	5.4 ± 1.3			
Non-hyperextended [b]	63	43 (68.3%)	5.6 ± 1.5	0.2 [-0.5 to 0.9]	0.547	0.15 [-0.34 to 0.64]
Hyperextended [b]	22	17 (77.3%)	5.3 ±1.4			

Abbreviations: *n*, number of participants; LESS, Landing Error Scoring System; MD, mean difference; CI, confidence interval.

[a] Hypermobile, participants with asymptomatic hypermobility and Beighton score ≥ 5 points for females and ≥ 4 points for males; non-hypermobile, participants with Beighton score < 5 points for females and < 4 point for males.

[b] Hyperextended, passive knee extension ≥ 10°; non-hyperextended, passive knee extension < 10°.

[c] Participants with LESS ≥ 5 errors.

9.4 Discussion

The purpose of this research was to investigate the relationship between LESS and Beighton scores, and to compare LESS scores and the proportion of individuals at risk of injury (LESS ≥ 5 errors) between non-hypermobile and asymptomatic hypermobile participants and between participants with passive knee extension < 10° and ≥ 10° (i.e., the fourth component of the Beighton score). In our cohort, there was no significant relationship between LESS and Beighton scores, and no difference in LESS scores and the proportion of participants at risk of injury between the subgroups analysed. The results indicate that Beighton scores in asymptomatic hypermobile participants and knee hyperextension measures do not influence LESS scores, which suggests that participants with asymptomatic hypermobility and knee hyperextension do not present a greater number of high injury risk movement patterns during landing task as assessed by the LESS compared to non-hypermobile and non-hyperextended individuals.

Previous studies have indicated altered movement patterns during stair ascent (Luder et al., 2015) and gait in hypermobile participants using 3D motion capture system (Fatoye et al., 2011; Galli et al., 2011; Simonsen et al., 2012). More specifically, biomechanical studies have revealed greater peak knee and hip abductor moments and greater peak knee extensor moments in hypermobile individuals compared to controls (Simonsen et al., 2012). These biomechanical parameters, especially knee abductor moment, have been strongly linked with ACL injury (Hewett et al., 2005). However, the participants with asymptomatic generalised hypermobility in our study did not display a greater number of errors upon LESS assessment, which detects the presence of movement patterns associated with ACL injury (Padua et al., 2009). The difference between study outcomes is likely due to the population explored. Mentioned studies explored children (Fatoye et al., 2011), individuals with hypermobile type of Ehlers–Danlos syndrome (Galli et al., 2011), combination of symptomatic and asymptomatic hypermobile participants (Luder et al., 2015), or not clearly defined hypermobility status of participants (Simonsen et al., 2012). It is possible that our sample of asymptomatic hypermobile individuals used different neuromuscular control strategies compared to symptomatic participants and participants with Ehlers–Danlos syndrome who were tested in previous studies. Asymptomatic hypermobile individuals may use strategies to actively stabilise their hypermobile joints during dynamic tasks, explaining

why they do not suffer chronic pain, micro traumas, and other symptoms typically associated with hypermobility. This assumption is supported by findings from Luder et al. (2015) of lower activation levels of the quadriceps muscles during stairs ascent in symptomatic hypermobile participants compared to non-hypermobile controls, yet no significant difference in muscle activation was detected between asymptomatic hypermobile participants and controls. We did not assess neuromuscular control using electromyography as part of this study; and hence, cannot confirm whether asymptomatic hypermobile individuals used different neuromuscular strategies compared to non-hypermobile participants.

Several literature reviews have identified hypermobility as an important risk factor for knee injuries (Dallinga et al., 2012; Donaldson, 2012; Pacey et al., 2010), including the ACL (Goshima et al., 2014; Sundemo et al., 2019). All the mentioned literature reviews included studies which were completed before the publication of the more recent framework for the classification of joint hypermobility and related conditions (Castori et al., 2017) that recommends classifying joint hypermobility into three groups (asymptomatic, symptomatic, and well-defined syndromes). Therefore, it is possible that besides increased mobility of the joint, other secondary manifestations of joint hypermobility, such as chronic pain and disturbed proprioception, are important confounding factors associated with injury incidence. As such, asymptomatic hypermobile individuals may be at lower risk of injury compared to symptomatic individuals. Similar to our study findings, two studies that did not clearly define hypermobility status of participants (Paszkewicz, McCarty, Van Lunen, & Research, 2013; Soper, Simmonds, Kaz, & Ninis, 2015) did not detect any significant association between hypermobility scores and performance during injury risk screening tests. Namely, no significant correlations between hypermobility scores and Functional Movement Screen™ composite scores or Star Excursion Balance Test scores were found (Paszkewicz et al., 2013; Soper et al., 2015). Both of these aforementioned clinical tests are comprehensive screening tests requiring muscle strength, range of motion, coordination, balance, and proprioception for optimal performance. Had a symptomatic hypermobile group been assessed, the outcomes from these studies might have been altered.

Furthermore, the differences between previous studies (Fatoye et al., 2011; Galli et al., 2011; Simonsen et al., 2012) that found differences in the movement patterns of hypermobile and control individuals in contrast to our study findings of no difference may be in part due to the laboratory-based versus clinical-based nature of investigations and tools used. The LESS is a clinical tool providing an indication of gross movement patterns and injury risk, unable to detect small changes in kinematics and kinetics. For a more detailed biomechanical analysis, 3D motion capture is considered the gold standard in human movement analysis and is more sensitive to biomechanical changes than clinical observations (Onate et al., 2010). The use of 3D motion during the jump-landing task rather than the LESS might have highlighted differences between our participant groups.

To our knowledge, this is the first study investigating the association between LESS scores and generalised hypermobility. Mohammadi et al. (2017) explored the relationship between LESS scores and knee hyperextension angles recorded during standing, reporting a negative correlation between measures (r = -0.4, p = 0.01) in 30 active males. Their results suggest that greater knee hyperextension is associated with a lower number of errors on LESS assessment, which disagrees with our findings of no difference between knee hyperextended and non-hyperextended groups, and contradicts most research on the topic of knee hyperextension and injury risk (Dallinga et al., 2012; Myer et al., 2008b). Differences in results between Mohammadi et al. (2017) and our study regarding the association between LESS scores and knee hyperextension could relate to the populations tested (30 males versus 85 females and males), methods used to assess knee hyperextension (weight-bearing knee extension in stance versus non-weight-bearing passive knee extension in supine), mean LESS scores of participants (3.3 ± 1.9 versus 5.4 ± 1.4 errors), or statistical approaches (correlation versus group comparison). Furthermore, the mean knee extension angles of 2.2 ± 1.1° reported by Mohammadi et al. (2017) suggests a low number of hyperextended individuals based on the Beighton criterion of ≥ 10°, with their description of knee extension assessment insufficient to determine whether angles were measured during habitual stance or whether participants were requested to actively hyperextend their knees. Hence, it is difficult to directly compare results from the two studies.

Older populations more often present with co-committing symptoms, such as acute or chronic pain, and it is hard to say if these symptoms are associated with hypermobility or other comorbidities, such as osteoarthrosis (Elliott, Smith, Penny, Smith, & Chambers, 1999). Furthermore, knee injuries, such as ACL ruptures, occur predominantly in the young active population (Sanders et al., 2016). Therefore, we recruited 85 active individuals mainly in their early twenties, which may limit the generalisability of our findings to younger or older athletic populations or less active groups. The main limitation of our study is that the samples of hypermobile and non-hypermobile and hyperextended and non-hyperextended groups were not balanced, and participants were not matched based on age, sex, and sport activity level. The underlying neuromuscular control during the LESS may differ between hypermobile and non-hypermobile individuals, although electromyography was not used as part of this study to confirm differences in muscle recruitment and activation patterns. As noted, the LESS is not able to detect small differences in kinetics and kinematics. Therefore, 3D motion analysis is required to assess in greater detail whether movement patterns differ between asymptomatic hypermobile and non-hypermobile individuals during dynamic tasks. It is important to note that only prospective studies could determine whether individuals presenting with asymptomatic generalised hypermobility are at the greatest risk of non-contact ACL injuries.

9.5 Conclusion

Despite LESS scores, Beighton scores, and knee hyperextension being identified risk factors for non-contact ACL injuries in the scientific literature; the latter two aspects did not influence LESS scores. Asymptomatic hypermobile individuals tested in our study had similar LESS scores to non-hypermobile participants. The use of electromyography or 3D motion analysis may have assisted determination of whether the underlying neuromuscular strategies and biomechanical movement patterns were similar between cohorts during this dynamic task. Further research on the neuromuscular control strategies of asymptomatic hypermobile individuals during dynamic sport-specific tasks could help guide prevention initiatives, as well as determine whether asymptomatic hypermobile individuals are at the greatest risk of injuries.

CHAPTER 10

The influence of asymptomatic hypermobility on unanticipated cutting kinematics

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Prelude: Chapter 9 reported a failure to detect differences between asymptomatic hypermobile and non-hypermobile individuals in terms of the number of movement errors when using the Landing Error Scoring System (LESS). The results from Chapter 9 indicated that asymptomatic hypermobile individuals may adapt to their condition and, therefore, present with movement patterns and levels of injury risk similar to non-hypermobile individuals. However, one of the highlighted limitations of Chapter 9 was that the LESS is not sensitive enough to detect small changes in biomechanics. Furthermore, Section 3 criticised the LESS screening task, stating that it is not representative of common sports movements associated with Anterior Cruciate Ligament (ACL) injury mechanisms. Hence, the use of more sensitive and accurate motion analysis methods is required to assess in greater detail whether movement patterns differ between asymptomatic hypermobile and non-hypermobile individuals during dynamic sport-specific tasks. Therefore, Chapter 10 incorporates three-dimensional (3D) motion capture during the performance of sport-specific movements which have been previously associated with risk of non-contact knee and ACL injuries (Hootman et al., 2007). This chapter explores unanticipated side-step cutting kinematics between asymptomatic hypermobile and non-hypermobile participants to elucidate if asymptomatic hypermobile individuals present with different movement patterns that could place them at greater risk of knee and ACL injuries in sports.

10.1 Introduction

Generalised joint hypermobility (GJH) is characterised by increased movement in multiple joints beyond normal ranges expected in a given population (Castori et al., 2017). Overall, most studies have reported a prevalence of GJH between 10 to 20% in the general population (Remvig et al., 2007b). Although people with GJH present with a wide variety of symptoms, the most common complaints involve the musculoskeletal system (Pacey et al., 2010; Remvig et al., 2007b). Connective tissue laxity, ligament injuries, and joint instability leading to subluxation or dislocation are common in hypermobile individuals (Pacey et al., 2010).

GJH has been reported to be an important risk factor for lower-extremity injury. More specifically, the scientific literature has identified GJH as a risk factor for non-contact knee injuries, including the ACL, although no increased risk was found for ankle joint injuries (Pacey et al., 2010; Sundemo et al., 2019). GJH is usually a congenital, inherited disorder and, therefore, cannot be prevented (Castori et al., 2017). Neuromuscular and biomechanical factors also play a central role in non-contact lower-extremity injuries; however, high injury risk movement patterns are modifiable using training interventions (Lopes et al., 2018). Studies have shown that GJH may affect posture and movement; for example, hypermobile individuals demonstrate postural deviances of hip and trunk (Booshanam, Cherian, Joseph, Mathew, & Thomas, 2011), altered movement patterns during stair climbing (Luder et al., 2015) and gait (Fatoye et al., 2011; Galli et al., 2011; Rombaut et al., 2011; Simonsen et al., 2012) compared to non-hypermobile individuals. More specifically, reduced ankle dorsiflexion and greater peak ankle plantarflexion, pelvic tilt range of motion, peak knee valgus moments, peak hip abductor moments, and peak knee extensor moments are observed in hypermobile individuals executing these tasks. These biomechanical parameters, especially knee valgus moments, have been strongly linked with non-contact ACL injuries (Hewett et al., 2005).

None of the previous studies explored 3D biomechanics of hypermobile individuals during sport-specific movements associated with high risk of non-contact knee and ACL injury. The identification of movement patterns specific to hypermobile individuals during sport-specific high injury risk movements could facilitate the development and implementation of targeted recommendations, exercises, and injury

prevention programs for this population. Furthermore, a recent framework for the classification of GJH suggests dividing hypermobile individuals into three categories: individuals with asymptomatic joint hypermobility, individuals with a well-defined syndrome associated with joint hypermobility, and individuals with symptomatic joint hypermobility (Castori et al., 2017). Most published studies have explored movement patterns in children, symptomatic hypermobile individuals, or individuals with inherited well-defined disorders. There is currently a lack of evidence concerning the asymptomatic hypermobile population (Fatoye et al., 2011; Galli et al., 2011; Rombaut et al., 2011).

Therefore, the aim of this study was to compare unanticipated side-step cutting biomechanics between asymptomatic hypermobile and non-hypermobile participants. We hypothesised that asymptomatic hypermobile participants would present biomechanical measures suggestive of a greater risk of non-contact knee or ACL injuries, such as greater knee valgus motion, greater lateral trunk flexion motion, and less knee flexion during unanticipated cutting.

10.2 Methods

10.2.1 Sample size calculation

This study aimed to test a total of 15 individuals with GJH based on sample sizes of previous studies exploring differences in biomechanical measures between adult participants with GJH (12 to 17 participants) and healthy controls (12 to 20 participants) (Galli et al., 2011; Simonsen et al., 2012). Given that participants were not screened for GJH prior to participation, this resulted in a total sample size of 42 individuals participating in this study (15 with GJH and 27 controls).

10.2.2 Participants

Participants were recruited through personal contacts, institutional e-mail lists and online forums, advertisements to local sport clubs, advertisement on social media, and word of mouth. The inclusion criteria were regular participation in a team sport that involved cutting and being free from any injury or illness that prohibited or limited physical activity participation. A history of a previous injury or surgery was not an exclusion criterion. Only asymptomatic hypermobile or non-hypermobile participants were eligible; therefore, participants with known diagnosis of medical syndromes

associated with joint hypermobility, e.g., Ehlers-Danlos syndrome and Marfan syndrome, or participants with symptomatic joint hypermobility were excluded. The institutional ethic committee approved the study protocol [HREC(Health)2018#27], which adhered to the Declaration of Helsinki. All participants signed a written informed consent document prior to participating, which explained the potential risks associated with testing.

10.2.3 Testing procedure

Participants were familiarised with the experimental protocol and all testing was completed in one session. After completing the baseline questionnaire and the self-administered short-form International Physical Activity Questionnaire (Craig et al., 2003), an experienced physiotherapist recorded Beighton scores following a standardised protocol using a goniometer (Smits-Engelsman et al., 2011). The Beighton score is a major criterion used in diagnosing GJH, and has been shown to be a valid and reliable diagnostic tool (Remvig et al., 2007a). In this study, sex and age-specific cut-off scores to identify hypermobile individuals based on Singh et al. (2017) were used. The cut-off score of $\geq$ 5 points was used for females and $\geq$ 4 points for males. After recording the Beighton scores, an unanticipated side-step cutting manoeuvre was tested. For the side-step cutting manoeuvre, participants started five meters in front of the target cutting area. When the participant moved within the target area, timing gates (Swift Performance SpeedLightTM) triggered one of two lights in a randomised order to signal the cutting direction (Figure 24). During cutting, participants were required to stay between two lines that were taped on the floor, which indicated a cutting angle between 60° and 90° (Figure 24). A minimum approach speed of 3.5 m/s at the penultimate foot contact was required based on previous studies to mimic a typical game setting (Saunders, 2006). Trials performed at a slower speed or outside of the taped lines were disregarded and repeated. After a familiarisation period of on average two attempts, each participant completed three successful repetitions of side-step cutting manoeuvres on the dominant and non-dominant legs. For right-leg dominant participants, cutting to the left side represented dominant leg cutting and to the right side represented non-dominant leg cutting. The Perceived Recovery Status Scale was used to monitor subjective ratings of recovery (Laurent et al., 2011). To ensure sufficient recovery times between trials, participants needed to self-report ratings $\geq$ 7

before starting the next trial; else, the rest periods were extended. Participants wore their own sport shoes for testing.

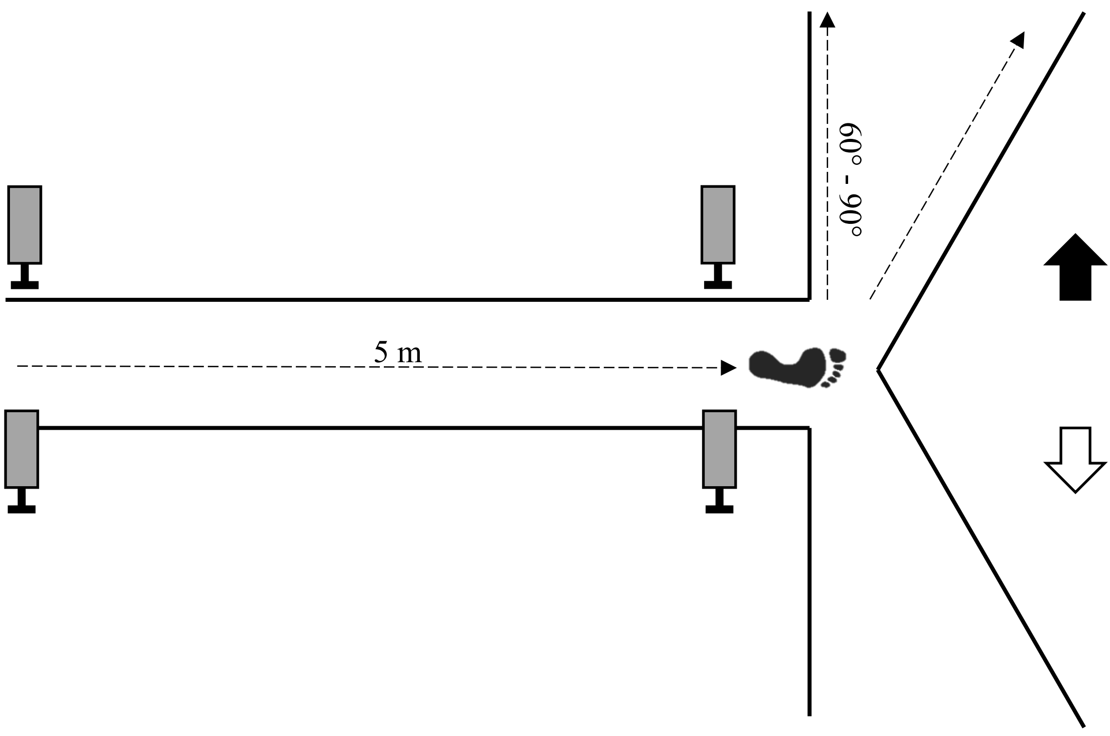

Figure 24. Scheme of unanticipated side-step cutting manoeuvre. The task involves participants approaching 5 m towards a cutting area. At the cutting area, participants perform 60° to 90° cut to the left or right based on the light signal triggered by timing gates.

10.2.4 Instrumentation

Whole-body motion was monitored during the cutting manoeuvres using an 8-camera Oqus 700 3D motion capture system at 200 Hz and the Qualisys Track Manager software version 2019.1 (Qualisys AB®, Gothenburg, Sweden). Forty-two 12.5 mm retroreflective markers and five clusters were taped onto the skin and shoes, which were modelled using the Calibrated Anatomical System Technique (Cappozzo et al., 1995) with an additional cluster placed on the right side of the pelvis to improve segment tracking (Figure 21, p. 133).

10.2.5 Data processing

The raw data were exported to the .c3d format and processed using Visual3D Professional^{TM} software version 6.01.36 (C-Motion Inc., Germantown, Maryland, USA). From the reference set of markers, a full-body biomechanical model with six degrees of freedom at each joint and 13 rigid segments was constructed, with the local coordinates of all body segments derived from a 5-seconds static trial captured prior to the cutting manoeuvre. Any gaps in the marker data less than ten frames were interpolated using a third order polynomial fit algorithm. Subsequently, the marker data were filtered using a fourth order low-pass Butterworth filter with a cut-off frequency of 15 Hz (Hanzlíková et al., 2019).

Kinematic parameters were calculated using an XYZ cardan sequence equivalent to the joint coordinate system proposed by Grood and Suntay (1983). Ankle, knee, hip, pelvis, and trunk angles in all three planes of motion were extracted from the first 100 milliseconds after initial contact (minimum, maximum, and range values) and foot-ground angles in all three planes of motion one frame before initial contact to explore pre-landing strategy (Harry et al., 2017). The timeframe of 100 milliseconds after initial contact was chosen as this has been reported to be the time within which ACL injuries are most likely to occur (Koga et al., 2010). Initial contact was defined as the instance when the cutting-leg foot centre of gravity acceleration in the vertical plane of the lab coordination system (z) reached a maximum value. Furthermore, the pelvis centre of gravity velocity at initial contact and cutting angle during the cutting manoeuvre were extracted to quantify cutting performance. The directionality and interpretation of joint movements are presented in Table 13, p. 134.

10.2.6 Statistical analyses

Joint angle data were exported to Excel where the values from three trials were averaged, which were then used for further processing. Given that our data showed significant differences related to leg dominance during cutting manoeuvres, dominant and non-dominant leg cutting was analysed separately. Mean ± standard deviation, median (interquartile range), and range (minimum to maximum) values were calculated from the descriptive and biomechanical data to describe the hypermobile and non-hypermobile groups based on variable type. Two-tailed *t*-tests with unequal variance or Mann-Whitney U tests were carried out to investigate differences in demographic

characteristics of the subgroups analysed. A multiple linear regression model was used to compare the biomechanical variables between the hypermobile and non-hypermobile groups with sex as a confounder. We controlled for sex due to the significant differences previously reported in cutting manoeuvres (Benjaminse, Gokeler, Fleisig, Sell, & Otten, 2011). When the sex confounder was not significant it was removed from the model. For statistically significant differences between hypermobile and non-hypermobile groups, mean differences with 95% confidence intervals [lower, upper] and corresponding effect sizes (Hedge's *g*) were calculated. Note that no analysis was performed if only the sex confounder was significant. Thresholds for interpreting the magnitude of Hedge's *g* were 0.20, 0.50, and 0.80 for small, moderate, and large effects, respectively (Lakens, 2013), with effect sizes < 0.20 considered trivial. The statistical significance level was set at $\alpha \leq 0.05$ for all analyses. All statistics were computed using Microsoft® Excel® for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2.

10.3 Results

A sample of 42 participants, 25 males and 17 females, participated in the study. Participants characteristics are presented in Table 16. No significant differences for age, height, mass, body mass index, and physical activity were seen between the hypermobile and non-hypermobile groups ($P > 0.05$, Table 16). A significant difference for Beighton scores was seen between the hypermobile and non-hypermobile groups ($P < 0.001$, Table 16) with a median of 6 (3) points and range of 4 to 9 in the hypermobile group, and a median of 2 (2) points and range of 0 to 4 in the non-hypermobile group. The majority of participants (93%) were right-leg dominant, assessed by the preferred leg when kicking a ball. According to the International Physical Activity Questionnaire, the level of physical activity was high for 53% and moderate for 47% of the hypermobile participants. The level of activity for non-hypermobile participants was high, moderate, and low in 63%, 33%, and 4% of participants, respectively. From our sample, 31% of participants played soccer, 26% rugby, 17% ultimate Frisbee, 14% netball, 7% basketball, and 5% field hockey. Participants' level of engagement with sport was 55% club level, 21% recreational, 17% national level, and 7% school level.

Table 16. Participant characteristics. Values are mean ± standard deviation and median (interquartile range).

	All	Hypermobile (n = 15)		Non-hypermobile (n = 27)	
		Males	**Females**	**Males**	**Females**
n	42	8	7	17	10
Age (years)	23.0 ± 4.8	22.3 ± 5.1	24.4 ± 7.1	24.2 ± 3.6	20.6 ± 4.1
Height (cm)	176.9 ± 9.0	180.1 ± 4.7	166.6 ± 7.5	183.2 ± 6.9	170.7 ± 4.3
Mass (kg)	76.6 ± 14.4	82.7 ± 11.0	59.3 ± 5.6	86.1 ± 12.4	66.3 ± 6.3
BMI (kg/m^2)	24.3 ± 3.1	25.4 ± 2.4	22.1 ± 2.7	25.6 ± 3.3	22.7 ± 1.8
Physical activity (hours per week)	6.7 ± 4.4	8.4 ± 6.4	5.2 ± 3.4	7.1 ± 4.5	5.5 ± 2.3
Physical activity (times per week)	3 (4)	5 (5)	2 (2)	4 (2)	3 (3)
Years practising cutting sport	10.5 ± 6.2	12.8 ± 6.4	5.1 ± 4.8	12.2 ± 6.3	9.5 ± 5.0
Beighton score (points)	3 (2)	5 (1)*	8 (1)*	1 (2)*	3 (2)*

Abbreviations: BMI, body mass index; n, number of participants

Hypermobile, Beighton score ≥ 4 points for males and ≥ 5 points for females; non-hypermobile, Beighton score < 4 point for males and < 5 points for females.

* Significant difference (Mann-Whitney U test p-value < 0.001) between hypermobile and non-hypermobile groups

Overall, the mean cutting angle was 58.3 ± 9.8° and cutting speed at initial contact was 3.4 ± 0.5 m/s. Mean ± standard deviation values of kinematic variables for the two groups during side-step cutting manoeuvres are presented in Table 17. During dominant leg cutting manoeuvres, both groups held their knees in a valgus position, with the hypermobile group having lower minimum knee valgus angles (mean difference 3.5° [0.3 to 6.8], P = 0.032, Hedge's g = 0.69) compared to the non-hypermobile group. During dominant leg cutting, hypermobile group presented with greater peak knee external rotation angles with a mean difference of -4.5° [-8.5 to -0.4] (P = 0.035, Hedge's g = 0.70) when compared to the non-hypermobile group. During non-dominant leg cutting manoeuvres, the hypermobile group presented lower peak ankle plantarflexion angles with a mean difference of 4.5° [0.5 to 8.4], (P = 0.027, Hedge's g = 0.73) compared to the non-hypermobile group. The magnitude of the effect

sizes of the differences between groups for all significantly different variables between groups was moderate based on the Hedge's *g* values.

Table 17. Mean ± standard deviation values of angles (°) for hypermobile (n = 15) and non-hypermobile (n = 27) participants during unanticipated side-step cutting manoeuvres. Significant differences ($P \leq 0.05$) between groups are bolded.

		DOMINANT LEG CUTTING[a]			**NON-DOMINANT LEG CUTTING**[a]		
	Kinematic variable	**Hypermobile**	**Non-hypermobile**	***p*-value**	**Hypermobile**	**Non-hypermobile**	***p*-value**
Foot-ground	Heel strike angle	4.5 ± 7.5	3.7 ± 6.1	0.456	4.3 ± 7.9	5.2 ± 5.3	0.371
	Eversion (-)	-11.4 ± 9.6	-11.3 ± 9.4	0.431	-11.5 ± 9.5	-12.5 ± 7.8	0.297
	Internal rotation	2.8 ± 11.6	4.9 ± 11.5	0.839	5.9 ± 10.8	2.5 ± 12.1	0.762
Ankle	Peak plantarflexion (-)	-11.1 ± 5.5	-10.6 ± 13.0	0.848	**-9.6 ± 5.9**	**-14.1 ± 6.1**	**0.027***
	Peak dorsiflexion	15.7 ± 6.4	20.5 ± 11.1	0.081	17.5 ± 7.3	13.0 ± 8.2	0.073
	Sagittal plane ROM	26.8 ± 4.5	31.1 ± 10.2	0.069	27.1 ± 5.5	27.0 ± 7.2	0.965
	Min adduction	17.8 ± 7.7	18.0 ± 6.4	0.927	17.4 ± 4.8	15.1 ± 6.0	0.426
	Max adduction	31.7 ± 6.3	32.6 ± 6.9	0.697	32.2 ± 8.2	32.2 ± 7.3	0.824[b]
	Coronal plane ROM	14.0 ± 8.7	14.6 ± 5.2	0.868[b]	14.8 ± 8.3	17.1 ± 6.6	0.364[b]
	Min external rotation (-)	-2.9 ± 8.9	-1.6 ± 13.5	0.710	-1.3 ± 8.0	-1.2 ± 8.5	0.342
	Max external rotation (-)	-14.3 ± 8.2	-11.7 ± 13.3	0.454	-13.2 ± 7.7	-9.0 ± 8.7	0.115
	Transverse plane ROM	11.4 ± 3.8	10.1 ± 3.5	0.318	11.9 ± 4.6	10.2 ± 3.2	0.226
Knee	Min flexion	26.4 ± 4.9	27.1 ± 6.3	0.697	26.5 ± 5.4	25.0 ± 4.6	0.348
	Max flexion	55.7 ± 7.7	55.9 ± 7.1	0.923	55.5 ± 8.0	54.8 ± 6.0	0.770
	Sagittal plane ROM	29.3 ± 5.5	28.8 ± 5.8	0.802	29.0 ± 7.6	29.9 ± 5.4	0.699
	Min valgus (-)	**-0.5 ± 4.8**	**-4.0 ± 5.1**	**0.032***	-2.2 ± 5.4	-4.7 ± 5.4	0.159
	Max valgus (-)	-10.5 ± 6.6	-13.7 ± 7.5	0.159	-13.5 ± 6.7	-16.3 ± 8.2	0.244
	Coronal plane ROM	10.0 ± 4.0	9.7 ± 3.9	0.803	11.3 ± 4.2	11.6 ± 4.3	0.857
	Peak external rotation (-)	**-6.5 ± 5.9**	**-2.0 ± 6.6**	**0.035***	-1.8 ± 9.2	-3.6 ± 7.7	0.535
	Peak internal rotation	7.1 ± 6.0	9.5 ± 7.2	0.262	11.5 ± 9.5	8.8 ± 8.3	0.371
	Transverse plane ROM	13.6 ± 3.3	11.5 ± 4.2	0.079	13.3 ± 3.1	12.4 ± 4.5	0.459

Hip	Min flexion	26.4 ± 12.3	26.5 ± 12.4	0.966	24.4 ± 15.4	24.9 ± 15.7	0.926
	Max flexion	36.6 ± 11.5	36.9 ± 10.9	0.930	36.6 ± 12.7	37.1 ± 15.3	0.916
	Sagittal plane ROM	10.2 ± 4.3	10.4 ± 4.3	0.914	12.2 ± 5.3	12.2 ± 4.0	0.998
	Min abduction (-)	-11.0 ± 6.0	-10.8 ± 7.0	0.939	-11.7 ± 9.4	-12.5 ± 6.4	0.934[b]
	Max abduction (-)	-17.6 ± 6.9	-17.6 ± 6.9	0.994	-20.1 ± 8.5	-18.9 ± 6.1	0.416[b]
	Coronal plane ROM	6.6 ± 2.0	6.7 ± 2.3	0.839	8.4 ± 4.4	6.5 ± 2.4	0.130
	Peak external rotation (-)	-9.3 ± 10.4	-10.4 ± 8.6	0.719	-18.7 ± 13.3	-19.8 ± 12.5	0.794
	Peak internal rotation	9.2 ± 9.2	6.7 ± 9.1	0.413	3.0 ± 10.3	0.2 ± 10.9	0.404
	Transverse plane ROM	18.5 ± 7.3	17.2 ± 6.2	0.566	21.7 ± 8.9	20.0 ± 6.8	0.510
Pelvis[e]	Min posterior tilt	4.0 ± 5.2	3.0 ± 9.2	0.642	1.2 ± 8.7	1.5 ± 9.3	0.927
	Max posterior tilt	11.7 ± 5.5	10.3 ± 9.3	0.521[b]	12.3 ± 9.1	11.6 ± 10.5	0.825
	Sagittal plane ROM	7.7 ± 2.7	7.3 ± 2.8	0.702	11.1 ± 4.8	10.1 ± 4.1	0.523
	Min contralateral pelvis drop[c]	2.5 ± 10.0	2.7 ± 25.5	0.959	3.6 ± 10.5	7.4 ± 6.4	0.215
	Max contralateral pelvis drop[c]	8.9 ± 10.2	9.1 ± 22.8	0.442[b]	10.9 ± 10.6	14.0 ± 7.0	0.331
	Coronal plane ROM	6.4 ± 3.0	6.4 ± 3.8	0.990	7.4 ± 3.3	6.6 ± 2.9	0.442
	Min contralateral rotation[d]	8.6 ± 18.7	17.1 ± 11.6	0.125	13.3 ± 21.5	16.1 ± 10.6	0.646
	Max contralateral rotation[d]	17.3 ± 20.0	24.9 ± 12.6	0.198	20.3 ± 21.7	23.7 ± 10.2	0.581
	Transverse plane ROM	8.7 ± 3.7	7.8 ± 2.8	0.419	7.0 ± 2.9	7.6 ± 2.3	0.517
Trunk[e]	Min flexion	5.8 ± 7.7	9.8 ± 8.2	0.161[b]	5.6 ± 7.7	9.3 ± 9.8	0.280[b]
	Max flexion	12.3 ± 7.8	16.1 ± 8.1	0.197[b]	13.3 ± 8.7	16.7 ± 9.6	0.355[b]
	Sagittal plane ROM	6.5 ± 3.8	6.3 ± 2.7	0.790	7.7 ± 4.1	7.4 ± 4.0	0.789
	Peak lateral flexion away from stance leg (-)	-4.1 ± 7.2	-3.1 ± 7.7	0.668	-1.4 ± 5.6	-3.1 ± 7.5	0.412

Peak lateral flexion towards stance leg	0.4 ± 5.7	0.9 ± 7.1	0.791	3.1 ± 7.2	0.9 ± 7.8	0.364
Coronal plane ROM	4.5 ± 2.2	4.0 ± 1.8	0.473	4.5 ± 3.2	4.0 ± 1.8	0.583
Min contralateral rotation[d]	0.6 ± 14.1	3.4 ± 11.5	0.516	1.6 ± 18.4	2.7 ± 13.0	0.839
Max contralateral rotation[d]	11.9 ± 14.0	15.3 ± 12.1	0.436	12.2 ± 18.2	13.4 ± 14.1	0.836
Transverse plane ROM	11.3 ± 4.6	11.9 ± 4.6	0.687	10.6 ± 5.2	10.7 ± 4.7	0.984

Abbreviations: Max, maximal; Min, minimal; ROM, range of motion.

*significant differences ($P \leq 0.05$) based on the multiple linear regression model.

[a] for right-leg dominant participants cutting to the left side was considered as dominant leg cutting and to the right side as non-dominant leg cutting.

[b] *p*-value from the multiple linear regression model with significant sex confounder. Note, that no analysis was performed if only sex confounder was significant.

[c] contralateral drop means drop on the opposite leg to the cutting leg.

[d] rotation in direction opposite to the cutting leg

[e] pelvis and trunk angles relative to the lab coordination system

10.4 Discussion

The purpose of this study was to compare the biomechanics of cutting manoeuvres between asymptomatic hypermobile and non-hypermobile participants. In our cohort, hypermobile individuals presented with lower minimum knee valgus angles and greater peak knee external rotation angles during dominant leg cutting, and lower peak ankle plantarflexion angles during non-dominant leg cutting compared to non-hypermobile group. Despite these significant and moderate differences in cutting kinematics identified between the two groups, current evidence suggests that these kinematic variables are unlikely to play crucial roles in non-contact knee and ACL injury mechanisms (Boden, Sheehan, Torg, & Hewett, 2010; Cowley, Ford, Myer, Kernozek, & Hewett, 2006; Greska, Cortes, Ringleb, Onate, & Van Lunen, 2017; Hewett et al., 2010; Sigward et al., 2015).

According to our results, the minimum knee valgus angle during the dominant leg cutting manoeuvres was significantly different between hypermobile (-0.5° ± 4.8°) and non-hypermobile (-4.0° ± 5.1°) groups. The peak knee valgus angle is a well-recognised risk factor for ACL injuries (Hewett et al., 2010; Hewett et al., 2005), however the minimum knee valgus angle has not been associated with injury risk. Besides of greater knee valgus angle, we hypothesized greater lateral trunk flexion and lesser knee flexion angles in the hypermobile group. However, in contradiction to our hypothesis, these variables were not significant different between groups.

The peak knee external rotation angles were significantly greater for the hypermobile compared to the non-hypermobile group during dominant leg cutting manoeuvres. Substantial external rotation of the tibia together with knee valgus can cause impingement of the ACL against the intercondylar notch and increase the strain in the ACL (Boden et al., 2010). This impingement is far more common when the knee is in a hyperextended position and can cause a midsubstance tear of the ACL. That said, the majority of sport-related non-contact ACL injuries occur in a partially-flexed knee position and ruptures are mostly located closer to the femoral attachment site (Boden et al., 2010). Therefore, greater peak external rotation angles of the tibia are not crucial biomechanical injury risk factors that could predispose asymptomatic hypermobile individuals to non-contact ACL injuries in this particular task, especially given the knee flexion angles observed (mean values ≥ 25° across groups, Table 17).

During non-dominant leg cutting, the hypermobile group had lower peak ankle plantarflexion angles compared to the non-hypermobile group with a mean difference of 4.5°. Ankle dorsiflexion range of motion is associated with an increased sagittal plane displacement during jump-landing tasks and a softer landing technique (Hoch et al., 2015). However, to the authors' knowledge there are no studies exploring how limited ankle dorsiflexion or plantarflexion influence the biomechanics of cutting manoeuvres. Several studies have highlighted the effect of foot strike angle on lower-extremity biomechanics during cutting manoeuvres (David, Mundt, Komnik, & Potthast, 2018; Yoshida et al., 2016). More specifically, fore foot strike was associated with a smaller knee valgus angle, greater muscle activity of hamstrings, and greater energy absorption at the ankle than at the knee; which altogether suggests a lower risk of ACL injury (David et al., 2018; Yoshida et al., 2016). However, foot-ground angles were similar between hypermobile and non-hypermobile participants tested in our study. Based on current evidence, we cannot conclude if the lower peak ankle plantarflexion angles found in the hypermobile group tested during the first 100 milliseconds of cutting can contribute to the higher knee injury risk reported in this population (Pacey et al., 2010; Sundemo et al., 2019).

Given that hypermobility is a risk factor for non-contact knee and ACL injuries (Pacey et al., 2010; Sundemo et al., 2019) and side-step cutting manoeuvres are a high-risk task for knee injuries, we anticipated observing a greater number of significant differences between the two groups, including peak knee valgus, lateral trunk flexion, and knee flexion. The difference between study outcomes and our hypotheses is likely to be due to the population tested. The new framework for the classification of joint hypermobility differentiates between three joint hypermobility types: individuals with asymptomatic joint hypermobility, individuals with a well-defined syndrome associated with joint hypermobility, and individuals with symptomatic joint hypermobility (Castori et al., 2017). Most previous studies exploring movement of hypermobile individuals recruited children (Fatoye et al., 2011; Jensen et al., 2016; Junge et al., 2015), symptomatic individuals (Simonsen et al., 2012), or individuals with well-defined disorders (Galli et al., 2011; Rombaut et al., 2011). These studies found that hypermobile individuals present reduced semitendinosus activation during a Single Leg Hop for a Distance test (Junge et al., 2015), altered muscle activation during isometric knee flexion and extension (Jensen et al., 2016), impaired balance (Rombaut

et al., 2011), increased fall frequency (Rombaut et al., 2011), and altered movement during gait (Fatoye et al., 2011; Galli et al., 2011; Rombaut et al., 2011; Simonsen et al., 2012). Based on the authors' knowledge, only two studies have specifically involved asymptomatic hypermobile individuals (Hanzlíková & Hébert-Losier, 2020a; Luder et al., 2015). Luder et al. (2015) found that hypermobile females had lower electromyographic activity of the quadriceps during stair ascent and descent compared to non-hypermobile controls. However, when hypermobile females were divided into symptomatic and asymptomatic hypermobile groups, these differences remained significant between the symptomatic hypermobile group and control group only. Moreover, Hanzlíková and Hébert-Losier (2020a) did not find any difference in gross movement patterns during jump-landing tasks between asymptomatic hypermobile and non-hypermobile participants. It may be that the asymptomatic hypermobile individuals examined in our study used different neuromuscular control strategies than symptomatic hypermobile participants and hypermobile participants with Ehlers–Danlos syndrome explored in previous studies. Hypermobile individuals without symptoms may be fully adapted to their condition and use strategies to actively stabilise their hypermobile joints during dynamic tasks, which may explain to some extent why they do not suffer from chronic pain, fatigue, micro traumas, and other symptoms associated with hypermobility. Furthermore, other symptoms associated with GJH may play a more important role in movement and injury risk than increased mobility beyond normal limits. For example, it is well known that chronic widespread musculoskeletal pain, common in connective tissue disorders, leads to changes in movement patterns and inhibition of related muscle activity, and therefore may contribute to injury to a larger extent (Hodges & Tucker, 2011).

Further research is needed to highlight any differences and clinical implications of any differences between symptomatic and asymptomatic hypermobile individuals as well as individuals with disorders affecting connective tissue. Knowledge of the differences between these groups may change the physical activity recommendations, prevention of injury, and rehabilitation approaches. For example, some research advises hypermobile individuals to participate in non-contact activities only, such as Pilates, Tai Chi, swimming, some forms of yoga, and dance, and to avoid physical exertion at a higher than normal rhythm (Diaz, Estevez, & Guijo, 1993; Simmonds & Keer, 2007). On the other hand, Murray (2006) recommended full participation in any sporting

activities for pain free hypermobile individuals. Furthermore, scientific evidence indicate that joint hypermobility is coupled with reduced joint proprioception (Smith et al., 2013) and muscle strength (Rombaut et al., 2012; Scheper et al., 2016). Therefore, these two areas appear to play an important role in prevention and rehabilitation approaches targeting hypermobile individuals. However, it remains unknown whether proprioception and muscle strength are affected to the same extent in all three hypermobility categories as defined by Castori et al. (2017).

Advancing age leads to a decline in range of motion of joints up to 57% in the elderly (Beighton, Solomon, & Soskolne, 1973; Schultz, 1992). Moreover, sport activity may result in positive adaptation and improve movement control of asymptomatic hypermobile individuals. Therefore, we caution that our sampled population of young active individuals may limit the generalisability of our findings to older or younger populations, or more or less active groups. Even though 3D motion capture system is considered "gold standard" in assessing human movement non-invasively with accuracy of less than 1 mm in marker tracing (van der Kruk & Reijne, 2018), error in marker placement and soft-tissue artifact may result in error of measurement up to 40 mm (Peters, Galna, Sangeux, Morris, & Baker, 2010). Previous research has shown significant differences in joint moments between hypermobile and non-hypermobile individuals (Simonsen et al., 2012); however, the kinetics of cutting manoeuvres could not be examined in our study. Furthermore, the underlying neuromuscular control during side-step cutting manoeuvres may differ between hypermobile and non-hypermobile individuals, although electromyography was not used as part of this study to confirm differences in muscle recruitment and activation patterns.

10.5 Conclusion

Although some significant differences in the kinematics of unanticipated cutting manoeuvres were identified between asymptomatic hypermobile and non-hypermobile groups, based on current evidence, these biomechanical variables do not seem to play crucial roles in non-contact knee and ACL injury mechanisms. It may be that the asymptomatic hypermobile individuals examined in our study were fully adapted to their condition and used strategies to actively stabilise their hypermobile joints during dynamic tasks. As such, this level of adaptation and functionality could explain why

these hypermobile individuals were asymptomatic and did not suffer from chronic pain or other symptoms commonly reported in symptomatic hypermobile individuals. Further research is warranted to explore the differences between asymptomatic and symptomatic hypermobile individuals as well as individuals with a well-defined syndrome associated with joint hypermobility to explore if these can explain the levels of injury risk and movement control.

CHAPTER 11

Propensity for conscious control of movement is unrelated to asymptomatic hypermobility or injury risk scores

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Prelude: In the previous chapters, asymptomatic generalised hypermobility was explored as a sport-related injury risk factor. Based on the results from these chapters and current scientific evidence, it seems that asymptomatic hypermobility is not linked to risky movement patterns during jump-landing and side-step cutting manoeuvres that could predispose these individuals to non-contact knee or Anterior Cruciate Ligament (ACL) injuries. Musculoskeletal manifestations of generalised hypermobility, such as greater joint range of motion, poor proprioception, muscle weakness, and altered movement patterns, are typically considered to play key roles in increased injury risk within this population (Hakim & Grahame, 2003). However, hypermobility is also associated with various psychological symptoms that can potentially lead to movement disruption and injury. Propensity for conscious control of movement (i.e., reinvestment) is one of the psychological factors that may influence human movements and is easily assessable using a self-administered questionnaire (Masters & Maxwell, 2008). Given that both generalised hypermobility and the propensity for movement-specific reinvestment have been linked to panic disorders and anxiety (Bulbena-Cabre & Bulbena, 2018; Garcia-Campayo, Asso, & Alda, 2011; Masters & Maxwell, 2008), it is possible that conscious engagement in movement contributes to increased injury risk in hypermobile populations. Furthermore, some non-hypermobile individuals may consciously control and monitor their own movements more than others, which can potentially lead to a greater number of movement errors during testing with the Landing Error Scoring System (LESS). The link between the propensity for conscious control of movement, hypermobility, and injury risk assessed by the LESS remains largely unexplored; and therefore, is the aim of this chapter. As mentioned above, the LESS is

currently the only valid clinical test to assess jump-landing movement patterns and was used in this chapter despite its limitations highlighted previously in this thesis.

11.1 Introduction

It is well known that human movements are influenced by various psychological factors, such as fear of movement-related pain (Meulders, Vansteenwegen, & Vlaeyen, 2011), motivation (Kadosh & Staunton, 2019), or reinvestment (Masters, 1992; Masters & Maxwell, 2008). Reinvestment is defined as 'manipulation of conscious, explicit, rule based knowledge, by working memory, to control the mechanics of one's movements during motor output' (Masters & Maxwell, 2004, p. 208). The Movement-Specific Reinvestment Scale (MSRS) is a valid and reliable measure of the propensity for conscious involvement in movement (Masters et al., 2005; Wong et al., 2008). The MSRS consists of 10 statements about a person's tendency to consciously process their movements or to be self-conscious about their style of movement (Table 18). Scoring of the MSRS statements is based on a Likert-type scale ranging from strongly agree (1 point) to strongly disagree (6 points). The maximum MSRS score is 60 points, with higher scores indicating greater propensity to consciously monitor and control movements. The theory of reinvestment proposes that consciously controlling and monitoring one's own movements can constrain or inhibit more effective automatic control processes, which can potentially lead to movement disruption (Masters & Maxwell, 2008). High MSRS scores are associated with greater movement errors under psychological pressure in sport (Chell, Graydon, Crowley, & Child, 2003; Jackson, Ashford, & Norsworthy, 2006; Masters, Polman, & Hammond, 1993; Maxwell et al., 2006), slowed surgical performance by medical students under time pressure (Malhotra, Poolton, Wilson, Ngo, & Masters, 2012), higher fall incidence in older adults (Wong et al., 2008), more severe functional impairment after stroke (Orrell et al., 2009), duration of Parkinson's disease (Masters, Pall, MacMahon, & Eves, 2007), and self-reported knee pain (Selfe et al., 2015).

The LESS is a reliable tool that identifies movement patterns linked with non-contact injuries using a jump-landing task (Hanzlíková & Hébert-Losier, 2020b; Padua et al., 2009). Clinicians evaluate frontal and sagittal plane videos from the LESS test and visually evaluate aberrant lower-extremity and trunk kinematics from initial ground contact until maximal knee flexion. The LESS score consists of 17 items; movement items 1 to 15 are scored as 0 (error absent) or 1 (error present). The last two items (16 and 17) are subjective and assess the overall sagittal plane displacement and quality of

landing. These two items are scored from 0 to 2 errors. The minimum (best) score is 0 an reflects the absence of movement errors, and the maximum (worst) score is 17 errors. Higher LESS scores indicate poorer jump-landing mechanics and greater risk of non-contact lower-extremity injury. Padua et al. (2015) concluded that 5 errors was the optimal cut-off score for determining increased risk of non-contact ACL injury incidence. The risk ratio for sustaining a non-contact ACL injury when LESS scores were 5 errors or greater (compared to lower than 5 errors) was 10.7 (Padua et al., 2015). A previous study concluded that elder fallers scored significantly higher on the MSRS compared to non-fallers (Wong et al., 2008). The authors argued that the high propensity to reinvest might contribute to cautious gait in those with fear of falling, which disrupts automaticity of walking and increases risk of falling and associated injury risk (Wong et al., 2008). Therefore, it is possible that athletes who consciously monitor their own movements may exhibit a greater number of landing errors during LESS assessment and be at greater risk of sport-related injuries.

Generalised hypermobility is an identified risk factor for injury (Dallinga et al., 2012; Donaldson, 2012; Pacey et al., 2010), including the ACL injury (Goshima et al., 2014; Sundemo et al., 2019). Generalised joint hypermobility is usually a congenital inherited disorder of connective tissue characterised by increased movement in multiple joints beyond normal physiological ranges expected in a given population (Castori et al., 2017; Malfait et al., 2017). Overall, the prevalence of generalised hypermobility reported to exist in the general population is between 10 to 20% (Remvig et al., 2007b). Generalised joint hypermobility can be categorised as individuals with asymptomatic joint hypermobility, individuals with well-defined syndrome associated with joint hypermobility, and individuals with symptomatic joint hypermobility (Castori et al., 2017). Besides a range of musculoskeletal symptoms (Hakim & Grahame, 2003), generalised hypermobility has been associated with a greater prevalence of panic disorder and anxiety (Garcia-Campayo et al., 2011), attention-deficit and hyperactivity disorder (Baeza-Velasco, Sinibaldi, & Castori, 2018), fatigue (Krahe, Adams, & Nicholson, 2018), and pain hypersensitivity (Bettini, Moore, Wang, Hinds, & Finkel, 2018). Given that the propensity for movement-specific reinvestment has also been linked to fear, anxiety, fatigue, and movement difficulties and disorders, there may be an association between hypermobility and conscious engagement in movement. Conscious engagement in movement may therefore be contributing to the altered

movement patterns (Fatoye et al., 2011; Galli et al., 2011; Luder et al., 2015; Simonsen et al., 2012) and increased injury risk (Pacey et al., 2010) in hypermobile individuals.

The association between propensity for movement-specific reinvestment, biomechanical control, and hypermobility has not been studied to date. The propensity for movement-specific reinvestment may be an important injury risk factor to consider that may assist injury prevention efforts via the development and implementation of more targeted, multi-modal interventions for these individuals. Participants with symptomatic generalised joint hypermobility or well-defined syndromes associated with hypermobility often present with chronic pain and fatigue to various extents, which may influence the results. Several physically active individuals present with asymptomatic generalised joint hypermobility (Luder et al., 2015) and are clinically perceived at a higher risk of injury given their hypermobile status, although limited research has focused on this population specifically. Therefore, the aim of this paper was to explore the relationship between MSRS, LESS, and Beighton scores in young active asymptomatic individuals, as well as to compare MSRS scores between participants at low and high injury risk, as well as between non-hypermobile and asymptomatic generalised hypermobile participants. We hypothesised that participants at high injury risk and those presenting with asymptomatic generalised hypermobility would exhibit greater MSRS scores than low injury risk and non-hypermobile participants, respectively.

Table 18. The Movement-Specific Reinvestment Scale. Adapted from Masters et al. (2005).

Conscious Motor Processing items
I remember the times when my movements have failed me.
I reflect about my movement a lot.
I try to think about my movements when I carry them out.
I am aware of the way my body works when I am carrying out a movement.
I try to figure out why my actions failed.
Movement Self-Consciousness items
If I see my reflection in a shop window, I will examine my movements.
I am self-conscious about the way I look when I am moving.
I sometimes have the feeling that I am watching myself move.
I am concerned about my style of moving.
I am concerned about what people think about me when I am moving.

11.2 Methods

11.2.1 Sample size calculation

Given that no published data exist regarding the association between MSRS, LESS, and Beighton scores, we calculated sample size requirements based on the ability to detect a correlation of moderate magnitude; i.e., 0.50 (Mukaka, 2012). Based on sample size calculations using a customisable statistical spreadsheet (Hopkins, 2006) from standard two-tailed hypothesis equations using an 90% power ($\beta = 0.10$) and 5% significance level ($\alpha = 0.05$), we needed at least 38 participants to detect a moderate correlation between measures. Given that 60 individuals agreed to participate, our study sample size is powered to detect a correlation of 0.40 in magnitude.

11.2.2 Participants

To be included, participants needed to be involved in sport activity; and be free from injury, pain, or any other issue that would limit physical activity at the time of study participation. Previous injuries were not an exclusion criterion. This study aimed to assess only non-hypermobile and asymptomatic hypermobile participants according to the framework for the classification of joint hypermobility proposed by Castori et al. (2017). Therefore, participants with chronic pain or known diagnosis of medical syndromes associated with joint hypermobility (e.g., Ehlers-Danlos and Marfan syndrome) were excluded. Sixty young adults (35 males, 25 females) fulfilled the

inclusion criteria and participated in this study. Age, height, and mass (mean ± standard deviation) for males were 23.2 ± 4.7 years, 181.2 ± 6.6 cm, and 83.9 ± 3.2 kg; and 22.2 ± 5.6 years, 169.3 ± 5.8 cm, and 66.2 ± 2.6 kg for females. Participants were involved in organised sport activity 3 times per week (median), on average for 6.4 ± 4.4 hours a week. The study protocol was approved by our institution's Health Research Ethics Committee [HREC(Health)#2018-27] and adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks associated with testing before participating. Note that participants were not screened for generalised joint hypermobility prior to participation.

11.2.3 Testing procedure

All tests were completed in a single session. After self-administered MSRS completion, half of the participants completed the LESS protocol followed by the Beighton diagnostic test for hypermobility, whereas the other half completed the tests in the reverse order. The MSRS has adequate internal reliability (coefficient alpha = 0.80), teste-retest reliability (Pearson product moment correlation coefficient = 0.74), and validity (Masters et al., 2005; Masters et al., 1993). The LESS has been validated against 3D motion capture and has good to excellent intra-rater [intraclass correlation coefficient (ICC), 0.82-0.99], inter-rater (ICC, 0.83-0.92), and inter-session (ICC, 0.81) reliability reported in the scientific literature (Hanzlíková & Hébert-Losier, 2020b). The Beighton score is a major criterion used in diagnosing joint hypermobility syndrome, and is a valid and reliable (kappa = 0.75 to 0.78) diagnostic tool for joint hypermobility (Remvig et al., 2007a). In this study, sex and age-specific cut-off scores based on Singh et al. (2017) were used to categorise hypermobility. Specifically, the cut-off score for hypermobility of ≥ 5 points was used for females, and ≥ 4 for males in our sample.

The LESS testing procedure used here was identical to the procedure described elsewhere (Padua et al., 2009). Participants jumped horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately jumped upward for maximal vertical height. Participants were instructed to jump off the box with both feet, land in front of the designated line, and jump as high as possible upward upon landing. We provided no feedback on landing technique unless participants were performing the task incorrectly. Participants were given as many practice trials as needed to become comfortable with the task (typically one). Each participant performed three trials of the

double-leg jump-landing task in their own footwear. To mitigate effects of fatigue, participants were allowed to rest until they felt ready to perform the second and third trial of the task. Two tripod-mounted digital cameras (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm) captured performance of the task at 60 Hz. The cameras were placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m to capture frontal and sagittal plane motion. One investigator (IH) with experience of over 400 LESS evaluations replayed the videos using the open-source Kinovea video analysis software (version 0.8.15, www.kinovea.org). The investigator scored the first landing of the jump-landing task of all three trials (i.e., when landing from the box) using the 17-item LESS scoring criteria (Padua et al., 2009). The investigator was blinded to the MSRS and Beighton hypermobility scores.

An experienced physiotherapist (IH) recorded the Beighton scores, consisting of five components: (1) passive dorsiflexion and hyperextension of the fifth metacarpal joints (little fingers) beyond 90°, (2) passive apposition of the thumbs to the flexor aspects of the forearms, (3) passive hyperextension of the elbows beyond 10°, (4) passive hyperextension of the knees beyond 10°, and (5) active forward flexion of the trunk with the knees fully extended so that the palms of the hands rest flat on the floor (Beighton et al., 1973), following standard protocols and using a hand-held goniometer (Smits-Engelsman et al., 2011). Note here that the first four elements can be given a maximum score of 2 points because these are performed bilaterally (i.e., 1 point for each hypermobile joint), whereas the last element has a maximum score of 1 point. Hence, a total score of 9 points is possible.

11.2.4 Statistical analyses

Mean ± standard deviation, median (interquartile range), and range (minimum to maximum) values were calculated to describe variables based on variable type. Note that the mean LESS score from the three trials completed by each participant was used for statistical analysis. Statistical significance level was set at $\alpha \leq 0.05$ for all analyses. The statistics were computed using Microsoft® Excel® for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2.

To investigate the relationship between MSRS, LESS, and Beighton scores, Spearman rank correlation coefficients (ρ) were calculated given the ordinal nature of

the data. The correlation coefficient values were interpreted using thresholds of 0.30, 0.50, 0.70, and 0.90 to indicate low, moderate, high, and very high correlations (Mukaka, 2012). Correlations below 0.30 were considered negligible.

Independent *t*-tests with equal variance were conducted to investigate differences in MSRS scores between low and high (LESS ≥ 5 errors) injury risk, and non-hypermobile and hypermobile (Beighton score ≥ 5 points for females and ≥ 4 points for males) participants. Mean differences and 95% confidence intervals [upper, lower] in MSRS scores between groups and corresponding effect sizes (Hedge's *g*) with 95% confidence intervals were calculated. Thresholds for interpreting the magnitude of Hedge's *g* were 0.20, 0.50, and 0.80 for small, medium, and large effects (Lakens, 2013). Effect sizes below 0.20 were considered trivial. There were no missing data, so data from all 60 participants were analysed. Note that analysis of each MSRS subscale (Conscious Motor Processing and Movement Self-Consciousness) separately yielded similar results.

11.3 Results

The mean MSRS score for all participants was 37.9 ± 8.3 points (range: 19 to 54). Mean LESS score was 5.3 ± 1.5 errors (range: 2.0 to 9.7). The median and interquartile range of Beighton score for all participants was 2.5 (4.0) points (range: 0 to 9).

There was a negligible non-significant relationship between MSRS and LESS scores ($\rho = 0.06$, $p = 0.625$) and MSRS and Beighton scores ($\rho = 0.09$, $p = 0.481$). The MSRS scores between participants at low and high injury risk were similar (Table 19). There was no significant difference in MSRS scores between non-hypermobile and hypermobile participants, with a trivial effect of grouping on MSRS scores (Table 19).

Table 19. Comparison of MSRS scores between groups in the sampled cohort (n = 60).

	n	MSRS scores (points)	MD [95% CI]	t-test	Hedge's g [95% CI]
At low risk [a]	21	37.8 ± 7.8	-0.2	0.933	-0.02
At high risk [a]	39	38.0 ± 8.6	[-4.7 to 4.3]		[-0.56 to 0.51]
Non-hypermobile [b]	41	37.5 ± 8.9	-1.5	0.524	-0.18
Hypermobile [b]	19	39.0 ± 7.0	[-6.1 to 3.2]		[-0.72 to 0.37]

Abbreviations: n, number of participants; MSRS, Movement-Specific Reinvestment Scale; MD, mean difference; CI, confidence interval.

[a] At low risk Landing Error Scoring System (LESS) scores < 5 errors; at high risk LESS scores ≥ 5.

[b] Hypermobile, Beighton score ≥ 5 points for females and ≥ 4 points for males; non-hypermobile, Beighton score < 5 points for females and < 4 point for males.

11.4 Discussion

The purpose of our study was to investigate the relationship between MSRS, LESS, and Beighton scores, and to compare MSRS scores between high and low injury risk participants and between non-hypermobile and asymptomatic hypermobile participants. In our cohort, there was no significant relationship between MSRS, LESS, and Beighton scores, and no difference in MSRS scores between the subgroups analysed. The results indicate that participants with greater propensity for conscious monitoring and control of their movements do not present with a greater number of high injury risk movement patterns during double-leg jump-landing as assessed by the LESS and propensity for movement-specific reinvestment does not vary in asymptomatic hypermobile individuals compared to non-hypermobile individuals.

The lack of an association between injury risk according to LESS scores and movement-specific reinvestment could be due to the phylogenetic nature of the LESS task, the manner in which reinvestment occurs, the low-pressure testing environment, or a combination of these factors. Unlike ontogenetic skills, which require people to learn them, phylogenetic skills (such as jumping) typically can be performed by anyone who is healthy, with minimal conscious processing (Masters & Poolton, 2012). Consequently, phylogenetic skills tend to be less susceptible to disruption by conscious control (reinvestment) than ontogenetic tasks (Masters & Poolton, 2012), which would mitigate differences between high and low MSRS scores. Previous studies have also

confirmed an association between high propensity for movement-specific reinvestment and poorer sport-specific task performance under psychological pressure (Chell et al., 2003; Jackson et al., 2006; Maxwell et al., 2006). Specifically, individuals with high MSRS scores displayed greater susceptibility to skill failure during soccer kicking (Chell et al., 2003), golf putting (Maxwell et al., 2006), and field-hockey dribbling (Jackson et al., 2006) under high pressure situations. These ontogenetic skills are seldom automated to the same extent as phylogenetic skills, so they require considerable concentration to be performed correctly and their execution is easily processed consciously. Psychological pressure amplifies the likelihood that performers (especially high reinventors) will process their movements consciously to ensure that their performance remains effective, but often this 'overthinking of movement' can disrupt fluid movement (Baumeister, 1984; Beilock & Carr, 2001; Gray, 2004; Masters, 1992). The double-leg jump-landing task tested by the LESS requires participants to jump horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately jump upward as high as possible upon landing. The task involves movements that are presumably highly automated, so it requires minimal concentration and cannot easily be processed consciously. Thus, performance of the task is less likely to be influenced by movement-specific reinvestment. Furthermore, the LESS testing environment imposes minimal pressure to perform well. Participants are not informed of the LESS scoring criteria when they perform the test and receive no performance feedback that might reveal innate movement patterns linked with a higher risk of sustaining non-contact lower-body and ACL injuries. As such, participants therefore are unaware of what characterises good LESS performance or whether they are performing well (or not). Results might have been different with presence of an overhead target given that it can act as an external motivator and performance indicator, thereby altering movement patterns (Ford et al., 2005a; Ford, Nguyen, Hegedus, & Taylor, 2017). Injury risk and propensity for conscious monitoring and control of movement may be related under certain circumstances, with the association only surfacing in cases where participants are highly motivated to perform successfully (e.g., under pressure) or when they are aware of what constitutes successful or unsuccessful performance. Future research should examine this possibility by testing biomechanics during demanding high-injury risk sport-specific tasks under psychological pressure similar to the competition environment. Only once such investigations are completed

will it be possible to reach conclusions about the potential role of movement-specific reinvestment in sport-related injuries.

The theory of reinvestment proposes that, in addition to psychological pressure, a variety of other contingencies can cause a person to direct attention to conscious movement processing. These include instructions, novel task demands, boredom, and performance errors (Masters & Maxwell, 2008). For the purposes of LESS task standardisation, participants received several instructions during testing. The instructions were to jump off the box with both feet, land in front of the designated line, and jump as high as possible upward upon landing (Padua et al., 2009). However, these instructions are unlikely to cause participants to direct their attention towards the mechanics of their movements; indeed, the instruction to jump upward for maximal vertical height is important in LESS testing because it shifts participants' focus towards performance rather than landing mechanics (Padua et al., 2009). Consequently, focusing externally on movement outcomes, in this case on the height of the jump, rather than internally on the movements is likely to have distracted attention away from the movement biomechanics, thereby reducing the likelihood of movement-specific reinvestment (Maxwell et al., 2006; Wulf, Weigelt, Poulter, & McNevin, 2003).

With progressing age, degenerative changes affect all body systems and often result in pain, fatigue, muscle weakness, sensory deficits, poor balance, cognitive deficit, and other comorbidities, which are common in the elderly population (Schultz, 1992). All of these signs and symptoms impair mobility and make every movement challenging (Schultz, 1992). It may be that elderly people with movement impairment consciously process movement to avoid pain, falls, or trauma. Increased reinvestment may lead to disturbed movement patterns and greater injury risk compared to low reinvestors, similar to elder fallers who scored significantly higher than non-fallers on the MSRS (Wong et al., 2008). Therefore, it is possible that an association between MSRS scores and injury risk exists and should be further explored in the older population. Furthermore, severity of movement impairment may be positively associated with MSRS scores given that propensity for reinvestment has been shown to be greater in people with stroke compared to age-matched controls (Orrell et al., 2009), and to be positively associated with duration of Parkinson's disease (Masters et al., 2007). Disorder of connective tissue and excessive joint movement increase the

likelihood of macro and micro traumas to the musculoskeletal system, which in turn lead to acute and persistent pain, early joint osteoarthrosis, and loss of function in hypermobile individuals (Castori et al., 2017; Tinkle et al., 2017). For instance, hypermobile individuals present with a higher degree of joint osteoarthrosis earlier in life compared to non-hypermobile peers (Tinkle et al., 2017). Therefore, the hypermobile population may present with greater movement impairment and associated pain earlier in life, which may lead to greater conscious processing of movements compared to non-hypermobile age-matched individuals. However, there is no supporting evidence currently available to support or refute that elder hypermobile individuals consciously process movements to a greater extent compared to age-matched non-hypermobile individuals.

The asymptomatic hypermobile participants tested in our study did not exhibit higher MSRS scores compared to non-hypermobile participants. The framework for the classification of joint hypermobility (Castori et al., 2017) used in our study suggests categorising hypermobile individuals as (1) those with asymptomatic joint hypermobility, (2) those with a well-defined syndrome associated with joint hypermobility (e.g., Ehlers-Danlos syndrome and Marfan syndrome), and (3) those with symptomatic joint hypermobility. Studies exploring injury risk and anxiety in hypermobile individuals have not differentiated between joint hypermobility groups according to this classification (Dallinga et al., 2012; Donaldson, 2012; Pacey et al., 2010), with most previous studies exploring movement of hypermobile individuals involving children (Fatoye et al., 2011; Junge et al., 2015), symptomatic individuals (Simonsen et al., 2012), or individuals with well-defined disorders (Galli et al., 2011; Rombaut et al., 2011). Based on our knowledge, a single study has involved asymptomatic hypermobile individuals (Luder et al., 2015). In this study, symptomatic hypermobile females showed significantly lower EMG activity for the quadriceps during stair climbing compared to females with normal mobility; however, the EMG activity of asymptomatic hypermobile females did not differ from controls. These results indicate that there may be some clinically relevant differences in neuromuscular control and muscle recruitment patterns between asymptomatic and symptomatic hypermobile individuals that require further exploration. It is possible that our sample of asymptomatic hypermobile individuals adapt to their condition and use strategies to actively stabilise their hypermobile joints during dynamic tasks, which may explain to

some extent why they do not suffer from chronic pain and other symptoms typically associated with hypermobility. Therefore, it may be that the asymptomatic hypermobile individuals tested in our study presented with similar injury risk, prevalence for anxiety, and movement control compared to our non-hypermobile individuals, which would explain the lack of significant differences between hypermobile and non-hypermobile participants in terms of MSRS scores. Furthermore, symptoms associated with symptomatic hypermobility (e.g., chronic pain or fatigue) potentially play a more important role in injury risk and be more strongly associated with MSRS scores compared to hypermobility itself. Therefore, we recommend that future research explores the MSRS in symptomatic hypermobile individuals and individuals with well-defined syndromes associated with joint hypermobility to fully elucidate whether or not conscious monitoring and control of movement plays a role in injury risk or movement control of hypermobile individuals.

11.5 Conclusion

Based on our results, propensity for movement-specific reinvestment was not significantly associated with injury risk assessed by the LESS, which may be due to the phylogenetic nature of the LESS task and the low-pressure testing environment. Examining the influence of reinvestment on the biomechanics of demanding sport and injury-specific tasks under psychological pressure similar to a competition environment is needed to determine whether reinvestment-specific interventions may assist injury prevention efforts. Participants with asymptomatic generalised hypermobility did not present with significantly different MSRS scores compared to non-hypermobile participants. Examination of the MSRS in symptomatic hypermobile individuals and individuals with well-defined syndromes is needed to elucidate whether or not conscious monitoring and control of movement plays a role in these conditions. This information would inform clinical practice and whether implementing motor learning strategies that discourage the propensity for reinvestment is of potential benefit during the rehabilitation process in these population groups.

CHAPTER 12

The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics

Hanzlíková, I., Richards, J., & Hébert-Losier, K. (under review). The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics.

Prelude: The last clinically assessable injury risk factor explored in this section is ankle dorsiflexion range of motion (ROM). Limited dorsiflexion ROM has been related to Anterior Cruciate Ligament (ACL) injury risky movement patterns during single-leg and double-leg landings (Fong et al., 2011; Hoch et al., 2015). However, the influence of dorsiflexion ROM on cutting manoeuvres is unknown despite cutting being a common task in sports with a high incidence of knee injuries. Therefore, the aim of this chapter is to explore the influence of dorsiflexion ROM on cutting kinematics and to identify whether dorsiflexion ROM is associated with movement patterns that may predispose athletes to non-contact ACL injuries.

12.1 Introduction

Landing technique is an important lower-extremity injury risk factor. Devita and Skelly (1992) compared stiff versus soft landing techniques and showed greater kinetic energy absorption by the muscular system (~19%) and lower vertical ground reaction force (~30%) during soft compared to stiff landings. These findings indicate that the muscles crossing the lower-extremity joints absorb more energy during soft landings and decrease the impact stresses on the musculoskeletal system, presumably reducing the probability of injury.

Ankle dorsiflexion ROM plays a prominent role in landing biomechanics and technique (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017). Previous studies have concluded that limited passive dorsiflexion ROM is related to lower ankle, knee, and hip sagittal plane displacement and greater ground reaction forces during single-leg and double-leg landings in healthy individuals as well as persons with chronic ankle instability (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017). The magnitude of the ground reaction forces during landing has been strongly associated with impact stresses on the body structures and is a risk factor for lower-extremity injuries, in particular to the ACL (Leppänen et al., 2017; Podraza & White, 2010). Furthermore, several studies have concluded that individuals with a history of an ankle injury have limited dorsiflexion ROM, which results in a more erect landing posture, greater ground reaction force, and potentially higher re-injury rate (Hoch et al., 2015; Mason-Mackay et al., 2017).

In sport, the ankle and knee are the most commonly injured sites and often involve unilateral loading during changes of direction, sudden decelerations, and landings (Swenson et al., 2013). Not surprisingly, knee and ankle injuries are most common in American football, soccer, volleyball, basketball, and handball, which are sports with a regular occurrence of 'risky movements' (i.e., changes of direction) (Swenson et al., 2013). Several studies have explored the influence of dorsiflexion ROM on human biomechanics during single-leg or double-leg landings (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017); however, the influence of dorsiflexion ROM on cutting manoeuvres, which are common in sports with the highest incidence of ankle and knee injuries, is currently unknown.

Therefore, our aim was to explore the influence of ankle dorsiflexion ROM on kinematics during unanticipated side-step cutting manoeuvres, and to identify whether limited dorsiflexion ROM is associated with specific movement patterns that may predispose individuals to non-contact ACL and other non-contact lower-extremity injuries. We hypothesised that limited dorsiflexion ROM would be associated with a more erect posture at IC and lower ROM of the lower-extremity joints.

12.2 Methods

12.2.1 Sample size calculation

Since no study so far has explored the correlation between dorsiflexion ROM and cutting biomechanics, we based our sample size requirements on findings from studies examining the association between dorsiflexion ROM and landing kinematic in males and females (Fong et al., 2011; Hoch et al., 2015). Dorsiflexion ROM influences predominantly sagittal plane kinematics (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017); and therefore, sample size requirements were calculated based on correlations reported to exist between dorsiflexion ROM and sagittal plane ROM at the ankle ($r = 0.47$), knee ($r = 0.46$ to 0.70), and hip ($r = 0.55$) (Fong et al., 2011; Hoch et al., 2015). From standard two-tailed hypothesis equations using an 80% power ($\beta = 0.05$) and a 5% significance level ($\alpha = 0.05$), and to detect the lowest correlation presented ($r = 0.46$), 35 participants were needed. To account for a potential 20% withdrawal or missing data, we recruited 42 participants.

12.2.2 Participants

The inclusion criteria were individuals who regularly participate in a team sport that involved cutting and being free from any injury or illness that limited physical activity. A Health Research Ethics Committee approved the study protocol [HREC(Health)2018#27], which adhered to the Declaration of Helsinki. All participants signed a written informed consent document prior to participating that explained the potential risks associated with testing, i.e., delayed onset muscle soreness.

12.2.3 Testing procedure

Participants were familiarised with the experimental protocol and all testing was completed in one session. After completing the baseline questionnaire and the self-administered short-form International Physical Activity Questionnaire (Craig et al.,

2003), an experienced physiotherapist measured ankle dorsiflexion ROM using the Weight-Bearing Lunge Test (WBLT). The WBLT is considered to be representative of ankle function during sporting activities due to its weight-bearing nature (Powden, Hoch, & Hoch, 2015). The WBLT has been shown to be reliable, with an intra-rater reliability intraclass correlation coefficient (ICC) of 0.85 to 0.99 and inter-rater reliability ICC of 0.80 to 0.99 (Powden et al., 2015). The WBLT has also been validated against two-dimensional (2D) motion capture analysis for the assessment of dorsiflexion ROM ($r = 0.71$ to 0.76) (Hall & Docherty, 2017). There are several WBLT measurement techniques; however placing a digital inclinometer 15 cm below the tibial tuberosity demonstrates the best validity against 2D motion capture ($r = 0.76$) (Hall & Docherty, 2017), and was therefore used in our study. One trial of the WBLT was measured for each lower extremity using a digital inclinometer (Bevel Box, Angle Sensor Technology).

After the WBLT was completed, the kinematics during an unanticipated side-step cutting manoeuvre were recorded. For the side-step cutting manoeuvre, participants started five meters in front of the target cutting area. When participants moved within the target area, timing gates (Swift Performance SpeedLight^{TM}) triggered one of two lights in a randomised order to signal the cutting direction (Figure 24, p. 162). Participants were asked to perform a side-step cutting manoeuvre similar to that during active game play. During cutting, participants were required to stay between two lines that were taped on the floor, which indicated a cutting angle between 60° and 90° (Figure 24, p. 162). A minimum approach speed of 3.5 m/s at the penultimate foot contact was required based on previous studies to mimic a typical game setting (Saunders, 2006). Trials performed at a slower speed or outside of the taped lines were disregarded and repeated. After a familiarisation period of typically two attempts, each participant completed three successful repetitions of side-step cutting manoeuvres on the dominant and non-dominant legs. For right-leg dominant participants, cutting towards the left side represented dominant leg cutting (i.e., right-leg cutting). The Perceived Recovery Status Scale was used to monitor subjective ratings of recovery (Laurent et al., 2011). To ensure sufficient recovery times between trials, participants needed to self-report ratings ≥ 7 before starting the next trial; else, rest periods were extended. Participants wore their own sport shoes for testing.

12.2.4 Instrumentation

Whole-body motion was recorded during all cutting tasks using an 8-camera Oqus 700+ 3D motion capture system at 200 Hz using the Qualisys Track Manager software version 2019.1 (Qualisys AB, Gothenburg, Sweden). Forty-two 12.5-mm retroreflective markers and five clusters were taped onto the skin and shoes, which were modelled using the Calibrated Anatomical System Technique (Cappozzo et al., 1995) with an additional cluster placed on the right side of the pelvis to improve segment tracking (Figure 21, p. 133). In addition, one inertial measurement unit (IMU) sensor (Delsys Trigno IM sensors, Delsys Inc., MA, USA) was attached to the sacrum and synchronised with the 3D motion capture system which recorded pelvis linear accelerations at 148 Hz.

12.2.5 Data processing

The raw data were exported to the .c3d format and processed using Visual3D Professional™ software version 6.01.36 (C-Motion Inc., Germantown, Maryland, USA). From the reference set of markers, a full-body biomechanical model with six degrees of freedom at each joint and 13 rigid segments was constructed, with the local coordinates of all body segments derived from a static trial captured prior to the cutting manoeuvre. To remove the initial offset between foot and ankle and to create more clinically relevant ankle joint angles, virtual foot segments were constructed by projecting lateral and medial malleoli and foot centre markers onto the floor to align the foot and laboratory coordinate systems. Any gaps in the marker data up to 10 frames were interpolated using a third order polynomial fit algorithm, and marker data were filtered using a fourth order low-pass Butterworth filter with a cut-off frequency of 15 Hz (Hanzlíková et al., 2019). IMU data were visually assessed using a range of cut-off frequencies (15 to 100 Hz), and 80 Hz was confirmed as the best at preserving all high-frequency signal characteristics, while also removing noise. The sacrum IMU acceleration data were corrected based on the pelvis angle in all three planes to estimate vertical accelerations.

Kinematic parameters were calculated using an XYZ cardan sequence equivalent to the joint coordinate system proposed by Grood and Suntay (Grood & Suntay, 1983). Based on the previous studies exploring dorsiflexion ROM and landing biomechanics (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017), we

expected kinematic changes predominantly in the sagittal plane. We were notably interested in examining values at IC and throughout the loading phase of the cutting manoeuvre, as examined elsewhere (Fong et al., 2011; Hoch et al., 2015). The kinematic values at IC, and the minimum, maximum, and range values between IC and maximal knee flexion for ankle, knee, hip, and trunk angles and pelvis linear accelerations in all three planes were extracted for dominant and non-dominant leg cutting manoeuvres. Furthermore, foot-ground angles in all three planes one frame before IC were extracted to explore pre-landing strategies (Harry et al., 2017). Trunk angles were calculated relative to the laboratory coordinate system. IC was defined as the instance when the cutting-leg foot centre of gravity vertical acceleration (z) reached a maximum value. Furthermore, the pelvis centre of gravity velocity at IC and cutting angle during the cutting manoeuvre were extracted to quantify cutting performance. The directionality and interpretation of joint movements are presented in Table 13, p. 134.

12.2.6 Statistical analyses

Kinematic data from the three trials on each leg were averaged and used for further processing. Mean ± standard deviation and range (minimum to maximum) values were calculated for all variables as descriptive statistics. An initial analysis showed that significant differences existed in relation to lower-extremity dominance during sport-specific cutting manoeuvres, therefore the dominant and non-dominant legs were analysed separately. Multiple linear regressions were used to model the relationship between kinematic variables during cutting manoeuvres, dorsiflexion ROM, and sex. We controlled for sex due to the significant differences reported to exist in kinematic measures between sexes during cutting manoeuvres (Benjaminse et al., 2011). When the sex confounder was not significant ($p > 0.05$), it was removed from the model. Note that no analysis was performed if only the sex confounder was significant as sex differences were not the aim of this study. We set the significance level at $\alpha \leq 0.05$ for all analyses. Statistical analyses were performed using Microsoft® Excel for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2.

12.3 Results

Forty-two individuals (25 males and 17 females) volunteered to participate. Age, height, and mass (mean ± standard deviation) for males were 23.6 ± 4.1 years (range

17 to 32 years), 182.2 ± 6.4 cm, and 85.0 ± 11.9 kg; and for females were 22.2 ± 5.7 years (range 16 to 35 years), 169.1 ± 6.0 cm, and 63.7 ± 6.8 kg. The majority of participants (93%) were right-leg dominant, assessed by the preferred leg when kicking a ball. According to the International Physical Activity Questionnaire, level of activity was high, moderate, and low in 60%, 38%, and 2% of participants, respectively. From our sample, 31% of participants played soccer, 26% rugby, 17% frisbee, 14% netball, 7% basketball, and 5% field hockey. Participants were involved in physical activity 3 times per week (median), on average for 7 hours per week. Overall, the mean cutting angle was 58.3 ± 9.8° and cutting speed at IC was 3.4 ± 0.5 m/s. Mean dorsiflexion ROM from the WBLT was 51.3° ± 6.5° (range: 35.9° to 70.0°) on the dominant leg and 50.2 ± 7.0° (range: 33.5° to 71.5°) on the non-dominant leg. Mean values and standard deviations for the kinematic variables measured during the dominant and non-dominant leg cutting manoeuvres are presented in Table 20. Data from all 42 participants were analysed, and there were no missing data.

For dominant leg cutting, significant regression equations were found for transverse plane knee ROM ($F_{(1, 39)} = 4.65$, $p = 0.037$, $R^2 = 0.11$), sagittal plane trunk ROM ($F_{(1, 39)} = 4.35$, $p = 0.044$, $R^2 = 0.10$), and trunk flexion angle at IC ($F_{(2, 39)} = 5.40$, $p = 0.009$, $R^2 = 0.22$), Figure 25. Transverse plane knee ROM increased by 0.20° and sagittal plane trunk ROM increased by 0.16° for each degree of dorsiflexion ROM measured during the WBLT. Trunk flexion angle at IC decreased by 0.39° for each degree of dorsiflexion ROM measured during the WBLT, with males exhibiting 5.89° greater trunk flexion at IC than females.

For non-dominant leg cutting manoeuvres, significant regression equations were found for peak lateral trunk flexion towards the stance leg ($F_{(1, 39)} = 4.56$, $p = 0.039$, $R^2 = 0.10$), sagittal plane hip ROM ($F_{(1, 39)} = 6.17$, $p = 0.017$, $R^2 = 0.14$), and coronal plane hip ROM ($F_{(1, 39)} = 8.79$, $p = 0.005$, $R^2 = 0.18$), Figure 26. Peak lateral trunk flexion towards the stance leg, sagittal plane hip ROM, and coronal plane hip ROM increased 0.36°, 0.24°, and 0.21° for each degree of dorsiflexion ROM measured during the WBLT, respectively.

Table 20. Means and standard deviation (SD) of kinematics variables measured during unanticipated side-step cutting from initial contact to maximal knee flexion.

	Variable	DOMINANT LEG CUTTING		NON-DOMINANT LEG CUTTING	
		Mean	**SD**	**Mean**	**SD**
Foot-ground angles (°)[a]	Heel strike angle	3.97	6.54	4.90	6.30
	Eversion (-)	-11.32	9.36	-12.16	8.36
	Internal rotation	4.15	11.46	3.72	11.63
Ankle angles (°)	Peak plantar flexion (-)	-10.93	10.85	-12.89	6.10
	Peak dorsiflexion	20.34	10.32	17.08	8.48
	Plantar flexion at IC (-)	-10.47	10.92	-11.91	6.16
	Sagittal plane ROM	31.27	8.97	29.96	6.95
	Min adduction	17.87	6.86	15.88	5.66
	Max adduction	32.38	6.52	32.83	7.13
	Adduction at IC	18.26	6.70	16.04	5.70
	Coronal plane ROM	14.51	6.58	16.95	7.09
	Min external rotation (-)	-2.00	11.93	-0.82	8.53
	Max external rotation (-)	-12.69	11.71	-10.61	8.56
	External rotation at IC (-)	-5.07	11.50	-3.40	8.47
	Transverse plane ROM	10.69	3.61	11.43	4.02
Knee angles (°)	Min flexion	26.84	5.78	25.53	4.87
	Max flexion	56.67	7.39	56.69	7.60
	Flexion at IC	27.16	5.83	25.70	4.94
	Sagittal plane ROM	29.82	5.93	31.16	7.01
	Min valgus (-)	2.70	5.25	3.74	5.55
	Max valgus (-)	12.65	7.37	15.42	7.69
	Valgus at IC (-)	5.27	5.25	6.08	5.13
	Coronal plane ROM	9.95	3.91	11.69	4.11
	Peak external rotation (-)	-3.67	6.64	-3.17	8.23
	Peak internal rotation	8.67	6.78	9.85	8.68
	Internal rotation at IC	0.93	8.27	1.47	8.97
	Transverse plane ROM	12.34	3.98	13.02	4.21
Hip angles (°)	Min flexion	26.08	12.38	23.35	15.27
	Max flexion	36.80	10.96	36.97	14.32
	Flexion at IC	35.13	10.47	35.66	13.86
	Sagittal plane ROM	10.72	4.36	13.62	4.60
	Min abduction (-)	-10.84	6.57	-12.17	7.55
	Max abduction (-)	-17.89	6.81	-19.65	7.01
	Abduction at IC (-)	-12.81	7.00	-17.08	7.12
	Coronal plane ROM	6.96	2.36	7.48	3.38

	Peak external rotation (-)	-10.08	9.24	-19.61	12.64
	Peak internal rotation	7.62	9.09	1.24	10.70
	Internal/external (-) rotation at IC	3.96	9.92	-2.45	10.14
	Transverse plane ROM	17.70	6.65	20.85	7.48
Trunk angles (°)[b]	Min flexion	8.30	8.37	7.87	9.01
	Max flexion	15.03	8.15	16.17	9.60
	Flexion at IC	9.02	8.64	8.31	9.40
	Sagittal plane ROM	6.73	3.31	8.30	4.78
	Peak lateral flexion away from stance leg (-)	-3.76	7.59	-2.57	6.87
	Peak lateral flexion towards stance leg	0.75	6.56	2.22	7.68
	Lateral flexion away from stance leg at IC (-)	-0.31	5.73	-1.32	6.20
	ROM in coronal plane	4.51	2.08	4.78	2.59
	Min rotation away from the stance leg	2.34	12.43	2.12	15.24
	Max rotation away from the stance leg	15.23	12.65	14.48	15.75
	Rotation away from the stance leg at IC	3.37	10.95	3.54	12.90
	ROM in transverse plane	12.89	4.81	12.36	5.29
Pelvis linear acceleration (m/s^2)	Minimal vertical acceleration	-8.69	2.79	-7.36	2.58
	Maximal vertical acceleration	1.14	1.06	1.08	0.87
	Vertical acceleration at IC	0.44	0.74	0.37	0.52
	Range in sagittal plane	9.82	3.40	8.45	3.11
	Minimal medio-lateral acceleration	-2.61	2.20	-7.13	3.24
	Maximal medio-lateral acceleration	7.93	3.53	2.78	2.18
	Medio-lateral acceleration at IC	-0.58	0.78	0.69	1.03
	Range in coronal plane	10.54	4.45	9.92	3.59
	Minimal anterior-posterior acceleration	-1.53	1.57	-1.12	1.01
	Maximal anterior-posterior acceleration	4.81	1.75	4.63	1.41
	Anterior-posterior acceleration at IC	0.16	1.12	0.41	1.08
	Range in transverse plane	6.34	2.88	5.75	2.20

Abbreviations: IC, initial contact; Max, maximal; Min, minimal; ROM, range of motion from initial contact to maximal knee flexion.

[a]Foot-ground angles extracted one frame before initial contact

[b]Trunk angle relative to the lab coordination system

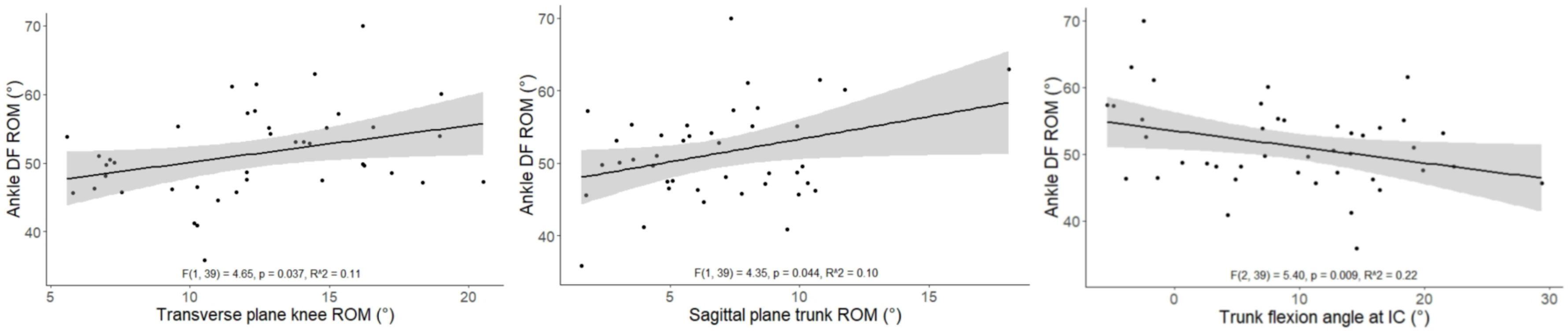

Figure 25. Significant associations between dorsiflexion (DF) range of motion (ROM) measured during the Weight-Bearing Lunge Test and dominant leg side-step cutting kinematics.

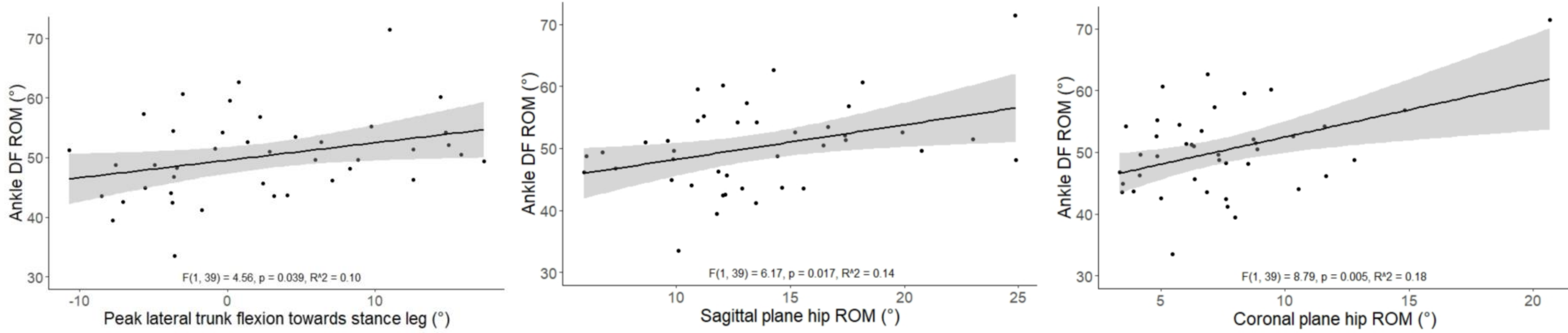

Figure 26. Significant associations between dorsiflexion (DF) range of motion (ROM) measured during the Weight-Bearing Lunge Test and non-dominant leg cutting kinematics.

12.4 Discussion

As hypothesised, the ankle dorsiflexion ROM tested using the WBLT significantly influenced sagittal plane kinematics during unanticipated side-step cutting manoeuvres. Significant associations between coronal and transverse plane kinematics and dorsiflexion ROM from the WBLT were also found. Given that some of these kinematic variables from the cutting task have been linked to non-contact ACL injuries (Boden et al., 2009; Hewett et al., 2009; Sheehan, Sipprell III, & Boden, 2012); dorsiflexion ROM, as measured using the WBLT, may contribute to the ACL injury mechanisms.

12.4.1 Significant associations in the sagittal plane

During dominant leg cutting, decreased trunk flexion at IC was significantly associated with increased dorsiflexion ROM tested by the WBLT. Decreased trunk flexion at IC may play role in ACL injury mechanism as indicate findings from video analyses of ACL injury situations whereby injured athletes demonstrated less peak trunk flexion at IC (mean: 1.6° to 4.0°) during injury compared to uninjured controls (mean: 14.0° to 16.0°) (Hewett et al., 2009; Sheehan et al., 2012). Furthermore, Hashemi et al. (2011) stated that the upright and extended position of the trunk causes the centre of mass to be positioned posteriorly relative to the knee joint; encouraging the knee to flex more than the hip, which results in anterior translation of the tibia and ACL strain.

The findings from the current study showed that participants with greater dorsiflexion ROM presented with a more extended or upright trunk position at IC, which could increase their risk of ACL injury. Noteworthy, however, is that these participants also demonstrated greater sagittal plane trunk ROM during the loading phase of the dominant leg during cutting. It may be that participants with greater dorsiflexion ROM compensate for the decreased trunk flexion at IC by having a greater trunk ROM during the loading phase.

During non-dominant leg cutting in this study, the sagittal plane hip ROM was lower in individuals with less dorsiflexion ROM recorded using the WBLT. The contribution of sagittal plane hip ROM to ACL injury is supported by video analyses showing that athletes during an ACL injury situation have greater peak hip flexion at IC and 160 milliseconds after IC, but limited hip ROM in the sagittal plane compared to uninjured controls (5.1° vs 15.4°) (Boden et al., 2009). One possible explanation is

that decreased sagittal plane ROM of the lower extremity joints shortens the loading phase, therefore limiting the time over which landing forces are dissipated (Podraza & White, 2010). Loading rate and magnitude of ground reaction forces are both risk factors for lower-extremity injuries, and have been linked with ACL injury (Leppänen et al., 2017; Podraza & White, 2010). However, despite shown to be significantly correlated to ground reaction forces (Gurchiek, McGinnis, Needle, McBride, & van Werkhoven, 2017), pelvis linear accelerations in this study were not significantly associated with ankle dorsiflexion ROM. Direct measurements of ground reaction forces would be needed to confirm similarities in forces during unanticipated cutting and their association with dorsiflexion ROM. Besides sagittal plane hip ROM, sagittal plane knee and ankle ROM also largely contribute to ground reaction forces (Devita & Skelly, 1992; Leppänen et al., 2017). It is possible that limited sagittal plane ROM in one joint is partly compensated with greater ROM in other lower-extremity joints to mitigate impact forces.

Our study did not show any significant association between dorsiflexion ROM assessed using the WBLT and ankle or foot-ground angles during cutting manoeuvres. These results contradict previous findings that identified significant correlations between static dorsiflexion ROM and ankle kinematics during a single-leg drop-landing task (Hoch et al., 2015). Furthermore, static dorsiflexion ROM measures have been shown to influence sagittal plane landing biomechanics during various jump or drop-landing tasks, explaining between 17% to 55% of the variance in sagittal plane ankle, knee, and hip motion (Fong et al., 2011; Hoch et al., 2015). On the other hand, the ankle dorsiflexion ROM explained only 10% to 22% of the variance across the sagittal plane cutting kinematic variables found to be significantly associated with dorsiflexion ROM in our study. Landing and side-step cutting manoeuvres have distinct kinematic and kinetic characteristics; with cutting manoeuvres being more mechanically demanding for the knee and hip, and landing tasks more demanding for the ankle (Chinnasee, Weir, Sasimontonkul, Alderson, & Donnelly, 2018). During single-leg landing, peak ankle joint moments, power, and work were greater and the plantarflexion angle at IC was almost tripled when compared to cutting manoeuvres (Chinnasee et al., 2018). The greater mechanical demands on the ankle during landing compared to cutting may explain the greater influence of ankle dorsiflexion ROM on sagittal plane landing

kinematics and kinetics, specifically at the ankle, compared to cutting (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017).

12.4.2 Significant associations in the coronal and transverse plane

In this study, the ankle dorsiflexion ROM had a greater influence on coronal and transverse plane kinematics compared to previous studies exploring various jump-landing tasks (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017). Compared to jump-landing, cutting manoeuvres are more demanding in terms of controlling coronal and transverse plane movements (Kristianslund & Krosshaug, 2013). For instance, knee valgus moments have been reported to be six times greater in cutting compared to a drop-jump task (Kristianslund & Krosshaug, 2013). For this reason, excessive or limited ankle ROM may result in greater alteration of more proximal segments in the coronal or transverse planes during cutting manoeuvres than the previously explored jump-landing tasks.

It has been shown that excessive knee internal and external rotation may contribute to ACL injury mechanisms (Fung & Zhang, 2003). However, in our study, peak knee internal and external rotations were not significantly associated with ankle dorsiflexion ROM, although the increased knee ROM in the transverse plane was associated with increased dorsiflexion ROM during dominant leg cutting manoeuvres. Similarly, the hip ROM in the coronal plane was associated with increased dorsiflexion ROM during non-dominant leg cutting manoeuvres. Greater ranges of motion may be due to poor neuromuscular control of the knee and hip joints (Booshanam et al., 2011; Shultz & Schmitz, 2009). Although transverse plane knee ROM and coronal plane hip ROM may not seem impactful in isolation, their effects when compounded with other potential risk factors and impact on other segment positions may contribute to non-contact ACL injury.

In our study, greater peak lateral trunk flexion towards the stance leg during non-dominant leg cutting was associated with increased ankle dorsiflexion ROM measured using the WBLT. Coronal plane trunk position plays an important role in non-contact lower-extremity injuries (Hewett & Myer, 2011). During all movements, the vertical ground reaction force is directed towards the centre of mass, which is located in the trunk segment. The trunk contains approximately half of the body mass; and therefore, if the trunk moves laterally the position of the centre of mass moves

laterally as well. A more laterally-oriented vertical ground reaction force produces a greater lateral lever arm relative to the knee joint centre and increases the knee valgus moment (Hewett & Myer, 2011). Moreover, video analysis of ACL injuries has confirmed that lateral trunk movement is coupled with knee valgus collapse (Hewett et al., 2009). Both Jamison et al. (2012) and Jones et al. (2015) concluded that cutting technique with the trunk leaning and rotating towards the stance leg produces greater peak knee valgus and internal rotation moments. Therefore, participants with greater ankle dorsiflexion ROM may be at greater risk of knee injury due to increased peak lateral trunk flexion towards the stance leg.

12.4.3 Practical implications

Our study provides novel evidence regarding how measures from a clinical test of ankle dorsiflexion ROM can relate to kinematic variables during unanticipated cutting manoeuvres. Based on our results, it seems that ankle dorsiflexion ROM may influence cutting kinematics and may contribute to the non-contact ACL injury mechanisms. Greater ankle dorsiflexion ROM was associated with decreased trunk flexion at IC and greater peak lateral trunk flexion towards the stance leg: both of these variables have been associated with increased knee load and ACL injuries (Hewett & Myer, 2011; Hewett et al., 2009; Jamison et al., 2012; Jones et al., 2015; Sheehan et al., 2012). Furthermore, greater dorsiflexion ROM was associated with greater knee ROM in the transverse plane and hip ROM in the coronal plane, which may suggest poorer movement control (Booshanam et al., 2011; Shultz & Schmitz, 2009). On the other hand, lower ankle dorsiflexion ROM was associated with a decreased sagittal plane hip and trunk ROM, which may result in greater stresses on lower-extremity joint structures (Boden et al., 2009; Jones et al., 2015). Therefore, incorporating whole-body neuromuscular control training using stabilisation joint exercises and exercises to improve ankle dorsiflexion ROM may be useful in rehabilitation and injury prevention initiatives for individuals with excessive or reduced ankle mobility, respectively.

12.4.4 Limitations

It is important to note that our study explored the association between ankle dorsiflexion ROM measured using the WBLT and cutting kinematics measured using a 3D system. However, we did not assess if ankle dorsiflexion ROM predicts specific movement patterns or incidence of ACL or other non-contact lower-extremity injuries. Therefore,

it is not possible to establish ankle dorsiflexion ROM thresholds that reflect high or low risk of injuries with respect to cutting manoeuvres. Prospective studies are needed for these purposes. The main limitation of this study is that joint moments, muscle activation patterns, and ground reaction forces were not included in our biomechanical analysis. However, pelvis linear acceleration, which has been previously associated with ground reaction forces, was measured using an IMU sensor as a proxy measure of ground reaction forces (Gurchiek et al., 2017). Furthermore, participants with very mobile and very limited ankle dorsiflexion ROM likely influenced the results from the regression analysis. These extreme ranges were not removed from the analysis given that similar ankle ROM has been reported elsewhere (Bennell et al., 1998). It may be possible that these participants are the ones with the largest influence of ankle dorsiflexion ROM on their cutting biomechanics and potential risk of injury. Moreover, the dorsiflexion ROM explained only 10% to 22% of variance across the cutting kinematic variables found to be significantly associated with dorsiflexion ROM. Therefore, although ankle dorsiflexion ROM explained some movement patterns that have been linked with ACL injury, other factors potentially play a more important role. We also caution that several studies relied on coded videos of ACL injuries (Boden et al., 2009; Hewett et al., 2009; Sheehan et al., 2012) that have not been calibrated for movement plane. Therefore, perspective or parallax errors may exist in these and influence the accuracy of results and corresponding interpretation.

12.5 Conclusion

Based on our results, ankle dorsiflexion ROM explained some movement patterns that have been linked with ACL injury. Therefore, use of a clinical measure of ankle dorsiflexion ROM for screening purposes may be useful in sports where cutting manoeuvres are common; however, other factors potentially play a more important role, such as muscle recruitment and movement control.

Summary of Section 4

To summarise the main findings from Section 4, asymptomatic generalised hypermobility does not seem to influence jump-landing and cutting movement patterns. Asymptomatic hypermobile individuals may be fully adapted to their condition and use movement strategies to actively stabilise their hypermobile joints during dynamic tasks. Hence, it seems that the same physical activity recommendations and training programmes as for non-hypermobile population are appropriate also for the asymptomatic hypermobile population. The propensity for conscious monitoring and control of movement assessed using the MSRS did not contribute to a greater number of jump-landing movement errors assessed by the LESS and did not distinguish between asymptomatic hypermobile and non-hypermobile individuals when defined using Beighton scores. However, this area is largely unexplored and further research incorporating more demanding sport-specific tasks under psychological pressure is needed to elucidate if propensity for movement-specific reinvestment is an important injury risk factor to consider in preventive efforts. Finally, ankle dorsiflexion ROM was significantly associated with certain side-step cutting kinematic variables associated with injury risk that may contribute to ACL injury mechanisms during cutting manoeuvres. Therefore, the use of clinical measures of dorsiflexion ROM for screening purposes may be useful in cutting sports.

CHAPTER 13

General discussion

13.1 Summary of main findings

The overall aim of this thesis was to explore the Landing Error Scoring System (LESS) and clinically assessable lower-extremity injury risk factors, and their associations with sport-related tasks to inform screening initiatives and injury prevention efforts. Two literature reviews and four cross-sectional studies focused on the LESS. More specifically, these studies explored the psychometric properties of the LESS and influencing factors on LESS outcomes, differences in methodological LESS procedures, and a series of jump-landing task variations to identify a more sport and injury-specific task than the double-leg jump-landing (DLJL) one used in the LESS. Four studies focused on asymptomatic generalised hypermobility, movement-specific reinvestment, and dorsiflexion range of motion (ROM) as these are identified clinically assessable injury risk factors that may play a role in sport-related injuries by influencing sport-related biomechanics.

13.1.1 Section 1: Literature reviews

Acceptable psychometric properties are essential for every testing tool used in clinics and research, as well as for understanding factors impacting test outcomes to ensure the proper implementation and interpretation of scores. Therefore, two literature reviews were completed within this thesis to critically appraise and summarise research on the psychometric properties of the LESS and influencing factors on LESS outcomes to ensure the justified use of the LESS in research and clinical practice.

The results of the systematic literature review addressing the psychometric properties of the LESS indicated that, based on intraclass correlation coefficient (ICC) values, the LESS has good to excellent intra-rater (ICC, 0.82 to 0.99), inter-rater (ICC, 0.83 to 0.92), and inter-session (ICC, 0.81) reliability. However, most studies used ICC to assess reliability whereby the nature of LESS outcomes would encourage use of Cohen's Kappa. Furthermore, some specific LESS items were less reliable than others, and most reliability studies involved young uninjured military and sport populations. Therefore, generalisability of these reliability findings to different population groups is uncertain. The LESS was developed based on clinicians and researchers who agreed that individuals presenting with LESS errors may be at greater risk of suffering ACL injuries (Padua et al., 2009). The concurrent validity of the LESS items against "gold standard" three-dimensional (3D) motion capture has also been explored (Hanzlíková

& Hébert-Losier, 2020b; Onate et al., 2010; Padua et al., 2009) to confirm that the subjective LESS ratings from visual observations agreed with laboratory-measured joint angles and body positions during landing. Although the concurrent validity of the individual LESS items was item dependent, most of the items addressing key risk factors for ACL injuries showed moderate-to-excellent validity versus 3D motion capture data. These findings support the LESS as a valid tool for visually and subjectively assessing jump-landing movement patterns associated with non-contact ACL injuries. The challenge in accurately determining angular measures from visual observations and the subjective nature of some of the LESS items may explain the poorer reliability and concurrent validity of some LESS items. A few solutions to these challenges could be to remove the two items that are subjective in nature (items 16 and 17), use a video analysis software for a more accurate quantification of angles, and use an automated quantification of LESS scores using markerless motion capture technology or wearable sensors.

The clinical construct of the LESS is to screen for ACL injury risk, therefore predictive validity is a crucial aspect. Padua et al. (2015) identified 5 errors as an optimal cut-off point for defining risk of sustaining a non-contact ACL injury in a prospective investigation. The 5-error threshold yielded a sensitivity of 86%, specificity of 64%, and 10.7 times greater relative risk of sustaining a non-contact ACL injury. On the other hand, Smith et al. (2012a) and James et al. (2016) did not find any significant relationship between LESS scores and risk of suffering ACL and other lower-extremity injuries. Therefore, the predictive value of the LESS for ACL and other non-contact lower-extremity injuries remains uncertain based on the current scientific evidence. The lack of agreement in the predictive value of the LESS between studies can be explained by the lack of statistical power in these studies, differences in the sampled population between studies in terms of age, sex, and injury history, and the non-sport-specific nature of the DLJL task used in the LESS.

To summarize, the LESS is a reliable clinical tool able to estimate jump-landing movement patterns. Padua et al. (2009) concluded that the LESS is able to differentiate between groups presenting with different jump-landing biomechanics. The clinical construct of the LESS is to screen for ACL injury risk; however, the ability of the LESS to predict injury remains unclear based on current evidence. Due to the complexity and multifactorial nature of sport-related injuries, the development of an appropriate

screening tool to predict injury is complicated. According to Bahr (2016), three steps are needed to validate a screening test to predict and prevent injuries. The first step is to identify a screening test with an outcome that demonstrates a strong association with injury risk in prospective studies. In terms of the LESS, stronger prospective studies confirming a strong association between LESS scores and individual LESS items with ACL injury risk are needed. The second step is to examine the properties of the screening test in several relevant populations using appropriate statistical metrics, such as likelihood ratio or receiver operating characteristics. In terms of the LESS, more work is required to improve the relatively poor predictive ability thus far established for the LESS and examine the most appropriate thresholds (if any) for relevant sports and populations (e.g., ages or maturation status). The final step is to explore if an intervention programme targeting athletes identified at "high risk" is more effective than the same intervention programme applied to all athletes. To date, there does not appear to be a screening tool that responds to all three criteria in sports. The LESS is one of the clinical injury risk screening tools that has shown some promise in predicting injuries (Padua et al., 2009) and is a suitable option for large scale screening without the need for advanced laboratory-based equipment. However, further work is needed to justify its use as an injury risk screening tool.

As stated above, understanding which factors may influence test scores is essential for the correct interpretation of outcomes and may clarify the conflicting results in terms of LESS predictive value for injury incidence. Therefore, a systematic literature review with meta-analysis of literature addressing age, sex, previous injury, and intervention programme as influencing factors on LESS scores was undertaken. The results from this review indicated that females have higher LESS scores than males; however, the difference of 0.6 errors was not clinically meaningful. Given that the mean age of participants in studies reporting significant and non-significant differences in LESS scores between sexes were 15.9 ± 1.5 and 20.2 ± 2.2 years, respectively; it may be that sex influences LESS scores to a greater extent in pubertal compared to post-pubertal age groups. The systematic review results that age may influence LESS scores in a clinically meaningful manner support this last assumption regarding sex differences. More specifically, LESS scores were seen to decrease with age when comparing under 15, 15 to 20, and over 21 years age groups. The mean age of the youngest age group (i.e., under 15 years old) was 12.4 ± 1.3 years, which may be

defined as puberty age given that puberty commonly occurs between 10 to 16 years. Furthermore, previous studies concluded that increased risk of injury in females tend to emerge during the pubertal growth spurt (Ford, Shapiro, Myer, Van Den Bogert, & Hewett, 2010) and that preventive neuromuscular programmes were more effective to reduce knee injury risk in females under 18 years compared to over 18 years of age (Myer et al., 2009; Myer et al., 2013b). It is also important to note that age may explain the conflicting results between studies exploring the predictive value of the LESS for non-contact ACL injuries. Smith et al. (2012a) tested participants that were 18.3 ± 2.0 years old and did not find any predictive value of the LESS in terms of ACL injury incidence. In contrast, Padua and colleagues (2015) tested participants that were 13.9 ± 1.8 years old and identified 5 errors as the optimal cut-off point for distinguishing between athletes with low and high risk of ACL injury. More studies are needed to explore the associations between age, sex, and LESS scores, and whether the same threshold for high and low injury risk is suitable across males and females and age categories.

According to our meta-analysis results, participants after ACL reconstruction or with ACL deficiencies have meaningfully higher LESS scores from a clinical perspective (mean difference of 1.2 errors) than controls. This finding was anticipated given that individuals who have sustained an ACL injury present with a long-term impairment in jump-landing biomechanics (Schmitt, Paterno, Ford, Myer, & Hewett, 2015; Trigsted et al., 2018). LESS scores of participants with other types of injuries were not significantly different to controls, which may be due to a lack of differentiation between contact and non-contact mechanisms of these injuries in some of the included studies. Therefore, studies comparing LESS scores between various non-contact lower-extremity injuries could clarify which one of these injuries meaningfully affect jump-landing movement patterns. This information would assist in targeting rehabilitation and prevention efforts.

Furthermore, the meta-analysis identified that neuromuscular programmes completed two to three times per week for at least six weeks that incorporated plyometric exercise and landing technique feedback were the most effective in improving LESS scores in a meaningful manner. However, studies disagree in regard

to the persistence of the effect once the intervention programme stops, as well as the training duration required for the most optimal and long-term effect.

13.1.2 Section 2: Differences in the Landing Error Scoring System methodological procedures

During the literature review process, which included 53 articles across the two reviews included in Section 1, differences in the LESS methodological procedures between studies were noted. Given that differences in the LESS methodological procedures may meaningfully affect reproducibility and comparability of LESS outcomes between studies, these differences were explored in Section 2.

Chapter 5 explored five different final LESS score calculation methods presented in the literature and their influence on LESS scores and risk categorisation. Results from this study showed that using the best jump from three DLJL trials to determine the final LESS score yields a meaningfully lower mean LESS score compared to the commonly used method taking the mean score from three DLJL trials. Furthermore, using the best jump score significantly alters group and individual-level risk categorisation compared to the mean score from three DLJL trials. Therefore, interpreting and comparing results from studies or clinical practices using the best jump computational method in relation to the method using the mean of three jumps should be done with caution. Overall, Chapter 5 recommended using the mean score from three DLJL trials to determine the final LESS score of individuals due to its common use in the scientific literature and that this calculation method is the only one with demonstrated predicative ability for injury (Padua et al., 2015). However, when testing large cohorts with time or financial restrictions, scoring only the 3rd jump to calculate final LESS scores offers a suitable option as mean LESS score, group, and individual-level risk categorizations are the most comparable to the mean score from three DLJL trials. Yet, it is important to highlight that variability is present in all human movements (Bates et al., 1992), and using a single trial may result in a poor representation of typical jump-landing movement patterns.

The LESS requires individuals to jump forward from a 30-cm box to a distance of 50% of their body height. However, scientific studies report using different landing distances. Therefore, Chapter 6 examined whether landing distance influences LESS outcomes. More specifically, mean LESS scores, group-level risk categorisation, and

individual-level risk categorisation were compared between two landing distance conditions: 50% of body height, as prescribed in the original LESS protocol, and self-selected landing distance. According to the results from this study, landing distance did not significantly influence the mean LESS scores, or proportion of participants categorised at high and low injury risk (i.e., group-level risk categorisation). Using a self-selected landing distance removes the need to adjust the landing distance to match 50% of an individual's height. Therefore, when only group mean LESS scores or the proportion of individuals at risk is of interest, using a self-selected landing distance may facilitate large cohort screening due to a shorter testing time. However, the results of Chapter 6 identified an inconsistency in occurrence of specific LESS errors and individual-level risk categorisation between the two landing distance conditions. Given that individual LESS scores are of primary interest in clinical and sport settings, and the injury risk threshold of 5 errors has not been validated for the self-selected distance, the use of the original LESS protocol is recommended until a validated alternative becomes available.

It is common in clinical practice and sport settings to explain LESS items and give feedback on an individual's landing technique after the LESS test. Previous studies have shown that knowledge of scoring criteria can potentially compromise the clinical utility of injury risk screening tools (Bryson et al., 2018; Frost et al., 2015). Therefore, the influence of knowledge of scoring criteria and prior performance on LESS outcomes were explored in Chapter 7. According to the results of Chapter 7, knowledge of scoring criteria and performance meaningfully improved LESS scores, altered risk categorisation, and changed the proportions of specific LESS errors. Therefore, when using the LESS, it is important that tested individuals have no knowledge of scoring criteria or their previous errors when the intention is to use the screening tool to assess innate movement patterns or use the tool again to monitor progress over time. Furthermore, within one education session, our participants were able to decrease their LESS scores and landing errors more than the reported decreases associated with following neuromuscular training programmes for several weeks (Owens et al., 2013; Padua et al., 2012; Pryor et al., 2017). This finding highlights the powerful impact of feedback on changing movement patterns acutely and lends support to incorporating technical feedback in injury prevention programmes.

13.1.3 Section 3: Sport and injury-specific jump-landing task

The DLJL used as a screening task for the LESS has several advantages. It is an easy task to perform and feasible to conduct movement screening on large cohorts with limited time, space, and equipment. The DLJL is also easily scored using the naked eye (i.e., real-time LESS) or video camera footage (i.e., original LESS) due to its reliance on observations of movements in a single plane (Padua et al., 2011a; Padua et al., 2009). However, the DLJL has several disadvantages, also. The most important disadvantage of the LESS is that the DLJL does not fully represent the movements associated with high risk of injury in a sporting context. Several studies have criticised the DLJL task, stating it is not sport-specific, not challenging enough to reveal movement patterns linked to non-contact lower-extremity injuries, and poor for predicting ACL injuries (Fox et al., 2017; Krosshaug et al., 2016; Mørtvedt et al., 2020; Smith et al., 2012a). Therefore, Section 3 aimed to identify a jump-landing task that was more sport and injury-specific, whilst keeping the benefits of the DLJL. The unanticipated side-step cutting manoeuvre has a realistic representation across several sport and is a common injurious situation in sports with the highest rates of non-contact lower-extremity injuries (Hootman et al., 2007). Therefore, Section 3 compared the level of association between whole-body kinematics of four jump-landing tasks to the unanticipated side-step cutting manoeuvre. Furthermore, the rating of perceived difficulty of each task was assessed.

The results from this investigation showed that the kinematics of the DLJL were the least associated with those of cutting, and the DLJL task was subjectively rated as the easiest task to perform from those assessed. These results support previous studies criticising the DLJL due to its lack of ecological validity and challenge (Fox et al., 2017; Krosshaug et al., 2016; Mørtvedt et al., 2020; Smith et al., 2012a).

The rotated DLJL ($DLJL_{rot}$) kinematics were the most strongly and consistently associated with cutting kinematics, followed by the rotated single-leg jump-landing ($SLJL_{rot}$) task. In general, when comparing jump-landing to cutting, the mechanical load applied to the ankles is greater; and to hips and knees, is lower (Chinnasee et al., 2018). On the other hand, pivoting manoeuvres place greater demands on knee structures than cutting (Cortes et al., 2011). Therefore, it may be that rotation in connection with landing places similar demands on lower-extremity joints as cutting,

explaining why the rotated jump-landing kinematics were the most strongly associated with those from cutting.

Overall, single-leg landings are biomechanically more challenging for the lower-extremity joints than double-leg landings and are more common in sports and during injury situations (Koga et al., 2010; Olsen et al., 2004). Furthermore, participants rated the perceived challenge of the single-leg tasks in a similar manner to cutting, and the $SLJL_{rot}$ as the most difficult task to perform. Hence, given the association with cutting kinematics and subjective difficulty ratings, $SLJL_{rot}$ may be better suited to reveal movement patterns present during more challenging sport situations and, in turn, have a greater association with injury risk profiles specific to ACL injuries from the tasks tested. However, it is important to consider that perceived difficulty of $SLJL_{rot}$ may result in kinesiophobia in some individuals and an inability to perform this task. Due to the difficulty of $SLJL_{rot}$, the landing distance was decreased from 50% to 25% of participant's body height. Given that athletes are used to performing difficult tasks during training and games (i.e., cutting and pivoting) and none of the physically active participants tested in our study expressed concerns associated with performing the $SLJL_{rot}$, the $SLJL_{rot}$ appears to be an appropriate task to undertake with athletes to screen for sport-related injuries. However, when screening older or less physically active population, the $DLJL_{rot}$ task may be more appropriate due to the lower perceived challenge.

13.1.4 Section 4: Clinically assessable injury risk factors

Besides the LESS explored in the previous sections, other clinically assessable injury risk factors that may help clinicians to identify athletes at risk of injury and assist to develop targeted prevention programmes were identified in the scientific literature (Dallinga et al., 2012; Donaldson, 2012; Mason-Mackay et al., 2017; Pacey et al., 2010; Wong et al., 2008). Section 4 explored some of these risk factors and their influence on sport-related movement patterns. More specifically, the influence of asymptomatic generalised hypermobility on landing and side-step cutting biomechanics; the association between movement-specific reinvestment, LESS, and Beighton hypermobility scores; and the influence of dorsiflexion ROM on side-step cutting biomechanics were explored in Section 4. Note, that despite its limitation, the LESS test was used to assess jump-landing biomechanics, given that the LESS is currently

the only valid screening tool easily administered in a clinical setting to assess jump-landing movement patterns.

A recent framework for the classification of generalised joint hypermobility suggests dividing hypermobile individuals into three categories: individuals with asymptomatic joint hypermobility, individuals with a well-defined syndrome associated with joint hypermobility, and individuals with symptomatic joint hypermobility (Castori et al., 2017). Due to the lack of evidence concerning dynamic movement patterns of asymptomatic hypermobile populations and relevance to the field of sport medicine, we explored the influence of asymptomatic generalised hypermobility and knee-hyperextension on jump-landing biomechanics assessed by the LESS. The results indicated that our cohort of participants with asymptomatic hypermobility and knee hyperextension did not present a greater number of LESS movement errors compared to non-hypermobile and non-hyperextended individuals. There was also no significant relationship between LESS and Beighton hypermobility scores. However, it is important to note that the LESS is unable to detect small changes in biomechanics and DLJL task has been criticised for its non-sport specific nature (Fox et al., 2017; Krosshaug et al., 2016). Therefore, to determine whether individuals with asymptomatic hypermobility present movement patterns suggestive of a greater risk of non-contact sport-related injuries compared to non-hypermobile individuals, we used a three-dimensional (3D) motion capture system and more sport and injury-related task. Specifically, we compared whole-body unanticipated side-step cutting kinematics between asymptomatic hypermobile and non-hypermobile participants. The results indicated some significant differences in cutting kinematics between the two groups analysed. However, based on current evidence, the identified differences were not crucial biomechanical injury risk factors that could predispose asymptomatic hypermobile individuals to non-contact injuries.

Given that hypermobility is a risk factor for non-contact knee and ACL injuries (Pacey et al., 2010; Sundemo et al., 2019), the LESS screens for ACL injury risk movement patterns during landing (Padua et al., 2015), and side-step cutting manoeuvres are a high-risk task for knee injuries (Hootman et al., 2007); a greater number of significant differences between hypermobile and non-hypermobile groups were anticipated across investigations. It is possible that our cohort of asymptomatic hypermobile individuals use different neuromuscular control strategies from

symptomatic hypermobile individuals and individuals with a well-defined syndrome associated with hypermobility explored in previous studies (Galli et al., 2011; Rombaut et al., 2011; Simonsen et al., 2012). Asymptomatic hypermobile individuals may be fully adapted to their condition and use strategies to actively stabilise their hypermobile joints during dynamic tasks, which may explain to some extent why they do not suffer from chronic pain, fatigue, micro traumas, and other symptoms associated with hypermobility. Another possible explanation is that besides increased mobility of joints, other secondary manifestations of joint hypermobility, such as chronic pain, fatigue, muscle weakness, and disturbed proprioception, are important confounding factors associated with injury incidence. As such, asymptomatic hypermobile individuals may be at lower risk of injury compared to symptomatic individuals. However, further research is needed to confirm these speculations and to highlight any differences between hypermobility groups to guide injury prevention effort, specific recommendations, and prevention programmes targeting hypermobile populations.

Another factor potentially contributing to sport-related injury risk is movement-specific reinvestment. Movement-specific reinvestment scores represent the propensity for conscious monitoring and control of movement, which can inhibit automated movement processes, potentially causing movement disruption. It is possible that athletes who consciously monitor their own movements exhibit a greater number of movement errors during LESS assessment and are at greater risk of sport-related injuries. Furthermore, given that both the propensity for movement-specific reinvestment and hypermobility have been linked to fear, anxiety, fatigue, and movement difficulties and disorders, there may be an association between hypermobility and conscious engagement in movement. Therefore, the associations between movement-specific reinvestment scores, LESS scores, and Beighton hypermobility scores was examined, and movement-specific reinvestment scores between participants at low and high injury risk, as well as between asymptomatic hypermobile and non-hypermobile group were compared. The findings indicated that movement-specific reinvestment did not contribute to a greater number of jump-landing movement errors assessed by the LESS. The lack of association between movement-specific reinvestment and LESS scores might be due to the phylogenetic nature of the LESS jump-landing task. Phylogenetic tasks require minimal conscious processing, and therefore tend to be less susceptible to disruption by reinvestment (Masters & Poolton,

2012). Moreover, individuals with a high propensity for movement-specific reinvestment perform poorly especially under psychological pressure (Chell et al., 2003; Jackson et al., 2006; Maxwell et al., 2006). Given that LESS testing imposes a low-pressure environment, the task is less likely to be influenced by conscious monitoring and control of movement. Therefore, testing biomechanics during demanding high-injury risk sport-specific tasks under psychological pressure similar to the competition environment is required to reach conclusions about the potential role of movement-specific reinvestment in sport-related injuries.

Furthermore, the propensity for movement-specific reinvestment did not vary in asymptomatic hypermobile individuals compared to non-hypermobile individuals. As mentioned above, there may be some clinically relevant differences between hypermobility groups. This assumption would explain the lack of significant differences between hypermobile and non-hypermobile participants in terms of movement-specific reinvestment scores. Therefore, examination of the movement-specific reinvestment in symptomatic hypermobile individuals and individuals with well-defined syndromes is needed to fully elucidate whether or not conscious monitoring and control of movement plays a role in injury risk or movement control across the hypermobility spectrum.

The last clinically assessable factor explored in this section was ankle dorsiflexion ROM. Limited dorsiflexion ROM has been related to ACL injury risk during landings (Fong et al., 2011; Hoch et al., 2015; Mason-Mackay et al., 2017). However, the influence of dorsiflexion ROM on cutting kinematics remained unexplored despite the high incidence of knee injuries reported to occur during such tasks. Therefore, we explored the influence of ankle dorsiflexion ROM measured using the Weight-Bearing Lunge Test on kinematics during unanticipated side-step cutting manoeuvres. Based on our results, dorsiflexion ROM tested by Weight-Bearing Lunge Test influenced the kinematics of a sport-specific cutting task. Given that some of these kinematic variables from the cutting task have been linked to non-contact ACL injuries (Boden et al., 2009; Hewett et al., 2009; Sheehan et al., 2012), dorsiflexion ROM may contribute to the ACL injury mechanisms during cutting manoeuvres. Hence, the use of clinical measures of ankle dorsiflexion ROM for screening purposes may be useful in cutting sports. However, it is important to note that dorsiflexion ROM explained only 10 to 22% of the variance across the cutting kinematic variables that were significantly

associated with ankle dorsiflexion ROM; and therefore, other factors potentially play a more important role in injury risk during cutting than dorsiflexion ROM. Furthermore, based on our results, it is possible that participants with very mobile or very limited dorsiflexion ROM are the ones with the largest influence of dorsiflexion ROM on cutting kinematics and potential risk of injury.

13.2 Clinical implications

The thesis intended to assist healthcare and sport professionals to understand and assess their athletes' sport-related injury risk factors using clinical tests. Based on the findings of this thesis, the following clinical implications may assist these professionals and guide injury prevention efforts:

- Current evidence supports the LESS as a reliable tool to assess landing mechanics; however, further work is needed to improve the concurrent validity of some LESS items against 3D motion capture and ascertain its predictive value for non-contact sport-related injuries.
- Age can influence LESS scores, indicating that the established threshold of 5 errors commonly used to define injury risk may not be appropriate across different age groups.
- Previous ACL injury meaningfully increases LESS scores likely due to residual long-term deficits in neuromuscular control or presence of compensatory strategies.
- Neuromuscular programmes completed two to three times per week for at least six weeks incorporating plyometric exercise and landing technique feedback are currently shown to be the most effective in improving LESS scores in a meaningful manner.
- Clearly documenting the final LESS score calculation method and landing distance used in the methodology section of manuscripts and in clinical notes is recommended for valid inferences.
- Calculating the final LESS score as a mean of three jumps and using the original LESS landing distance is recommended to researchers and clinicians when it is feasible to implement.
- Comparing studies using different final LESS score calculation methods and landing distances during LESS assessment should be done with caution.

- Explaining the scoring criteria and individual movement errors to tested individuals when there is an intention to use the tool to assess innate movement patterns or to monitor progress over time should be done with caution.
- Clinicians should focus on maximising jump height after the first landing to shift an individual's attention to performance rather than landing technique. These directives are more likely to reveal innate movement patterns that have been linked with a higher risk of sustaining non-contact lower-extremity and ACL injuries.
- Rotated jump-landing tasks may be more appropriate than the DLJL to reveal risky movement patterns present during rapid changes of direction and landing, which could be implemented in large-scale screening across a variety of sports. However, scientific validation is needed.
- Asymptomatic hypermobile individuals do not appear to present a greater number of risky movement patterns during landing and cutting tasks, which would predispose them to non-contact lower-extremity injuries compared to non-hypermobile individuals. Therefore, it seems that physical activity recommendations and neuromuscular training programmes prescribed to non-hypermobile individuals are appropriate for asymptomatic hypermobile individuals, also.
- Higher movement-specific reinvestment scores did not contribute to a greater number of jump-landing movement errors assessed by the LESS. However, this area is largely unexplored and further research is needed to elucidate if propensity for movement-specific reinvestment is an important injury risk factor to consider in preventive efforts, especially given the uncertain predictive value of the LESS.
- The use of a clinical measure of ankle dorsiflexion ROM for screening purposes may be useful in sports where cutting manoeuvres are common, with both limited and excessive dorsiflexion potentially increasing risk.
- Incorporating whole-body neuromuscular control training using joint-stabilisation exercises and exercises to improve ankle dorsiflexion ROM may be useful in rehabilitation and injury prevention initiatives for individuals with excessive or reduced ankle mobility, respectively.

13.3 Limitations

The main limitations of the systematic reviews of the literature presented in Section 1 were the varied study designs, methodological quality, and risk of bias of the included studies. The heterogeneity, risk of bias, and indirectness and imprecision of outcomes resulted in very low quality of evidence according to the Grading of Recommendations Assessment, Development and Evaluation (GRADE) scale in the systematic literature review with meta-analysis. Another important limitation of Section 1 is that testing protocols and calculations of final LESS scores varied across studies, which can influence LESS scores as shown in Section 2 of this thesis. Furthermore, no specific tools to assess risk of bias in cross-sectional observation studies exists, therefore the Newcastle – Ottawa Assessment Scale was used even though it does not solely assess risk of bias. Besides sex, age, previous injury, and intervention programme, other factors may also influence LESS scores, including fatigue (Bell et al., 2016; Gokeler et al., 2014; Wesley et al., 2015), sport and competition level (DiStefano et al., 2018; Kraus et al., 2019; Theiss et al., 2014), strength levels (Beutler et al., 2009; Lepley et al., 2013; Mohammadi et al., 2017), and knowledge of scoring criteria and prior performance (as highlighted in Section 4); however, all of these factors were not explored in this thesis.

Overall in this thesis, group-level and individual-level risk categorisation were based on a threshold of 5 errors per Padua et al. (2015). This threshold derives from a population of young (13.9 ± 1.8 years) male and female elite soccer players and might not be appropriate for the population of predominantly young, physically active adults explored in this thesis. Furthermore, the LESS was used to assess jump-landing movement patterns in Chapter 9 and 11 despite its previously stated limitations. Assessing landing biomechanics during a more sport-specific landing task than the double-leg jump-landing one would offer better representation of sport-related injury risk. Although, there are no validated single-leg rotated clinical rating scales yet available for use.

The main limitation of the chapters exploring 3D motion biomechanics is that due to absence of force plates, computing joint moments through inverse dynamics and ground reaction forces was not possible, which could have provided further insight into the research questions. Furthermore, use of electromyography could have been

beneficial for this thesis to confirm differences in muscle recruitment and activation patterns between tasks and populations explored. It is important to note that only prospective studies could determine whether individuals presenting with asymptomatic generalised hypermobility, higher propensity for movement-specific reinvestment, and limited or excessive ankle dorsiflexion ROM are at greater risk of sport-related non-contact lower-extremity injuries. Moreover, prospective studies also need to confirm if rotated tasks are better able to predict sport-related injuries compared to DLJL.

13.4 Future research

Considering the findings and limitations of this thesis, the following directions for future research are suggested. Future research could address LESS limitations highlighted in this thesis and develop a modified LESS tool. Based in this thesis, the modified LESS could incorporate the $SLJL_{rot}$ task instead of the DLJL task used in the original LESS, with a premise to increase the ecological validity of the LESS to identify athletes displaying movement patterns that place them at high risk of lower-extremity injury during challenging sport movements. The scoring scale would need modifying to suit the new screening task. The scoring scale of the modified LESS could limit the number of items that are subjective in nature to improve LESS reliability and make the automated quantification of the LESS easier. The purely subjective rating or ranking of human movement to define performance (Cochrum et al., 2020) or injury risk (Mørtvedt et al., 2020) has been criticised and has been shown to be inaccurate; thus, incorporating more objective and quantifiable measures to clinical assessing human movement might yield higher sensitivity and predictive value. A preliminary template for a modified LESS applied to a $SLJL_{rot}$ with rationale for the suggested thresholds to use in scoring is presented in Appendix G, but the proposed template and thresholds requires further development and validation.

Given the results concerning the original LESS testing protocols, any modified LESS should calculate a final LESS score as a mean of three jumps, use a specified landing distance, and not explain the scoring criteria or prior performance to participants. Of course, studies would need to investigate whether any modified LESS screening tool developed is valid, reliable, and still a viable option for large-scale screening initiatives in a practical setting. Prospective studies would be required to explore the predictive value of any modified LESS for non-contact lower-extremity

incidence and establish high and low injury risk thresholds. Moreover, studies are needed to explore whether the same injury risk threshold is suitable across males and females and age categories.

Besides differences in the LESS methodological procedures explored in this thesis, other differences in LESS testing protocols were noted. For instance, Kraus et al. (2019) used a 40-cm high box instead of a 30-cm high box suggested in the original LESS protocol. Vertical ground reaction forces have been shown to increase with increasing landing heights (Dufek & Bates, 1989; McNitt-Gray, 1989). Knee angles at initial contact and maximum knee flexion angles are also enhanced with a higher box (Huston et al., 2001). Another factor that should be considered during LESS testing is what participants are wearing. For instance, participants were wearing rucksacks in the study of Distefano et al. (2013a) and were barefoot in the study of O'Malley et al. (2017). Additional weight influence vertical ground reactions forces and are 1.1 times greater when landing barefoot compared to wearing shoes (Dufek & Bates, 1991). Finally, the sampling frequency of the cameras substantially vary between studies (Hébert-Losier et al., 2020; Kuenze et al., 2018). All of these factors may influence LESS outcomes and the comparability between studies; and therefore, should be explored further.

The automated quantification of the LESS is also a highlighted area for ongoing research. Deep-learning-based computer vision technologies enable the automatic identification and quantification of human motion without the need for markers or depth sensor cameras; and therefore, reduce testing and scoring time and a need for expert clinicians. A preliminary investigation provided evidence that it is feasible to automate the LESS from 2D video recordings alone (Hébert-Losier et al., 2020); however, further work is needed to improve automation outcomes and enhance the strength of the agreement between clinical and automated LESS scores. The automatic identification and accurate quantification of LESS movement errors would pave the way to smartphone-based applications for injury risk screening. If successfully applied to the LESS, a similar automation framework could be extended to any modified LESS testing protocol and scoring to enhance accessibility and screening efficiency.

As highlighted in the chapters exploring hypermobility, there may be important differences in movement control, injury risk, and psychological characteristics between

symptomatic and asymptomatic hypermobile individuals as well as individuals with disorders affecting connective tissue. Therefore, further research is needed to highlight any differences between hypermobility groups as these differences may change the physical activity recommendations, injury prevention strategies, and rehabilitation approaches in hypermobile populations.

The last area suggested for future research is further exploration of movement-specific reinvestment as a potential injury risk factor. No association between movement-specific reinvestment and injury risk assessed by the LESS was detected in this thesis. However, given the limitations of our study, injury risk and propensity for conscious monitoring and control of movement may be related under certain circumstances. For instance, a relationship may surface in cases where participants are highly motivated to perform successfully (e.g., under pressure), when they are aware of what constitutes successful or unsuccessful performance, or when they have had a previous ACL injury. Future research should examine this possibility in a cohort with heterogeneous movement-specific reinvestment scores by testing biomechanics during demanding high-injury risk sport-specific tasks under psychological pressure similar to those of competition. Only once such investigations are completed will it be possible to reach conclusions about the potential role of movement-specific reinvestment in sport-related injuries.

13.5 Conclusion

This thesis provided novel evidence concerning the LESS, asymptomatic hypermobility, movement-specific reinvestment, ankle dorsiflexion ROM, and their influence on sport-related movement patterns. Overall, the evidence supports using the LESS for screening of risky movement patterns linked with non-contact lower-extremity injuries. However, incorporating a rotated jump-landing task into the LESS assessment may improve the predictive value of the screen for sport-related injuries incidence. The final LESS score calculation method, landing distance, and knowledge of scoring criteria and prior performance altered LESS outcomes. Therefore, using the original LESS testing protocol when feasible in a first instance and avoiding explaining scoring criteria and movement errors to tested individuals are recommended practices for reproducible and comparable outcomes. From the clinically assessable factors explored, ankle dorsiflexion ROM was significantly associated with some side-step

cutting kinematic variables and may contribute to ACL injury mechanisms during cutting manoeuvres. Consequently, use of a clinical measure of ankle dorsiflexion ROM for screening purposes may be useful in cutting sports.

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APPENDICES

Appendix A. Published manuscripts presented in the thesis

Appendix A1. *Is the Landing Error Scoring System reliable and valid? A systematic review.*

Is the Landing Error Scoring System Reliable and Valid? A Systematic Review

Ivana Hanzlíková, PT,*† and Kim Hébert-Losier, PT, PhD†

Context: The Landing Error Scoring System (LESS) is a clinical tool often used in research and practice to identify athletes presenting high injury-risk biomechanical patterns during a jump-landing task.

Objective: To systematically review the literature addressing the psychometric properties of the LESS.

Data Sources: Three electronic databases (PubMed, Web of Science, and Scopus) were searched on March 28, 2018, using the term "Landing Error Scoring System."

Study Selection: All studies using the LESS as main outcome measure and addressing its reliability, validity against motion capture system, and predictive validity were included. Original English-language studies published in peer-reviewed journals were reviewed. Studies using modified versions of the LESS were excluded.

Study Design: Systematic literature review.

Level of Evidence: Level 4.

Data Extraction: Study design, population, LESS testing procedures, LESS scores, statistical analysis, and main results were extracted from studies using a standardized template.

Results: Ten studies met inclusion criteria and were appraised using Newcastle-Ottawa Quality Assessment Scale adapted for cross-sectional studies. The overall LESS score demonstrated good-to-excellent intrarater (intraclass correlation coefficient [ICC], 0.82-0.99), interrater (ICC, 0.83-0.92), and intersession reliability (ICC, 0.81). The validity of the overall LESS score against 3-dimensional jump-landing biomechanics was good when individuals were divided into 4 quartiles based on LESS scores. The validity of individual LESS items versus 3-dimensional motion capture data was moderate-to-excellent for most of the items addressing key risk factors for anterior cruciate ligament (ACL) injury. The predictive value of the LESS for ACL and other noncontact lower-extremity injuries remains uncertain based on the current scientific evidence.

Conclusion: The LESS is a reliable screening tool. However, further work is needed to improve the LESS validity against motion capture system and confirm its predictive validity for ACL and other noncontact lower-extremity injuries.

Keywords: injury risk; injury prevention; movement screen; sport injury; jump-landing

Increased participation in physical activities increases the likelihood of sustaining sport-related injuries.[54] Noncontact mechanisms explain approximately 18% of injuries in game situations and 37% of injuries in practice or training situations.[22] Neuromuscular and biomechanical factors are key in the prevention of noncontact injuries, as modifiable through targeted training interventions.[17,42]

The Landing Error Scoring System (LESS; Appendix Table A1, available in the online version of this article) is a clinical assessment tool[40] often used in research to identify individuals at high risk of sustaining noncontact injuries and to quantify changes in neuromuscular and biomechanical performance subsequent to intervention across sports[14,15,18] and performance levels.[27,49] The LESS has also been used in participants with a history of injury[24,30] and after anterior cruciate ligament (ACL) reconstruction[2,20] to quantify residual functional impairments and outcomes from rehabilitation.

It is essential that testing methods provide outcomes that are reproducible and valid so that changes in scores reflect meaningful changes in function of individuals and identify individuals with differing abilities. In the LESS, lower scores should reflect a reduction in injury risk and high injury-risk movement

From †Division of Health, Engineering, Computing and Science, School of Health, Sport and Human Performance, University of Waikato, Tauranga, New Zealand
*Address correspondence to Ivana Hanzlíková, PT, University of Waikato, Adams Centre for High Performance, 52 Miro Street, Mount Maunganui, Tauranga, 3116, New Zealand (email: xhanzlikova@gmail.com) (Twitter: @Hanzlikovalvana).
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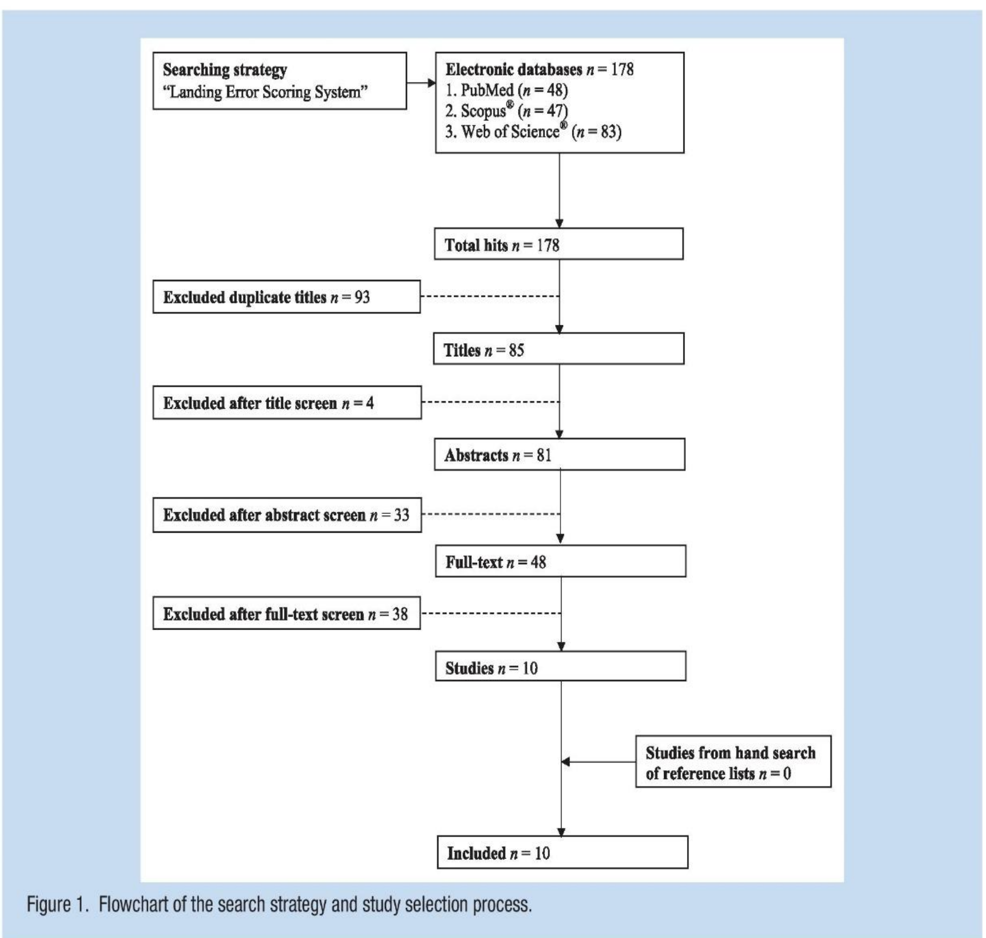

Figure 1. Flowchart of the search strategy and study selection process.

patterns. The LESS was previously addressed in critically appraised topics[32,44,47] and literature reviews[4,7,19,34,48]; however, no systematic review has critically appraised and summarized research on its psychometrics properties (reliability and validity). Such a systematic review is warranted to ensure the justified use of the LESS in large-scale screening initiatives, monitoring changes in risk factors, establishing the effects of injury prevention programs, and identifying athletes at high risk of injuries. Therefore, our aim was to systematically review and critically appraise studies addressing the psychometric properties of the LESS.

METHODS

Protocol and Registration

Literature review methods and inclusion criteria were specified in advance and registered on PROSPERO (CRD42018107210).

Eligibility Criteria

Studies that used the LESS as a main outcome measure and examined its reliability, validity against motion capture, and predictive validity were included for review regardless of participant, intervention, or study design characteristics. Only original research published in English in peer-reviewed (abstract available) journals were considered. Letters to the editor, symposium publications, conference abstracts, books, expert opinions, critically appraised topics, and literature reviews were excluded. Studies using modified versions of the original LESS protocol (eg, iLESS, real-time LESS, and automated quantification of the LESS) were excluded.[23,33,50]

Information Sources and Search Strategy

Three electronic databases (Figure 1) were searched using the keywords "Landing Error Scoring System" on March 28, 2018. Psychometric property terms were not included in the search strategy to favor an all-inclusive approach and avoid missing studies that addressed the reliability or validity of the LESS as part of their methodology without its being a primary aim. In addition, a hand search of the reference lists of all included studies was conducted.

Study Selection

The electronic search was conducted by 1 reviewer. Duplicate hits were removed first. Titles, abstracts, and full texts were screened sequentially for inclusion and exclusion criteria. In case of uncertainty regarding inclusion, a second reviewer was consulted.

Data Collection Process

Data concerning study design, population (number, sex, age, and activity level), LESS testing procedures, LESS scores, statistical analysis, and main results were extracted from studies using a standardized template by 1 reviewer, with the completeness of extraction verified by a second reviewer. The study design was reported according to Parab and Bhalerao.[41] Studies were categorized into the following subcategories: reliability, validity against motion capture, and LESS predictive value for injury incidence. Four authors were contacted by email to request additional information regarding 8 of the included studies. Three authors responded, with 2 authors providing additional data for 2 studies.

Risk of Bias in Individual Studies

Two reviewers independently assessed the methodological quality of included studies (n = 10) using the Newcastle-Ottawa Quality Assessment Scale (NOS) adapted for cross-sectional studies.[36] Potentially identifiable information from studies was removed prior to quality appraisal to reduce assessment bias. The 2 reviewers achieved a consensus rating on all quality scores without the need for a third reviewer.

The NOS uses a "star system," wherein more stars indicates a superior methodological quality. The NOS adapted for cross-sectional studies awards a maximum of 10 stars: 5 for selection (representativeness of the sample, sample size, nonrespondents, and ascertainment of the exposure), 2 for comparability, and 3 for outcome (assessment of outcome and statistical test). Reviewers agreed that for the statistical test item, the highest star rating would be allocated for the reporting of confidence intervals, quartiles, or limits of agreement. The methodological quality of studies was divided into 3 groups based on the number of stars awarded: weak (0-3 stars), moderate (4-6 stars), and strong (7-10 stars). Given that the reliability for NOS adapted for cross-sectional studies has not yet been determined, we assessed intra- and interrater reliability of our scores. Based on intraclass correlation coefficient (ICC) and confidence interval values, intrarater (ICC, 0.98; 95% CI, 0.94-0.99) and interrater (ICC, 0.94; 95% CI, 0.80-0.98) reliability of scores was excellent.[37] Finally, the level of evidence for each study was determined using the Oxford Centre for Evidence-Based Medicine 2011 table.

Summary Measures

Descriptive statistics were computed using Microsoft Office Excel 2016 and expressed in terms of means and SDs, minimum to maximum ranges (min to max), percentages (%), and counts (n). Weighted mean ± SD values based on sample size were computed to describe age and LESS scores of participants across studies. ICC values were interpreted according to Koo and Li[26] using thresholds of 0.50, 0.75, and 0.90 to indicate moderate, good, and excellent reliability, respectively, with ICCs <0.50 indicating poor reliability. Standard error of measurement and minimal detectable change values were calculated for reliability studies when possible. Percentage of agreement between individual LESS items or categories based on LESS score (excellent, good, moderate, and poor) and 3-dimensional (3D) motion capture was reported for construct validity.

RESULTS

Study Selection

Figure 1 illustrates the search strategy and study selection process. A total of 10 studies met inclusion requirements and were reviewed.

Study Characteristics

Since the majority of studies did not report descriptive characteristics of the sample used for reliability assessment, study characteristics were calculated from all participants tested with the LESS in included studies (Tables 1 and 2). The study sample size ranged from 13 participants[49] to 2691 participants.[40] A total of 3835 participants were represented across the 10 studies. All studies tested physically active populations. Sex distribution was described in all studies, totaling 2102 males (55%) and 1733 (45%) females. The mean age was reported in all but one[40] of the 10 studies. The weighted mean age was 15.7 ± 2.0 years (minimum mean age 13.9 years[39] and maximum mean age 28.5 years[9]). Overall LESS scores were reported in all but one[38] of the 10 studies. Note that for interventional studies, LESS score before intervention was included in calculation. The calculated weighted mean for overall LESS score was 5.2 ± 1.7 errors (minimum mean LESS score of 4.4 errors[39] and maximum mean LESS score 6.5 errors[1]). Only 3 studies reported the range of LESS scores,[9,18,24] with the smallest and largest values being 0.0 errors[9,18] and 13.3 errors.[24]

Risk of Bias Within Studies

Quality scores, levels of evidence, and study designs are presented in Appendix Table A2 (available online). Overall, studies were of moderate quality based on the NOS adapted for cross-sectional studies (10-point scale: mean 7.0 ± 1.5 points, range 4-9). The level of evidence ranged between 2 and 4 based on the Oxford Centre for Evidence-Based Medicine 2011 table.

Psychometric Properties of the LESS

Reliability

Reliability values for LESS were reported in 9 studies[1,9,18,24,38,40,49,53,55] and derived from a total of 191 participants (Table 1). Both intra- and interrater reliability of the

Table 1. Summary of studies reporting reliability of the Landing Error Scoring System (LESS)

Study (Year)	Quality[a] (Category)	Sample Size [Study Sample Size]	Population	Age, y[b]	LESS Score[b]	Intrarater	Interrater	Intersession
Padua et al (2009)[40]	6 stars (moderate)	50 (M: 25, F: 25) [2691]	US military freshmen	Not specified	4.9 ± 1.7	ICC = 0.91 SEM = 0.42 MDC = 1.16	ICC = 0.84 SEM = 0.71 MDC = 1.97	×
Onate et al (2010)[38]	4 stars (moderate)	19 (M: 0, F: 19) [19]	Division I college soccer players	19.6 ± 0.8	Not specified	×	ICC = 0.84	×
Smith et al (2012)[53]	8 stars (strong)	10 [92]	College and high school athletes	18.3 ± 2.0	5.1 ± 1.95[c]	ICC = 0.97 SEM = 0.52 MDC = 1.44	ICC = 0.92	×
Beese et al (2015)[1]	8 stars (strong)	40 (M: 0, F: 40) [40]	Soccer players and multisport athletes	15.2 ± 1.2	6.5 ±1.9	ICC = 0.91 SEM = 0.48 MDC = 1.33	×	×
Wesley et al (2015)[55]	7 stars (moderate)	5 [36]	Athletes	19.3 ± 1.15[c]	5.0 ± 2.0	ICC = 0.99 SEM = 0.19 MDC = 0.53	×	×
James et al (2016)[24]	6 stars (moderate)	34 (M: 19, F: 15) [34]	NCAA Division I soccer players	19.6 ± 1.2	5.4	ICC = 0.95	×	×
Fox et al (2017)[18]	6 stars (moderate)	10 (M: 0, F: 10) [32]	Subelite netball players	23.2 ± 3.1	4.9 ± 2.3	Cohen κ = 0.93	Cohen κ = 0.75	×
Scarneo et al (2017)[49]	9 stars (strong)	13 (M: 2, F: 11) [13]	Recreationally active population	21 ± 2	6.2 ± 1.7	×	×	ICC = 0.81 SEM = 0.81 MDC = 2.25
Dar et al (2019)[9]	8 stars (strong)	10 [49]	Recreationally active population	28.5 ± 5.6	4.8 ± 2.3	ICC = 0.82 (CI = 0.571-0.947)	ICC = 0.83 (CI = 0.451-0.956)	×

F, females; ICC, intraclass correlation coefficient; M, males; MDC, minimal detectable change; NCAA, National Collegiate Athletic Association.
[a]Methodology quality assessment score based on Newcastle-Ottawa Quality Assessment Scale adapted for cross-sectional studies, weak (0-3 stars), moderate (4-6 stars), and strong (7-10 stars).[36]
[b]Mean ± SD values for age (years) and LESS scores (errors) are shown for all the participants in the study, not the subsample assessed for reliability.
[c]Weighted mean and weighted SD.

Table 2. Summary of studies exploring Landing Error Scoring System (LESS) predictive value for injury incidence

Study (Year)	Quality[a] (Category)	Study Sample Size	Type of Lower-Extremity Injury	Population	Age, y[b]	LESS Score Uninjured[b]	LESS Score Injured[b]	Significance Value
Smith et al (2012)[53]	8 stars (strong)	92 (U: 64, I: 28)	Noncontact ACL	College and high school athletes	18.3 ± 2.0	5.0 ± 2.0	5.5 ± 1.9	$P = 0.320$
Padua et al (2015)[39]	8 stars (strong)	829 (U: 822, I: 7)	Noncontact ACL	Elite youth soccer players	13.9 ± 1.8	4.4 ± 1.7	6.2 ± 1.8	$P = 0.005$
James et al (2016)[24]	6 stars (moderate)	34 (U: 11, I: 10)	Any injury that causes a player to miss 1 or more practices	NCAA Division I soccer players	19.6 ± 1.2	5.8 ± 3.4	5.5 ± 2.5	$P = 0.830$

ACL, anterior cruciate ligament; I, injured; NCAA, National Collegiate Athletic Association; U, uninjured.
[a]Methodology quality assessment score based on Newcastle-Ottawa Quality Assessment Scale adapted for cross-sectional studies, weak (0-3 stars), moderate (4-6 stars), and strong (7-10 stars).[36]
[b]Mean ± SD values for age (years) and LESS (errors).

total LESS score was good to excellent based on ICCs (0.82-0.99 and 0.83-0.92, respectively). In addition to data reported in Table 1, Onate et al[38] reported percentage agreement and kappa statistics between novice and expert raters for all individual LESS items, except for hip flexion at initial contact (IC) and hip flexion at maximal knee flexion, which were not clearly addressed. There was no significant agreement between raters for knee and trunk flexion at IC, and moderate agreement (65% agreement; $\kappa = 0.533$; $P = 0.011$) between raters for overall impression. For the remaining items, agreement between novice and expert raters ranged from 80% to 100% ($\kappa = 0.459\text{-}1.0$; $P < 0.015$). Only 1 study assessed the intersession reliability of the overall LESS score,[49] which was good (ICC, 0.81).

Validity Against Motion Capture System

Two studies reported the validity of the LESS against "gold standard" 3D motion capture.[38,40] Padua et al[40] found that numerous lower-extremity kinematics and kinetics jump-landing measures significantly differed between participants subdivided into 4 quartiles based on excellent (LESS ≤ 4), good (4 < LESS ≤ 5), moderate (5 < LESS ≤ 6), and poor (LESS > 6) LESS performances. Accordingly, the authors concluded the LESS is a valid clinical assessment tool for detecting poor jump-landing biomechanics.[40] Onate et al[38] dichotomized 3D motion capture data into 0 and 1 to match LESS scoring and investigated the association between LESS scores and 3D motion data using phi correlations and percentage agreements. The last 2 items (joint displacement and overall impression) were not included because of the subjective nature of scoring, and the authors did not report any results for the hip flexion at IC and hip flexion at maximal knee flexion. Poor agreement (10% to 42%) was found for knee flexion at IC, lateral trunk flexion at IC, and symmetric foot contact at IC. Moderate agreement (68% to 74%) was found for trunk flexion at IC, knee valgus at IC, stance width (narrow), and knee valgus displacement. The remaining LESS items showed excellent agreement (84% to 100%). Hence, Onate et al concluded that validity of the LESS was item dependent.

LESS Predictive Value for Injury Incidence

Two studies with total sample size of 921 participants reported the predictive value of the LESS for noncontact ACL injury incidence (Table 2).[39,53] The longitudinal cohort study[39] concluded that the LESS has a screening potential for noncontact ACL injury, identifying 5 errors as an optimal cutoff point, yielding a sensitivity of 86% (95% CI, 42% to 99%) and specificity of 64% (95% CI, 62% to 67%). On the other hand, the case-control study[53] did not find any significant relationship between LESS score and risk of suffering ACL injury, either for all participants as a combined group ($P = 0.32$) or for subgroups of male ($P = 0.67$), female ($P = 0.16$), high school ($P = 0.37$), or college ($P = 0.66$) participants. Likewise, there was no significant relationship between LESS as categorical variable (ie, poor, moderate, good, and excellent performances) and noncontact ACL injury incidence ($P = 0.35$).

One study[24] compared preseason LESS scores between soccer players with no previous lower-extremity injury who suffered an injury in the subsequent season and those who remained uninjured (Table 2). Lower-extremity injury was defined as any injury that caused players to miss 1 or more practices or games. There were no statistically significant differences ($P = 0.83$) in preseason LESS scores between those who sustained a lower-extremity injury and those who remained uninjured.

DISCUSSION

Reliability

Findings from 9 studies of relatively strong methodological quality indicated good-to-excellent intrarater, interrater, and intersession reliabilities. Noteworthy is that reliability of the overall LESS score was derived from uninjured military freshmen and sportspeople with a mean age between 15 and 28 years. Although LESS has been used in younger[14,46] and injured[20,29] individuals; generalizability of reliability findings across these population groups is not confirmed. Furthermore, the findings showed that some individual items in LESS scoring are less reliable than others.[38] More specifically, no significant agreement between raters was found for knee and trunk flexion at IC and moderate agreement for overall impression. Given that knee flexion during landing and stiff landing with less ankle, knee, hip, and trunk flexion are key risk factors for knee injury incidence,[13,31,43] the lack of agreement in these LESS metrics is of concern. In the LESS, a knee flexion at IC of less than 30° defines an error (Appendix Table A1, available online). Accurately determining an angular measure from visual observations is challenging,[16,25] which can explain the lower reliability of the knee flexion angle at IC item. The overall impression item is subjective in nature, and the representation of an excellent, average, and poor landing may differ between raters. One solution could be to use a video analysis software to objectively assess angle-related items during LESS scoring to decrease the subjective nature of items. Although outcomes from such assessments might be more accurate, the scoring process would take more time. To decrease scoring time and improve consistency of LESS ratings, the automated quantification of the LESS using markerless motion capture technology has been developed recently.[9,33] The markerless method is as reliable as expert LESS raters.[33] The time and cost saving benefits of the markerless method, however, need to be weighed against the additional hardware and software expenditures.

Validity Against Motion Capture System

Some of the most frequently addressed biomechanical risk factors linked with ACL injury include increased knee valgus angle and moment[8,11,12,21,28,35] and increased ground-reaction force resulting from stiff landing.[5,6,10,13,45,51,52] Padua et al[40] associated poor LESS scores with decreased peak knee and hip flexion angles and increased peak knee valgus angles and moments. Onate et al[38] found that the validity of LESS items was strictly item dependent. Again, one of the main concerns is that angles are difficult to estimate visually. A small kinematic difference (eg, knee angle 29° = error present; knee angle 30° = error absent) in performance can result in poor agreement between clinical LESS scoring and motion capture scoring. Onate et al suggested creating a range of acceptable angular values (eg, knee angle at IC between 25° to 30°) to improve scoring validity, although no further studies were undertaken.

The validity of the LESS was strictly item dependent,[38] which might mean modification of the original LESS scoring template. The fact that most of the key factors for ACL injury had moderate and excellent agreement nonetheless supports the LESS as a valid screening tool for assessing ACL injury risk jump-landing biomechanics.

LESS Predictive Value for Injury Incidence

Two studies of strong methodological quality explored the predictive value of the LESS for ACL injury incidence and reported equivocal results.[39,53] Padua et al[39] employed a prospective study design. Of the 829 elite young soccer players with a mean age of 13.9 ± 1.8 years, 7 participants suffered a noncontact ACL injury during the 2.5-year observation period. Based on the data, 5 errors were identified as an optimal cut point for distinguishing between athletes with low and high risk of ACL injury. Sample size calculations and post hoc power analyses were not reported.

The study conducted by Smith et al[53] assessed a population of college and high school athletes from a range of sports with a mean age of 18.3 ± 2.0 years. The study was designed as a prospective cohort with 5047 screenings within a 3-year period. Smith et al did not find any significant relationship between LESS scores and risk of ACL injury.

The lack of agreement in the predictive value of the LESS between studies can be explained by differences in sampled populations in terms of age, main sporting events, and exclusion criteria (Smith et al[53] excluded athletes with a history of ACL injury, whereas Padua et al[39] did not). Furthermore, the lack of statistical power in both studies[39,53] is a limiting factor to the generalization of results.

One moderate quality study[24] recorded preseason LESS scores of soccer players without lower-extremity injury history and did not find any significant difference between participants who sustained an injury during the subsequent season and those who remained uninjured. The study is deemed to have several limitations that could explain the lack of association between LESS and lower-extremity injuries, including the relatively small sample size ($n = 34$), short follow-up period, and lack of differentiation between contact and noncontact mechanisms of injury. Fundamentally, the LESS was developed as an injury risk screening tool that identifies poor biomechanical control, which is a risk factor for noncontact, rather than contact, lower-extremity injuries. Thus, the relevance of the findings from James et al[24] is questioned.

Based on the current scientific evidence, the predictive value of the LESS for noncontact lower-extremity injury incidence remains uncertain. Studies with a greater statistical power are

needed to affirm the relationship between LESS scores and noncontact ACL injury incidence, as well as incidence of other noncontact lower-extremity injuries.

Limitations

This systematic review combines data across studies to detail the reliability, validity against motion capture, and predictive validity of the LESS. The main limitations of this review were the varied methodological quality of studies and the inability to perform meta-analysis of data due to lack of detail. Another important limitation is that populations included, testing protocols, and calculations of total LESS score varied across studies. Population characteristics—for example, age, sex, and activity level—can significantly influence LESS scores,[3,27,53] and therefore the results of this literature review are most relevant to uninjured military freshmen and sportspeople with a mean age between 14 and 28 years.

CONCLUSION

The current evidence indicates that the overall LESS score has good-to-excellent intrarater, interrater, and intersession reliabilities. The validity of the individual LESS items against 3D motion capture is item dependent; however, the validity of LESS items addressing key knee-injury risk factors is moderate to excellent. The LESS predictive value for noncontact ACL injury and other noncontact lower-extremity injury incidence cannot be ascertained based on the current scientific evidence. Larger scale multicenter studies are needed to confirm the association between LESS scores and ACL injury incidence, as well as other noncontact lower-extremity injury incidence.

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Appendix A2. *Factors influencing the Landing Error Scoring System: Systematic review with meta-analysis.*

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Review

Factors influencing the Landing Error Scoring System: Systematic review with meta-analysis

Ivana Hanzlíková[a,*], Josie Athens[b], Kim Hébert-Losier[a]

[a] Division of Health, Engineering, Computing and Science, Te Huataki Waiora School of Health, Adams Centre for High Performance, University of Waikato, New Zealand

[b] Department of Preventive and Social Medicine, University of Otago, New Zealand

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A B S T R A C T

Objectives: Systematically review the literature addressing age, sex, previous injury, and intervention program as influencing factors of the Landing Error Scoring System.

Design: Systematic review with meta-analysis.

Methods: Three databases (PubMed, Web of Science®, and Scopus®) were searched on 1 April 2020. Original studies using the Landing Error Scoring System as primary outcome and exploring age, sex, previous injury, and intervention program were included, assessed for risk of bias, and critically appraised. Three meta-analyses were performed using one random and two mixed effect models with dependent variables: sex, previous injury and intervention program, respectively. Grading of Recommendations Assessment, Development and Evaluation was used to evaluate the strength of the evidence. PROSPERO registration number CRD42018107210.

Results: Fifty-two studies were included. Pooled data indicated that females have higher Landing Error Scoring System scores than males ($p < 0.001$, mean difference = 0.6 error). Participants with previous anterior cruciate ligament injury have higher LESS scores than healthy controls ($p = 0.004$, mean difference 1.2 error). Neuromuscular training programs lasting a minimum of six weeks and other intervention programs decrease Landing Error Scoring System scores ($p < 0.001$, mean difference 1.2 error and $p = 0.042$, mean difference 0.5 error, respectively). There is limited evidence suggesting that age may influence Landing Error Scoring System scores in clinically meaningful manner. Overall, Grading of Recommendations Assessment, Development and Evaluation ratings suggest very low strength of evidence.

Conclusions: History of anterior cruciate ligament injury and undertaking neuromuscular training for a minimum of six weeks meaningfully altered Landing Error Scoring System scores. These findings, however, should be interpreted cautiously considering the very low Grading of Recommendations Assessment, Development and Evaluation rating of the evidence.

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Practical implications

- Age can influence Landing Error Scoring System (LESS) scores, indicating that the established thresholds defining injury risk may not apply across different age groups.
- Females have higher LESS scores than males; however, the difference of 0.6 errors is not clinically meaningful, indicating that differences in landing mechanics assessed by LESS are not the only factor contributing to the overall higher risk of anterior cruciate ligament (ACL) injury seen in females.
- Previous ACL injury meaningfully increases LESS scores likely due to residual long-term deficits in neuromuscular control or presence of compensatory strategies.
- Previous injuries other than ACL do not appear to affect LESS scores given that the existing research includes contact injuries, which the LESS was not designed to predict.
- Neuromuscular programs completed two to three times per week for at least six weeks incorporating plyometric exercise and landing technique feedback are currently shown to be the most effective in improving LESS scores in a meaningful manner. Other intervention programs significantly decreased LESS score, but the difference of 0.5 errors is not clinically meaningful.

* Corresponding author.
E-mail address: xhanzlikova@gmail.com (I. Hanzlíková).

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1. Introduction

The Landing Error Scoring System (LESS) is an easy and convenient field-based testing method that examines the presence of biomechanical movement patterns previously linked to non-contact Anterior Cruciate Ligament (ACL) injury.[1] The LESS involves the performance of a double-leg jump-landing task and relies on the use of two standard video cameras, one placed to capture the motion from front view and other to capture the motion from side view. Clinicians evaluate the frontal and sagittal plane videos from the LESS and visually evaluate aberrant lower extremity and trunk kinematics between initial ground contact (IC) and peak knee flexion and note the number of "movement errors" observed. The LESS consists of 17 items. Movement items 1 to 15 are scored as 0 (error absent) and 1 (error present). The last two items (16 and 17) of the LESS are subjective in nature and assess the overall sagittal plane displacement and quality of landing which are scored from 0 to 2 errors. The minimum LESS score is 0 and the maximum score is hypothetically 19 errors. However, it is unlikely that an individual presents a wide and narrow stance or an internal and external rotation of the foot simultaneously. Consequently, the real maximum score is 17 errors. A higher score means a greater number of landing errors, poorer landing biomechanics, and greater risk of non-contact lower extremity injuries.[1]

A recent systematic review of the literature concluded that the overall LESS score has good to excellent intrarater (intraclass correlation coefficient [ICC], 0.82–0.99), interrater (ICC, 0.83–0.92), and intersession (ICC, 0.81) reliability.[2] Validity of the overall LESS score against 3-dimensional (3D) jump-landing biomechanics was good when individuals were divided into four quartiles based on LESS scores, although the validity of the individual LESS items was item dependent.[2] Poor agreement (10–42%) between 3D motion data and LESS ratings was found for knee flexion at IC, lateral trunk flexion at IC, and symmetric foot contact at IC. The remaining LESS items showed moderate to excellent agreement (68–100%).[3] Padua et al.[4] concluded from a prospective investigation that LESS scoring had a good sensitivity (86%) and acceptable specificity (64%) to identify risk of non-contact or indirect-contact ACL injury. More specifically, the relative risk of ACL injury was 10.7 times greater when LESS scores were $\geq$5 errors. However, Smith et al.[5] did not find any significant relationship between LESS and primary ACL injury incidence in their case–control analysis. Based on the recent review,[2] the predictive value of the LESS for non-contact ACL injury and other non-contact lower extremity injury incidence is unclear. The reasons for the conflicting results are likely due to under-powered sample sizes and differences in sampled populations in terms of age, proportion of females and males, and injury history.[2] All of these factors can potentially influence LESS scores and explain between study differences in findings.

Due to its clinical-friendly focus and minimal use of equipment, space, and time; the LESS lends itself well to movement screening initiatives involving a large number of athletes and is often used in practice and research.[6–8] Therefore, it is important to understand what factors might impact LESS scores for the proper interpretation of outcomes. To date, there has been no systematic evaluation of factors that can influence LESS scores. Therefore, the aim of this systematic review with meta-analysis was to systematically review the literature addressing age, sex, previous injury, and intervention program as influencing factors of the LESS. The results of this systematic review with meta-analysis may assist in establishing thresholds defining injury risk for different sexes, age groups and previous injuries and may guide prevention effort in intervention programs with highest impact on gross movement jump-landing biomechanics.

2. Methods

A systematic review with meta-analysis was undertaken and followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines.[9] Literature review methods and inclusion criteria were specified in advance, and prospectively registered with PROSPERO (CRD42018107210).

Studies using the LESS as main outcome measure and reported age, sex, previous injury, or intervention program were included regardless of participants, intervention, or study design. Only original research (excluding case reports) in the English language published in peer-reviewed journals were considered. Studies using modified versions of the original LESS (e.g., real-time LESS,[10] iLESS,[11] automated quantification of the LESS,[12] or LESS with additional items[13]) were excluded.

Three electronic databases [PubMed (1950–), Web of Science® (1965–) and Scopus® (1970–)] were searched using the key words "Landing Error Scoring System". The final search was undertaken on 1st April 2020, by one reviewer (IH). Titles, abstracts, and full-texts were screened sequentially for inclusion and exclusion criteria. In case of uncertainty regarding inclusion, a second reviewer (KHL) was consulted. Reference lists of included articles were hand-searched for additional records.

Data concerning study design, population (number, sex, age, and activity level), LESS scores, statistical analysis, and results concerning LESS were extracted from articles using a standardized template by one reviewer (IH), with the completeness of extraction verified by a second reviewer (KHL). We contacted seven authors by email to request additional information from 10 studies.[1,5–7,14–19] Two authors responded,[17,19] with one author[19] providing additional data for one study.

Three validated risk of bias assessment tools: Newcastle–Ottawa Assessment Scale adapted for cross-sectional studies (NOS)[20], revised tool for Risk of Bias in randomized trials (RoB 2.0),[21] and Risk Of Bias in Non-randomized Studies – of Interventions (ROBINS-I)[22] were used. Two reviewers (IH and KHL) independently assessed the risk of bias of included studies. Prior to assessment, the two reviewers met to discuss and familiarize themselves with the scales. All identifiable information (i.e., authors, affiliations, countries, and sources of publication) were removed from articles by a third party to blind the two reviewers (IH and KHL) and reduce the assessment bias. The risk of bias for each study was assessed specifically for the LESS outcome score as recommended.[23] Disagreements in the risk of bias assessment scores were resolved by discussion between the reviewers. Consensus scores are presented in this review article.

The RoB 2 assessed the risk of bias across six domains through which bias can be introduced into the results of randomized controlled trials.[21] The ROBINS-I assessed the risk of bias across seven domains through which bias might be introduced into non-randomized interventional studies.[22] Both the RoB2 and ROBINS-I tools have been rigorously developed and recommended to assess the risk of bias in sport and exercise medicine.[23] The risk of bias in outcomes from the observational studies were assessed using the NOS as it is a suitable alternative to the ROBINS-I.[24] Using the NOS star system, a maximum of two stars for each numbered item can be allocated, with an overall maximum of 10 stars. Therefore, more star indicates superior methodological quality and lower risk of bias. Reviewers agreed to award the highest score in the statistical test section for the reporting of confidence intervals, quartiles, limits of agreement, or standard errors.

In addition, the level of evidence for each study was determined using the Oxford Center for Evidence-Based Medicine 2011 table. The level of evidence ranges from 1 to 5, with 1 indicating the highest level of evidence and 5 the lowest. Study design was categorized according to Parab and Bhalerao.[25] Furthermore, the outcomes of

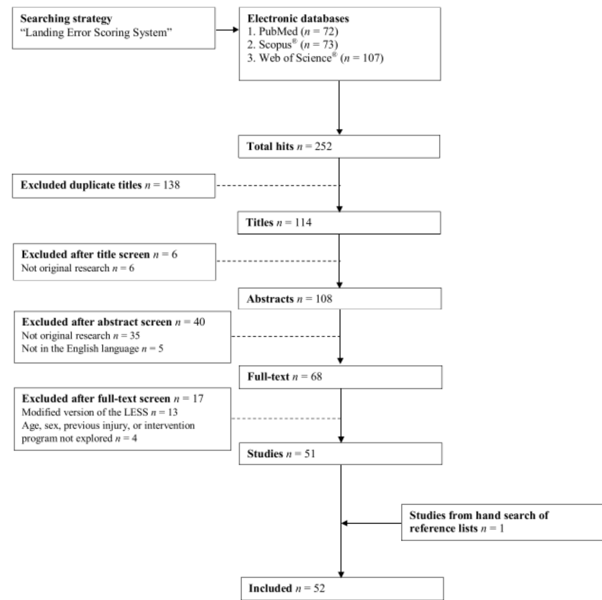


Fig. 1. Flow chart of the search strategy and study selection process.

the meta-analysis were evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) scale.[26] No study was excluded based on risk of bias assessment, level of evidence, or study design.

Descriptive statistics were computed using Microsoft® Office Excel 2016 and expressed in terms of means and standard deviations (mean ± SD) weighted based on sample size, minimum to maximum ranges (min to max), percentages (%), and counts (*n*). Note that for interventional studies, LESS score pre-intervention was included in calculating and analyzing study characteristics. Hedge's *g* was calculated as a measure of effect size when data were reported in sufficient detail. Thresholds for interpreting the magnitude of the effect were: $g < 0.20$ for trivial, $0.20 \leq g < 0.50$ for small, $0.50 \leq g < 0.80$ for medium, and $g \geq 0.80$ for large.[27]

Five or more studies are needed to achieve reasonable power from a random effect model meta-analysis.[28] Therefore, meta-analysis was attempted when at least five studies reported results in sufficient detail. Three meta-analyses were undertaken exploring sex, previous injury, and intervention program as potential influencing factors of LESS scores. Heterogeneity was explored statistically using Cochrane *Q* and quantified using I^2. The *Q* test has a low power in meta-analysis when studies have small sample sizes or are few in numbers.[29] Therefore, statistical significance for Cochrane *Q* was set to $p < 0.10$. The I^2 was interpreted according Higgins et al.,[29] with 0–40% indicating "heterogeneity might not be important", 30–60% "moderate heterogeneity", 50–90% "substantial heterogeneity" and 75–100% "considerable heterogeneity". When meta-analysis had one moderator and heterogeneity was significant, a random effect model was used to account for both within-study and between-study variance. For meta-analysis with two moderators, a mixed effect model was used. Raw mean difference between scores with associated 95% confidence intervals [CI] were calculated for all meta-analyses. Statistical significance was set at $p \leq 0.05$, and clinical meaningfulness of differences in LESS score means was set at one error based on Padua et al.[1] who identified one error change in total LESS score to be associated with moderate to large differences in biomechanical variables previously linked to ACL injury. Meta-analysis calculations were undertaken in RStudio® Version 1.1.456 with R version 3.5.1 using the metafor package.[30] Note, that if meta-analysis was not possible due to small number of studies, a qualitative analysis was undertaken.

Funnel plots were constructed for every meta-analysis to assess publication bias. Egger's test (model of weighted regression with multiplicative dispersion) was performed on the random effect model for each meta-analysis to assess funnel plot asymmetry as suggests metafor package.[30]

3. Results

The systematic database search generated 252 hits related to the Landing Error Scoring System. Following the removal of duplicates, 114 studies remained. An additional 63 studies were removed following title (not original research $n = 6$), abstract (not original research $n = 35$; not in English language $n = 5$), and full-text screen (modified version of the LESS $n = 13$; age, sex, previous injury, or intervention program not explored $n = 4$), with 1 article subsequently identified via hand searching of reference lists. Fifty-two studies met inclusion and were reviewed (Fig. 1).

All studies reported the number of participants tested with the LESS. The sample size ranged from 11[31] to 2753[32] participants. A total of 11,672 participants were represented across the 52 studies. Four studies did not specify the activity levels of their cohorts.[17,33–35] All remaining studies (92%) tested individuals engaged in some level of physical activity (see Table 1). Sex distribution was described in 51 (98%) studies, totaling 6925 males (59%)

Table 1
Summary of studies (by year) comparing the influence of sex, previous injury, and training program on Landing Error Scoring System scores.

Study (year)	Sample size (n)	Population	Age (years)[a]	LESS score (errors)[a]	Hedge's g	Comparison M vs F
Sex						
Beutler et al. (2009)[32]	Total: 2753 M: 1707, F: 1046	Cadets of US military	18 – 24	M: 4.7 ± 1.7 F: 5.3 ± 1.5	0.37	$p < 0.001$
Padua et al. (2009)[1]	Total: 2691 M: 1655, F: 1036	US military freshmen	Not specified	Not specified		Females higher scores than males $p < 0.001$
DiStefano et al. (2009)[14]	Total: 173 M: 90, F: 83	Soccer players	13.0 ± 2.0	M: 4.4 ± 1.7 F: 5.8 ± 1.9	0.78	Not specified
Smith et al. (2012)[5]	Total: 92 M: 29, F: 63	College and high school athletes	M: 18.5 ± 2.5 F: 18.0 ± 1.7	M: 5.5 ± 2.1[b] F: 5.0 ± 1.9[b]	0.26	Non-significant $p = 0.22$
Lam & McLeod (2014)[45]	Total: 215 M: 116, F: 99	Athletes competing in interscholastic sports	M: 19.4 ± 1.5 F: 19.1 ± 1.1	M: 5.1 ± 2.5 F: 5.8 ± 2.3	0.29	Non-significant $p > 0.05$
Theiss et al. (2014)[46]	Total: 277 M: 222, F: 55	Cadets of US military	19.3 ± 0.8	M: 5.1 ± 0.2[b] F: 5.6 ± 0.5[b]	1.75	$p = 0.05$
Wesley et al. (2015)[56]	Total: 36 M: 18, F: 18	Athletes	M: 19.4 ± 1.4 F: 19.2 ± 0.9	M: 5.0 ± 2.3 F: 6.3 ± 1.9	0.70	$p \leq 0.05$
Bell et al. (2016)[69]	Total: 39 M: 20, F: 19	Recreationally active population	M: 20.9 ± 1.2 F: 21.2 ± 1.4	M: 4.7 ± 2.3 F: 5.3 ± 2.1	0.27	Non-significant $p = 0.56$
Welling et al. (2016)[8]	Total: 40 M: 20, F:20	Ball team sport athletes	22.50 ± 1.62	M: 2.8 ± 1.0[b] F: 3.1 ± 0.7[b]	0.35	Non-significant $p > 0.05$
de la Motte (2016)[40]	Total: 521 M: 431, F: 90	Military applicants entering US army	M: 20.8 ± 3.0 F: 20.9 ± 3.2	M: 5.5 ± 2.1 F: 6.5 ± 1.8	0.49	$p < 0.001$
Garbenytė-Apolinskienė et al. (2018)[70]	Total: 31 M: 15, F: 16	Basketball players	15.4 ± 0.3[b]	M: 6.9 ± 2.3 F: 6.6 ± 1.8	0.13	Not specified
DiStefano et al. (2018)[6]	Total: 355 M: 122, F: 233	Soccer and basketball players	11.0 ± 2.0	Not specified	Not specified	Non-significant $p > 0.05$
Jacobs et al. (2018)[57]	Total: 40 M: 20, F: 20	Recreationally active population	M: 24.4 ± 1.8 F: 23.4 ± 2.8	M: 5.1 ± 2.2 F: 5.1 ± 1.5	0.01	Non-significant $p = 0.624$
Kuenze et al. (2018)[52]	Total: 168 M: 41, F: 127	Participants after ACL reconstruction	M: 20 (median) F: 19 (median)	M: 4.6 ± 2.3 F: 6.1 ± 2.3	0.65	$p < 0.001$

Study (year)	Sample size (n)	Population	Age (years)[a]	LESS score (errors)[a]	Hedge's g	Comparison injured vs uninjured
Previous injury						
Smith et al. (2012)[5]	Total: 92 ACL: 28 Control: 64	College and high school athletes	18.3 ± 2.0	ACL: 5.5 ± 1.9 Control: 5.0 ± 2.0	0.25	$p = 0.32$
Lam & McLeod (2014)[45]	Total: 215; Mild knee injury (MI): 31; Severe knee injury (SI): 36; No knee injury (control): 148	Athletes competing in interscholastic sports	19.3 ± 1.4[b]	MI: 5.3 ± 2.6 SI: 5.9 ± 2.6 Control: 5.4 ± 2.4	MI vs Control 0.04 SI vs Control 0.20	Non-significant
Bell et al. (2014)[33]	Total: 54 ACLR: 27 Control: 27	Not specified	ACLR: 19.9 ± 1.7 Control: 20.5 ± 1.6	ACLR: 6.7 ± 2.1 Control: 5.6 ± 1.5	0.60	$p = 0.04$
Gokeler et al. (2014)[17]	Total: 20 ACLR: 10 Control: 10	Not specified	ACLR: 27.4 ± 9.6 Control: 21.0 ± 0.8	ACLR: 6.5 Control: 2.5 (median)		Not specified
Kuenze et al. (2015)[34]	Total: 46 ACLR: 22 Control: 24	Not specified	ACLR: 22.5 ± 5.0 Control: 21.7 ± 3.6	ACLR: 6.0 ± 3.6 Control: 2.8 ± 2.2	1.08	$p = 0.002$
Padua et al. (2015)[4]	Total: 1217 ACL: 7 Control: 1210	Soccer players	ACL: 14.9 ± 0.70 Control: 13.9 ± 1.8	ACL: 6.2 ± 1.8 Control: 4.4 ± 1.7	1.06	$p < 0.005$
James et al. (2016)[18]	Total: 34 History of injury (HI): 13 No history of injury (NHI): 21 Injured during study (IDS): 10 Never injured (NI): 11	NCAA division I soccer players	HI: 19.7 ± 1.2 NHI: 19.6 ± 1.3 IDS: 19.6 ± 1.2 NI: 19.6 ± 1.4	HI 4.9 ± 2.4 NHI: 5.6 ± 2.9 IDS 5.5 ± 2.5 NI: 5.8 ± 3.4	HI vs NHI 0.26 IDS vs NI 0.10	HI vs NHI $p = 0.50$ IDS vs NI $p = 0.83$

Table 1 (*Continued*)

Previous injury

Study (year)	Sample size (n)	Population	Age (years)[a]	LESS score (errors)[a]	Hedge's g	Comparison injured vs uninjured
van Melick et al. (2019)[55]	Total: 33 ACLR: 14 Control: 19	Recreational soccer players	ACLR: 23.2 ± 3.6 Control: 21.3 ± 3.0	ACLR: 4.0 ± 2.0 Control: 4.0 ± 2.0	0.00	Non-significant
John et al. (2019)[35]	Total: 40 CAI: 20 Control: 20	Students	CAI: 23.3 ± 3.3 Control: 25.5 ± 3.4	CAI: 7.4 ± 1.6 Control: 6.1 ± 1.5	0.80	$p = 0.010$

Training program

Study (year)	Sample size (n)	Population	Age (years)[a]	Intervention	Duration	Test times	LESS score (errors)[a]	Hedge's g	Comparison between groups
DiStefano et al. (2009)[14]	Total: 173 M: 90, F: 83	Soccer players	13.0 ± 2.0	Stratified and generalized injury prevention TP	10–15 mi, 3–4 times/week for 3 months	Pre TP Post TP	Males Pre: 4.4 ± 1.7 Post: 3.9 ± 1.8 Females Pre: 5.8 ± 1.9 Post: 4.8 ± 1.7	Males 0.29 Females 0.55	Males vs Females $p = 0.35$
Padua et al. (2012)[66]	Total: 84 M: 20, F: 64 Short duration: 33 Long duration: 51	Soccer players	14.0 ± 2.0	Injury prevention TP short duration (3 months) vs Injury prevention TP long duration (9 months)	10–15 mins, 3–4 times/week for 3 or 9 months	Pre TP Post TP 3months post TP	Short TP Pre: 5.2 ± 1.5 Post: 3.4 ± 1.1 3 months post: 4.7 ± 1.6 Long TP Pre: 5.7 ± 1.7 Post: 4.1 ± 1.4 3 months post: 4.2 ± 1.3	Short TP pre vs post 1.37 pre vs 3 months post 0.32 Long TP pre vs post 1.03 pre vs 3 months post 0.99	Short and long TP significantly lower scores pre vs post Long TP significantly lower scores 3 months post $p < 0.05$
DiStefano et al. (2013a)[15]	Total: 30 M: 25, F: 5 IRTP: 15 ITP: 15	Participants of weight training course	19.0 ± 1.0	Isolated resistance TP (IRTP) vs Integrated TP (ITP)	45 min, 2 times/week for 8 weeks	Pre TP Post TP	IRTP Not specify ITP Pre: 3.9 ± 1.0 Post: 3.0 ± 1.0	ITP 0.9	ITP Pre vs post $p = 0.02$
Owens et al. (2013)[67]	Total: 273 M: 158, F: 115	Participants of Military Movement course	17 to 25	Military Movement course (MMC)	19 sessions of 50 min (8 weeks)	Pre MMC Post MMC	Pre MMC: 5.0 ± 1.8 Post MMC: 4.5 ± 2.0	0.26	Pre vs post $p < 0.001$
DiStefano et al. (2016)[16]	Total: 1104 M: 928, F: 176	US military freshmen	17 to 22	Standard warm up vs Dynamic integrated movement enhancement injury prevention TP	10–12 min, 2–3 times/week for 6 weeks	Pre TP Post TP 2, 4, 6, 8, months post TP	Not specified		Non-significant group differences in scores at all time point
Pfile et al. (2016)[31]	Total: 11 M: 0, F: 11	Division I basketball players	19.4 ± 1.4	Plyometrics and neuromuscular control TP	18 sessions of 30 min in 6 weeks	Pre TP Post TP 9 months post TP	Pre: 7.3 ± 3.4 Post: 4.9 ± 1.2 9 months post: 5.4 ± 1.8	Pre vs post 0.94 Pre vs 9 months post 0.70	Pre vs post $p = 0.024$ Pre vs 9 months post $p = 0.030$
Welling et al. (2016)[8]	Total: 40 M: 20, F: 20 IF: 10, EF: 10, V: 10, C: 10	Ball team sport athletes	22.5 ± 1.6	4 groups: Internal focus instruction (IF). External focus instruction (EF). Video instruction (V) and Control (C)	1 session	Pre TP Post TP 1 week (1W) post TP	IF Pre: 2.9 ± 1.0 Post: 3.2 ± 1.1 1W post: 3.1 ± 1.5 EF Pre: 3.1 ± 1.0 Post: 2.3 ± 1.0 1W post: 2.3 ± 0.5 V Pre: 2.8 ± 0.9 Post: 2.0 ± 0.6 1W post: 2.0 ± 0.6 C Pre: 3.0 ± 0.6 Post: 3.1 ± 0.7 1W post: 2.9 ± 0.5	IF pre vs post 0.29 IF pre vs 1W post 0.16 EF pre vs post 0.8 EF pre vs 1W post 1.01 V pre vs post 1.05 V pre vs 1W post 1.05 C pre vs post 0.15 C pre vs 1W post 0.18	Males in V group Pre vs post $p < 0.05$ Pre vs 1W post $p < 0.05$ Female in V and EF group Pre vs post $p < 0.05$ Pre vs 1W post $p < 0.05$

Table 1 (*Continued*)

Training program

Study (year)	Sample size (*n*)	Population	Age (years)[a]	Intervention	Duration	Test times	LESS score (errors)[a]	Hedge's g	Comparison between groups
ÓMalley et al. (2017)[36]	Total: 78 NTP: 41 Control: 37	Gaelic footballers and hurling athletes	18.5	Neuromuscular TP (NTP) vs Usual team training (Control)	15 min, 2 times/week for 8 weeks	Pre TP Post TP	NTP Pre: 7.1 ± 3.8 Post: 4.1 ± 3.2 Control Pre: 8.1 ± 3.3 Post: 7.2 ± 2.9	NTP 0.89 Control 0.29	NTP vs control $p < 0.001$
Parson et al. (2017)[61]	Total: 36 M: 0, F: 36 WTP: 19, Control: 17	Athletes	12.3 ± 1.4	Weight TP (WTP) vs Control (arm training)	60 min, 2 times/week for 12 weeks	Pre TP Post TP	WTP Pre: 6.8 ± 1.5 Post: 6.0 ± 1.8 Control Pre: 6.4 ± 1.6 Post: 6.1 ± 1.8	WTP 0.48 Control 0.18	WTP vs control Non-significant $p = 0.85$
Scarneo et al. (2017)[65]	Total: 15 M: 0, F: 15	Active population with real time LESS > 4	21.0 ± 2.0	Aquatic neuromuscular TP	7–10 min 3 times/week for 6 weeks	Pre TP Post TP 4 months post TP	Pre: 6.3 ± 1.8 Post: 4.5 ± 1.7 4 months post: 4.2 ± 1.7	Pre vs post 1.03 Pre vs 4 months post 1.20	Pre vs post $p < 0.01$ Pre vs 4 months post $p < 0.01$
Pryor et al. (2017)[7]	Total: 89 M: 41, F: 48 IPTP (experienced): 43 Control (novice): 46	Soccer players	8 to 14	2 stages: Stage 1: Injury prevention IP (IPTP) vs Control Stage 2: group with experience of IPTP vs novice group without experience of IPTP	10–12 min 3 times/week for 8 weeks	Pre TP Post TP	Stage 1: IPTP Pre: 6.2 ± 1.0 Post: 4.9 ± 1.8 Stage 2: Experienced group Pre: 5.9 ± 1.6 Post: 5.0 ± 1.5 Novice group Pre: 6.1 ± 1.6 Post: 5.3 ± 1.9	Stage 1: 1.02 Stage 2: Experienced 0.58 Novice 0.46	Stage 1: IPTP Pre vs post $p = 0.01$ Stage 2: Experienced Pre vs post $p < 0.01$ Novice Pre vs post $p < 0.01$
Garbenytė-Apolinskienė et al. (2018)[70]	Total: 31 M: 15, F: 16	Basketball players	15.4 ± 0.3[b]	Integrated exercise TP	Individual dosage, 5 times/week for 5 months	Pre TP Post TP	Males Pre: 6.9 ± 2.3 Post: 4.6 ± 2.9 Females Pre: 6.6 ± 1.8 Post: 6.0 ± 2.9	Males 0.88 Females 0.25	Males pre vs post $p = 0.001$ Females pre vs post Non-significant
Parsons et al. (2019)[62]	Total: 43 M: 0, F: 43 FIFA 11+: 29, Standard warm up: 18	Soccer players	11.1	FIFA 11+ vs standard warm up	10–30 min 2 times/week for 5 months	Pre TP Post TP	FIFA 11+ Pre: 6.9 ± 1.6 Post: 6.2 ± 1.6 Warm up Pre: 6.6 ± 1.7 Post: 6.1 ± 1.3	FIFA 11+ 0.42 Warm up 0.31	FIFA 11+ vs Warm up $p = 0.66$
Akbari et al. (2019)[63]	Total: 24 M: 24, F: 0 FIFA 11+: 12, Standard warm up: 12	Elite soccer players	16.8 ± 1.2	FIFA 11+ vs standard warm up	20–25 min 3 items/week for 8 weeks	Pre TP Post TP	FIFA 11+ Pre: 4.4 ± 0.7 Post: 2.3 ± 1.3 Warm up Pre: 4.6 ± 1.3 Post: 4.7 ± 1.4	FIFA 11+ 1.86 Warm up 0.07	FIFA 11+ vs Warm up $p < 0.001$

Abbreviations: ACL, Anterior Cruciate Ligament; ACLR, Anterior Cruciate Ligament reconstruction; CAI, Chronic ankle instability; F, females; FIFA, Federation International de Football Association, LESS, Landing Error Scoring System; M, males; NCAA, National Collegiate Athletic Association; TP, training program; US, United States.

[a] Mean ± standard deviation values for age (years) and LESS score (errors).

[b] Mean ± standard deviation values weighted based on sample size.

and 4669 (40%) females, with the sex not reported for the remaining 78 participants (1%) in one study.[36] The mean age was reported in 46 (88%) studies (weighted mean: 16.2 ± 1.3 years), with the average ranging from 11[6] to 28[19] years.

The overall LESS score was reported in 47 (90%) studies. The calculated weighted mean for overall LESS score was 4.9 ± 1.7 errors using pre-intervention LESS scores for computations. The minimum reported mean LESS score for a group was 2.0[8] and maximum was 8.1[36] errors. Only four studies reported the range of individual LESS scores,[18,19,37,38] with a minimum of 0.0[19,37] and maximum of 13.3[18] errors (average of three trials).

The NOS adapted for cross-sectional studies was used for 33 (64%) studies. Out of a maximum of 10 stars, 2 studies scored two stars,[35,39] 4 studies four stars,[40–43] 7 studies five stars,[44–50] 10 studies six stars,[1,18,32,37,38,51–55] 2 studies seven stars,[56,57] 7 studies eight stars,[4,5,19,33,58–60] and 1 study nine stars.[6] The RoB 2 was used for 9 (17%) studies. There was some concern regarding risk of bias in 3 studies[8,61,62] and a high risk of bias in the remaining 6 studies.[7,14–16,36,63] The ROBINS-I was used for 10 (19%) studies. Risk of bias was considered moderate in 4 of these studies[31,34,64,65] and serious in the remaining 6 studies.[17,66–70] The level of evidence ranged between 2 and 4 based on the Oxford Center for Evidence-Based Medicine 2011 table. Studies were most often of level 3 ($n = 30$, 58%) and cross-sectional in design ($n = 25$, 48%). Risk of bias scores, level of evidence, and study design of studies are presented in Appendix A in the Supplementary Material. The risk of bias of the studies considered in examining each one of the influencing factors of the LESS is presented in Appendix B in the Supplementary Mate-

Table 2
Summary of findings regarding influencing factors (sex, previous injury, intervention program) of the Landing Error Scoring System (LESS).

Outcome	Certainty assessment						Summary of findings		
	Studies (n)	Study design	Risk of bias	Indirectness	Imprecision	Publication bias	Participants included in meta-analysis (n)	Results	Quality of the evidence (GRADE)
Sex	12	Observational, randomized and non-randomized interventional studies	Very serious[a]	Serious[b]	Serious[c]	Undetected	Males: 2729 Females: 1656	Females 0.6 errors higher LESS scores than males	⊕○○○ Very low
Previous injury	8	Observational and non-randomized interventional studies	Very serious[a,d]	Serious[b,e]	Serious[f]	Undetected	Previously injured: 208 Uninjured: 1692	Participants with ACL injury had 1.2 errors higher LESS scores than uninjured controls Participants with other types of injury had 0.3 error higher LESS scores than control	⊕○○○ Very low
Intervention program	13	Randomized and non-randomized interventional studies	Serious[g]	Serious[b,h]	Not serious	Undetected	927	Compare to pre-preintervention, LESS score post-intervention decreased by 1.2 error for NTP and by 0.5 errors for other interventions	⊕○○○ Very low

Abbreviations: ACL, Anterior Cruciate Ligament; GRADE, Grading of Recommendations Assessment, Development and Evaluation; NTP, neuromuscular training program with minimal duration of 6 weeks.

[a] At least a half of observational studies did not justify sample size, describe response rate, blind assessment of outcome, and did not use appropriate statistical tests. At least a half of interventional studies had high or moderate risk of bias due confounding and in selection of the reported results (see Appendix B).

[b] The heterogeneity may be explained by the varying risk of bias of included studies, different age groups, and population (athletes participating in different sports and different sport levels) explored in the meta-analysis.

[c] Differences in age (pre versus post pubertal) in included studies may seriously affect the results of the meta-analysis.

[d] All observational studies had poor representativeness of the sample and a half of interventional studies had the high risk of bias due to missing data (see Appendix B).

[e] The heterogeneity may be explained by different types of injuries included in the meta-analysis.

[f] Participants with contact injuries were included into the meta-analysis.

[g] Majority of studies (n = 8) had high or moderate risk of bias due deviations from the intended intervention (adhering to intervention). Five studies had high or moderate risk of bias in selection of the reported results (see Appendix B).

[h] The heterogeneity may be explained by different intervention programs with varying duration.

rial. Overall, GRADE ratings suggest that the strength of evidence in relation to LESS influential factors explored by meta-analysis is very low (Table 2).

The NOS adapted for cross-sectional studies was used for 33 (64%) studies. Out of a maximum of 10 stars, 2 studies scored two stars,[35,39] 4 studies four stars,[40–43] 7 studies five stars,[44–50] 10 studies six stars,[1,18,32,37,38,51–55] 2 studies seven stars,[56,57] 7 studies eight stars,[4,5,19,33,58–60] and 1 study nine stars.[6] The RoB 2 was used for 9 (17%) studies. There was some concern regarding risk of bias in 3 studies[8,61,62] and a high risk of bias in the remaining 6 studies.[7,14–16,36,63] The ROBINS-I was used for 10 (19%) studies. Risk of bias was considered moderate in 4 of these studies[31,34,64,65] and serious in the remaining 6 studies.[17,66–70] The level of evidence ranged between 2 and 4 based on the Oxford Center for Evidence-Based Medicine 2011 table. Studies were most often of level 3 (n = 30, 58%) and cross-sectional in design (n = 25, 48%). Risk of bias scores, level of evidence, and study design of studies are presented in Appendix A in the Supplementary Material. The risk of bias of the studies considered in examining each one of the influencing factors of the LESS is presented in Appendix B in the Supplementary Material. Overall, GRADE ratings suggest that the strength of evidence in relation to LESS influential factors explored by meta-analysis is very low (Table 2).

The Egger's test for funnel plot asymmetry was not significant in any meta-analysis, suggesting that publication bias was not present (Appendix C in the Supplementary Material). The p-values of Egger's test for meta-analysis exploring sex, previous injury, and intervention program were 0.757, 0.914, and 0.072, respectively.

Only Smith et al.[5] compared overall LESS scores between different age categories and reported significantly lower overall LESS scores in older college athletes compared to younger high school athletes. Seven studies[4,6,7,14,61,62,66] tested and reported overall LESS scores for 1997 participants 15 years or younger; 17 studies[5,15,18,31,33,36,38,45,46,49,52,56,58,63,64,67,70] for 1613 participants aged from 15 to 20 years inclusively; and 24 studies[8,17,19,32–35,37,39–44,47,48,51,55,57,59,60,65,67,68] for 4566 participants older than 20 years. The weighted mean LESS scores for participants 15 years or younger was 6.1 ± 1.7, for participants aged from 15 to 20 years was 5.5 ± 1.9, and for participant older than 20 years was 5.1 ± 1.8 errors.

Fourteen studies compared LESS scores between males and females (Table 1). Six studies found females to have significantly higher overall LESS scores compared to males,[1,32,40,46,52,56] six

studies found no significant difference in overall scores between sexes,[5,6,8,45,57,69] and the remaining two studies did not specify if the differences were significant.[14,70] Thirty studies reported overall LESS scores separately for males ($n = 3294$) and females ($n = 1910$), with resulting weighted mean scores for males of 5.0 ± 1.8 and 5.6 ± 1.7 errors for females.

Twelve studies testing 2729 males and 1656 females reported the results in sufficient detail for meta-analysis.[5,8,14,32,40,45,46,52,56,57,69,70] A random effect model was used given the significant and substantial heterogeneity ($Q = 21.34$, $p = 0.030$, $I^2 = 66\%$, Fig. 2A). Findings from the meta-analysis indicate statistically significant higher LESS scores in females than males ($p < 0.001$), but the mean difference of 0.6 [0.4, 0.8] errors was not clinically meaningful (i.e., less than 1 error, Fig. 2A). The quality of evidence was very low according to the GRADE scale (Table 2).

Nine studies compared LESS scores between previously injured and control participants (Table 1). Five of these studies[4,17,33–35] reported significantly higher LESS scores for the previously injured groups compared with controls. The remaining four studies[5,18,45,55] reported no significant difference in scores between previously injured athletes compared with those with no injury history, as well as between athletes who suffered lower extremity injury during a season compared to those who remained injury free during the same season. Weighted mean LESS scores for all previously injured participants ($n = 450$) was 5.7 ± 2.3 errors. Weighted mean scores were 5.5 ± 2.3 for ACL injured or reconstructed ($n = 338$), 5.8 ± 2.4 for other types of injury ($n = 110$), and 4.4 ± 1.9 errors for uninjured controls ($n = 100$).

Eight studies were included in the meta-analysis exploring the difference in LESS scores between previously injured and uninjured participants,[4,5,18,33–35,45,55] with two studies exploring two subgroups of injuries.[18,45] The meta-analysis compared the difference in LESS scores from 208 previously injured participants (98 ACL and 110 other injuries) and 1692 uninjured controls. Given the presence of significant ($Q = 16.95$, $p = 0.031$, Fig. 2B) moderate ($I^2 = 54\%$, Fig. 2B) heterogeneity and two moderators (study-level variables: ACL and other injury), a mixed effect model was used to examine to what extent the type of injury (moderator) influenced the size of the average true effect. The results indicate that participants with a previous ACL injury have statistically significant higher LESS scores ($p = 0.004$), with a clinically meaningful mean difference of 1.2 [0.4, 2.0] errors. LESS scores of participants with other types of previous injury are similar to those of uninjured controls ($p = 0.441$), Fig. 2B. The quality of evidence was very low according to the GRADE criteria (Table 2). A total of 14 studies explored the influence of intervention programs on LESS (Table 1). The explored interventions included diverse injury prevention, isolated resistance training, weight training, military movement course, aquatic training, static warm up, dynamic warm up, standard warm up, and internal, external, and video instruction programs.

External focus and video instructions had significantly greater potential in decreasing LESS scores compared to internal focus instructions.[8] Two studies found that participants with poor landing technique improved the most with training.[14,61] Pryor et al.[7] showed that preventive training programs had a beneficial effect on decreasing LESS scores regardless of coaches and players previous experience with programs.

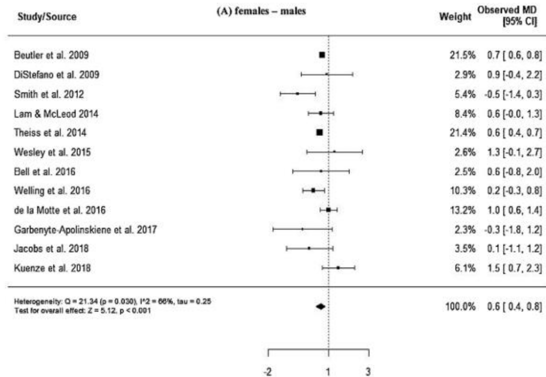
Four studies examined the persistence of LESS score improvements following intervention programs.[16,31,65,66] DiStefano et al.[16] reported that even when training programs improved LESS scores, changes were no longer apparent 6 months post-intervention cessation. Padua et al.[66] compared programs of 3–9 months in duration and found that improved scores remained 3 months post-intervention only in the 9-month group. Oppositely, a 6-week neuromuscular training program improved LESS scores, and improvements were sustained 4[65] and 9 months[31] post intervention cessation.

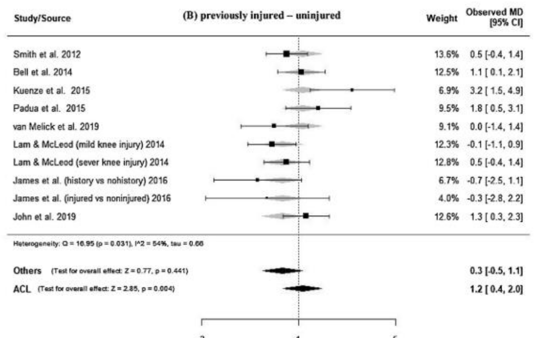
Thirteen studies involving 927 participants and 19 different interventions were included in the meta-analysis exploring the effect of intervention program on LESS scores by comparing differences between pre-intervention and post-intervention scores.[7,8,14,15,31,36,61–63,65–67,70] Note that LESS scores recorded several months post-intervention were not included into the meta-analysis to focus on the more immediate effects of training. Of the participants, 803 completed neuromuscular training programs with a minimum duration of 6 weeks and 124 completed "other" intervention programs. The 6-week threshold for neuromuscular training programs was selected as evidenced to reduce ACL injury rates.[71] Given the presence of significant ($Q = 49.50$, $p < 0.001$, Fig. 2C) moderate ($I^2 = 53\%$, Fig. 2C) heterogeneity and two moderators (study-level variables: neuromuscular and other intervention program), a mixed effect model was used to determine to what extent the type of intervention program (moderator) influenced the size of the average true effect. Meta-analysis indicated that neuromuscular training programs with minimal duration of 6 weeks significantly and meaningfully decreased LESS scores by 1.2 [0.9, 1.5] error ($p < 0.001$). The "other" training programs significantly improved LESS scores from a statistical perspective ($p = 0.042$), however the 0.5 [0.0, 0.9] error difference was not clinically meaningful, Fig. 2C. The quality of evidence was very low according the GRADE criteria (Table 2).

4. Discussion

A single study[5] compared overall LESS scores between younger high school and older college athletes, and found significantly better overall scores in the older athletes. When weighted means of LESS scores were calculated for three age groups (under 15, 15 to 20, and over 21 years), scores were seen to decrease with age. Padua et al.[4] stated that the natural decrease in LESS scores in older athletes could be an effect of maturation or selection in competitive sports that might limit the ability of LESS to predict ACL injury in older athletes. Smith et al.[5] who tested older participants (18.3 ± 2.0 years) compared to Padua et al.[4] (13.9 ± 1.8 years) did not find any predictive values for ACL injury incidence whereas Padua and colleagues[4] identified 5 errors as optimal cut point for distinguishing between athletes with low and high risk. There is strong evidence showing that females have higher risk of non-contact ACL injury compared to males.[72] However, there is no strong evidence of this sex difference in injury rate in prepubertal females.[73] Age also significantly influences the effectiveness of ACL injury prevention neuromuscular programs in females with greater knee injury reduction in those under 18 years compared to older.[73] These findings indicate that age is an important injury risk factor. More evidence is needed to conclude whether age influences LESS score and whether the same threshold is suitable to identify athletes at high risk of injury across different age categories.

It is well documented that on average, females have a four to six times higher incidence of knee injury than males participating in the same sport.[72] Specifically, the risk of non-contact ACL injury is more than double for females compared to males.[72] Several theories have emerged to explain these sex differences in injury rates that include sex-specific hormonal, anatomical, and neuromuscular abilities differences.[74] Despite hormonal involvement in injury incidence being a topic of considerable scientific interest, the overall strength of evidence for hormonal involvement in injury incidence remains still low.[75] Anatomical measures often do not correlate with dynamic injury mechanisms and are difficult to modify.[74] The higher incidence of knee injury seen in female athletes is clearly of multifactorial origin, with specific movement





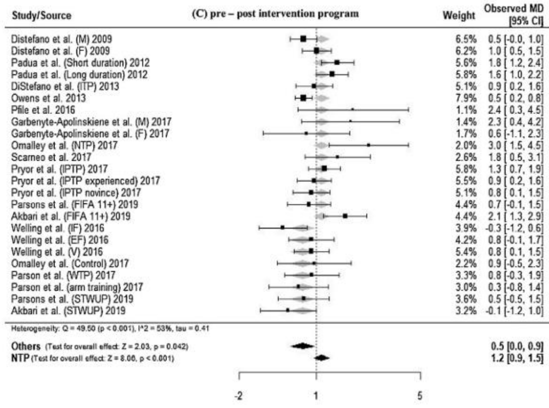


Fig. 2. Forest plots comparing mean difference (MD) in Landing Error Scoring System scores between (A) sexes (females–males), (B) previously injured and uninjured individuals (previously injured–uninjured), and (C) pre and post intervention programs (pre–post). *Abbreviations:* ACL, Anterior Cruciate Ligament injury; CI, Confidential Intervals; EF, external focus instruction; F, females; FIFA, Federation International de Football Association; IF, internal focus instruction; IPTP, injury prevention training program; ITP, integrated training program; M, males; NTP, neuromuscular training program; Q, Cochrane Q; STWUP, standard warm up; V, video instruction; WTP, weight training program. Cochrane Q statistical significance set at $p < 0.10$; statistical significance for overall effect set at $p \leq 0.05$; clinical meaningful effect threshold set at one error. Shaded diamonds in the background represent the two moderators.

patterns and altered neuromuscular control playing an important role in this increased ACL injury risk.[32]

Six studies[1,32,40,46,52,56] reported statistically significant difference in LESS scores ($p \leq 0.05$) between males and females. These studies together included 6446 participants overall with a weighted mean age of 20.2 ± 2.2 years (two studies did not specify mean age). The six other studies who reported no significant difference in LESS scores between males and females[5,6,8,45,57,69] tested 781 participants altogether with a weighted mean age of 15.9 ± 1.5 years. The different mean age between studies reporting statistically significant and non-significant differences between sexes can be one of the underlying reasons for the discrepancy given that mechanics associated with increased risk of injury in females tend to emerge after the pubertal growth spurt (i.e., puberty commonly between 10 and 16 years).[76] The significant differences found in some studies might have been linked to differences in sample sizes; and, albeit being statistically significant, these differences in LESS scores might not have been clinically meaningful. In fact, based on the weighted mean from all studies (mean difference between females and males of 0.6 errors) and results from our meta-analysis (mean difference between females and males of 0.6 errors), the finding of statistically significant higher overall LESS scores in females compared to males is substantiated. However, the difference is not clinically meaningful based on the one error threshold[1]. Risk of bias was high for a number of domains, and the overall GRADE rating suggests very low strength of evidence.

A prior systematic review[77] agrees that previous injuries are a strong risk factor of sustaining not only the same, but also another type, of injury. When dividing previous injury into two subgroups (ACL and others), our meta-analysis identified the ACL group as having meaningfully higher LESS scores from a clinical perspective (mean difference of 1.2 errors) than the control group. The LESS scores of the group with other types of injuries than ACL were not significantly different from control group ($p = 0.441$). One explanation for these findings may be that the LESS was developed to screen for risk of ACL injury, and therefore targets movements linked with this type of injury. That said, knee valgus and stiff landing are movement patterns linked with various non-contact lower extremity injuries,[78] suggesting that the LESS should be a useful screening tool for a range of injuries other than ACL. Two out of three studies exploring the effect of other types of previous injury on LESS[18,45] did not differentiate between contact and non-contact mechanisms of injury (e.g., contusion was recorded as an injury), which could also explain why the meta-analysis identified no significant difference in LESS scores between the other injury and control groups. Furthermore, injures were self-reported in these two studies.[18,45] Research shows that only 61% of athletes accurately recall their 12 months injury history,[79] which highlights the difficulty of using self-reported data in research. On the other hand, John et al.[35] concluded that individuals with chronical ankle instability have significantly higher LESS scores compared to a healthy controls with a meaningful difference of 1.3 errors between groups, suggesting that LESS may be a useful tool for identifying movement patterns linked with injury risk in individuals with ankle instability. Nonetheless, the strength of the evidence regarding the influence of injury on LESS scores was considered very low based on the GRADE scale, and there was high risk of bias in several domains.

The meta-analysis of meta-analysis provide evidence for the effectiveness of neuromuscular training in reducing the incidence of ACL injury.[80] It is therefore logical to expect that intervention programs influence LESS scores. Fourteen studies[7,14–16,31,36,61–63,65–67,70,81,82] together tested 2031 participants and explored the influence of a variety of intervention programs on LESS scores. Seven training programs[7,31,36,63,65,66,70] meaningfully improved LESS scores (change ≥ 1 error), all of which implemented injury prevention training programs with neuromuscular components. O'Malley et al.[36] concluded that injury prevention training programs involving strength, core stability, balance, movement control, plyometric, and agility exercises are statistically significantly superior in decreasing LESS scores compared to usual training methods that do not emphasize neuromuscular control. Training programs with meaningful decreased in LESS scores[7,31,36,63,65,66,70] were implemented in diverse cohort groups, including males and females from 8[7] to 21[65] years of age; soccer,[7,63,66] basketball,[31,70] Gaelic football,[36] and hurling[36] players; and recreational[65] to elite[63] level of sport participation. Given this diversity, it is difficult to ascertain whether sex, age, sport, or sport level also contributed to LESS score improvements following these intervention programs.

From all programs tested, the most effective in improving LESS scores were: (1) plyometric and neuromuscular training programs (decreased scores by 2.4 errors[31]), and (2) neuromuscular training programs with strength, core stability, movement control, plyometric, and agility exercises (decreased scores by 3 errors[36]). Both training[31,36] programs emphasized landing technique, with only one having controls completing their usual training program for comparison.[36] The programs consisted of two to three session per week over six to eight weeks, each lasting approximately 15–30 min. Meta-analysis exploring the effect of intervention on ACL injury incidence[71] highlighted the importance of plyometrics and technique feedback in intervention programs. Both of these components were present in the most effective training programs in improving LESS scores.[31,36] Noteworthy is that both studies involved cohorts with some of the highest pre-intervention mean LESS score (7.3 ± 3.4[31] and 7.1 ± 3.8[36] errors), which could have contributed to their higher relative LESS improvements given research indicating that individuals with the poorest landing technique improve the most with training.[14,61]

The results from our meta-analysis showed that neuromuscular training programs with a minimum duration of 6 weeks meaningfully reduced LESS scores (mean difference: 1.2 errors, $p < 0.001$). Different interventions or training programs with a shorter duration than 6 weeks did significantly reduce LESS scores ($p = 0.042$), but the mean difference of 0.5 error was not clinically meaningful. These finding are in agreement with meta-analysis showing 6 weeks as a minimum duration of intervention programs that can assist in reducing ACL injury incidence[71]. Based on our results, there is evidence that neuromuscular training programs with a minimum duration of 6 weeks can meaningfully influence LESS scores. However, studies disagree in regard to the persistence of the effect once the intervention program stops (e.g., improvements persist up to 9-months versus improvements no longer present at 3-months or 6-months) and the training duration required (e.g., 3-week, 3-month, 9-month programs) for the most optimal and long-term effect.[16,31,65,66] Furthermore, the strength of the evidence was considered very low based on GRADE and high risk of bias was present, notably in relation to adherence, confounding, and selection of reported results.

This systematic review with meta-analysis explored the influence of age, sex, previous injury, and intervention program on LESS scores. The main limitations of this review and associated findings are the varied study design and heterogeneity between studies, risk of bias of the included studies, indirectness and imprecision of outcomes which resulted in very low quality of evidence according to the GRADE scale (Table 2). We included all studies exploring LESS as a main outcome measure regardless of study design, population tested, or risk of bias to systematically review and analyze all the scientific literature available on the topic. However, the results and corresponding interpretations may differ if only randomized control trials with low risk of bias studies were included. Another limitation is the use of the NOS as a risk of bias assessment tool given that there are no specific tools to assess risk of bias in cross-

sectional observation studies. Furthermore, the testing protocols (e.g., sampling frequency of the cameras,[38,52] landing distance,[64] and landing surface[57]) and calculations of total LESS score (mean of three jumps[66] versus the best jump[70]) varied across studies, which can influence LESS scores.[83]

Based on this review of the literature, there is indication that the influence of sex on LESS scores may vary in different age groups (pre versus post puberty). Therefore, it is probable that multiple influencing factors interact with each other. For example, females in puberty age with a history of ACL injury who do not participate in injury prevention programs may have the greatest LESS scores, and males older than 20 years with no previous injury and who have adhered to a neuromuscular training program lasting over 6 weeks potentially exhibit the lowest LESS scores. However, we did not explore this assumption specifically, hence, it is not possible to make conclusions regarding interactions between influencing factors and specifically regarding the influence of sex on LESS scores across different age groups. Moreover, studies that did not differentiate between contact and non-contact mechanisms of injury were included into the meta-analysis, which could explain the lack of significant difference in LESS scores between the other injury and control groups. Given the limited number of studies exploring other injury in this meta-analysis ($n = 3$), we did not explore how the results would change if we excluded those studies involving contact injuries ($n = 2$). Besides sex, age, previous injury, and intervention program, other factors (e.g., fatigue,[17,56,69] sport and competition level,[6,41,46] and strength levels[32,44,51]) may also influence LESS scores; however, these factors were not explored in this review.

5. Conclusion

The goal of this literature review was to critically appraise and summarize research addressing age, sex, previous injury, and intervention program as factors potentially influencing LESS scores. The meta-analysis results provide evidence that sex, previous ACL injury, and training programs significantly influence LESS scores. However, only previous ACL injury and neuromuscular training programs with a minimal duration of 6 weeks were associated with a clinically meaningful change of one error. Our qualitative analysis of the reviewed studies suggests that LESS scores may be influenced by age; however, more evidence is needed to confirm the potential influence of age on LESS scores. These findings, however, should be interpreted cautiously considering the very low GRADE rating of the evidence. Further research is required to enhance our certainty regarding which factors influence LESS scores.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at https://doi.org/10.1016/j.jsams.2020.08.013.

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Appendix A3. *Clinical implications of Landing Error Scoring System calculation methods.*

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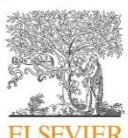

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Original Research

Clinical implications of Landing Error Scoring System calculation methods

I. Hanzlíková [a, *], J. Athens [b], K. Hébert-Losier [a]

[a] Division of Health, Engineering, Computing and Science, Te Huataki Waiora School of Health, Adams Centre for High Performance, University of Waikato, 52 Miro Street, Mount Maunganui, 3116, New Zealand

[b] Department of Preventive and Social Medicine, University of Otago, PO Box 56, Dunedin, 9054, New Zealand

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Objectives: To explore whether final Landing Error Scoring System (LESS) scores differ between calculation methods used in literature.
Design: Cross-sectional.
Setting: Laboratory.
Participants: 328 individuals.
Main outcome measures: LESS scores from 984 drop-jumps were extracted. Final LESS scores were calculated for every participant according to five methods: mean of 3 jumps, 1st jump score, 3rd jump score, best jump score, and sum of errors present in at least 2 jumps. The influence of the calculation method on group mean LESS score and group-level risk categorization using threshold of 5 errors was estimated using Generalized Estimating Equations, with the mean of 3 jumps score set as the reference method. The agreement in individual-level risk categorization was assessed using odds ratios and McNemar's tests.
Results: Compared to the reference, estimated group mean LESS score was 0.92 errors lower ($p < 0.001$) using the best jump method, as was group-level risk categorization (odds ratio: 0.50, $p < 0.001$). Individual-level risk categorization between calculation methods was inconsistent for 8–15% of participants compared to the reference method, significantly different from reference for the best jump score method ($p < 0.001$).
Conclusions: Calculation method meaningfully influences final LESS scores and risk categorization.
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1. Introduction

The Landing Error Scoring System (LESS) is a clinical-based screening tool developed by Padua et al. (2009) used to identify individuals at risk of suffering a non-contact anterior cruciate ligament (ACL) injury through the evaluation of potentially high-risk biomechanical movement patterns. The LESS relies on the use of two standard video cameras to capture motion in the frontal and sagittal planes during three trials of a double-leg vertical drop-jump (VDJ) task. When compared to three-dimensional motion capture systems, which is considered the "gold standard" tool for quantifying human movement, standard two-dimensional video cameras require considerably less financial outlay as well as preparatory time and space to perform the analysis. Therefore, the LESS is more practical for large-scale screening initiatives. To score the LESS, an investigator visually evaluates lower-extremity and trunk kinematics during landing from the video recordings, noting the number of 'movement errors' using a 17-item scoring sheet (Padua et al., 2009). LESS scores range from 0 to 17 errors, where higher scores indicate a greater number of landing errors.

The LESS has been shown to be a reliable screening tool (Hanzlíková & Hébert-Losier, 2020). Although the validity of the LESS against three-dimensional motion capture data has been shown to be strictly item dependent; the items representing the key risk factors for ACL injury were shown to be valid (Hanzlíková & Hébert-Losier, 2020). Padua et al. (2015) evaluated ACL risk in elite-youth soccer players in a prospective study and concluded that LESS scoring exhibited good sensitivity (86%) and acceptable specificity (64%) to identify risk of non-contact ACL injury, ascertaining 5

* Corresponding author. University of Waikato, Adams Centre for High Performance, 52 Miro Street, Mount Maunganui, 3116, New Zealand.
E-mail addresses: xhanzlikova@gmail.com (I. Hanzlíková), josie.athens@otago.ac.nz (J. Athens), kim.hebert-losier@waikato.ac.nz (K. Hébert-Losier).

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errors as the threshold for high injury risk. More specifically, the relative risk of sustaining an ACL injury was 10.7 times greater in individuals with a LESS score of 5 or more (high risk) compared to less than 5 (low risk). In contrast, Smith et al. (2012) did not find any significant relationship between LESS and ACL injury incidence. Differences in sampled populations in terms of age, main sporting event, and previous injury status, as well as lack of statistical power in both studies (Padua et al., 2015; Smith et al., 2012), are potential underlying factors to the diverging findings on the predictive value of the LESS.

Padua et al. (2009) provided operational definitions and scoring details for each item of the LESS on conception, but the authors did not explicitly specify how to compute the final LESS score from the 3 recommended VDJ trials (e.g., whether to use the mean or the best trial). In the footnotes of online Appendix that presented how frequent positive scores were in their population, Padua et al. (2009) stated: "For items 1 to 15, a positive score was defined as an error on at least 2 of the 3 trials. For item 16 and 17, a positive score was defined as Average on at least 2 of 3 trials or Poor/Stiff on at least 1 of 3 trials." These footnotes infer that final LESS scores derived from items where errors were present in at least 2 of 3 trials, but this computational approach was never clearly stated in the methods. Furthermore, in subsequent articles from the same group of authors, the mean score of 3 VDJ trials was used to allocate the final LESS score to individuals (Padua et al., 2012, 2015).

In scientific literature, most studies using the LESS as an outcome measure calculate the final LESS score for an individual as a mean of 3 VDJ trials (Beese, Joy, Switzler, & Hicks-Little, 2015; Beutler, de la Motte, Marshall, Padua, & Boden, 2009; DiStefano et al., 2018; DiStefano, Padua, DiStefano, & Marshall, 2009; Kuenze, Foot, Saliba, & Hart, 2015; Mohammadi, Shojaadin, Letafatkar, Ebrahimi, & Eslami, 2017; Padua et al., 2012; Padua et al., 2015; Pfile, Gribble, Buskirk, Meserth, & Pietrosimone, 2016; Scarneo et al., 2017; Smith et al., 2012; Theiss et al., 2014; Welling, Benjaminse, Gokeler, & Otten, 2016; Wesley, Aronson, & Docherty, 2015), although some studies have used the LESS score of the 1st jump (Onate, Cortes, Welch, & Van Lunen, 2010), 3rd jump (O'Malley, Murphy, Persson, Gissane, & Blake, 2017), or best jump (Garbenytė-Apolinskienė; Šiupšinskas, Salatkaitė, Gudas, & Radvila 2017; Kraus, Schutz, & Doyscher, 2017) for analysis. Additionally, two studies scored an error if the participant demonstrated the specific error in at least 2 of the 3 VDJ trials (Bell, Smith, Pennuto, Stiffler, & Olson, 2014; Pryor et al., 2017). Only a few authors justified their selected calculation methods: Onate et al. (2010) scored the 1st jump only to reduce possible biases between the two raters scoring each participant; whereas Bell et al. (2014) and Pryor et al. (2017) selected the sum of errors present in at least 2 jumps method to analyse the frequency of individual LESS item errors. There is a lack of knowledge on the effect of computational method on the final LESS score and risk categorization of individuals.

It is essential in both research and practice that outcomes from assessments are reproducible and comparable between studies to improve healthcare management and scientific inference. Therefore, our aim was to explore whether final LESS scores significantly differ between calculation methods used in the scientific literature. We hypothesized that the calculation method would significantly influence the estimated group mean LESS score, group-level risk categorization, and individual-level risk categorization, anticipating lower scores and lesser individuals categorized at high risk using the LESS score from the best trial versus the mean of 3 VDJ trials. On the other hand, we expected similar scores between methods based on the mean score from 3 VDJ trials and sum of errors present in at least 2 trials.

2. Methods

2.1. Power analysis

The sample size calculation for this study was based on data from the two methods we assumed would demonstrate the smallest mean difference; (i.e., mean of 3 jumps (Root, Trojian, Martinez, Kraemer, & DiStefano, 2015) and sum of errors present in at least 2 jumps (Pryor et al., 2017)). Sample size requirements were calculated using a customizable statistical spreadsheet (Hopkins, 2006) from standard two-tailed hypothesis equations using an 90% power ($\beta = 0.10$), 5% significance level ($\alpha = 0.05$), critical values of the t distribution, and data from previous studies (Pryor et al., 2017; Root et al., 2015) on similar cohorts (i.e., healthy young individuals). These equations indicated that we needed 273 participants to identify group differences in mean LESS scores between these two calculation methods. To account for 20% of potential withdrawals and missing data, we recruited 328 participants.

2.2. Participants

A sample of 328 participants (167 males and 159 females) volunteered to participate. Age, height, mass, and body mass index (mean ± standard deviation) for males were 18.3 ± 4.0 years (range 15–42 years), 180.9 ± 7.9 cm, 86.7 ± 16.4 kg, and 26.5 ± 4.7 kg/m^2; and for females were 17.8 ± 4.6 years (range 12–41 years), 168.9 ± 6.2 cm, 67.9 ± 12.1 kg, and 23.8 ± 4.0 kg/m^2. All participants were involved in physical activity: On average 3 times per week, 6 h a week. The majority of participants (90%) participated in team sports (53% rugby, 21% netball, 7% soccer, 5% field hockey, and 4% other team sports). Participants had to be free from injury, pain, or any other issue limiting physical activity participation at the time of study participation. Previous injuries were not an exclusion criterion. The study protocol was approved by our Human Research Ethics Committee [HREC(Health)#41] and adhered to the Declaration of Helsinki. All participants and their legal guardian when younger than 16 years of age signed a written informed consent document that explained the potential risks associated with testing.

Table 1
Comparison of the group mean Landing Error Scoring System score between other methods versus reference method using Generalized Estimating Equations.

Method	Mean difference in LESS scores* (error) [95% CI]	p − value*
1st jump score	−0.16 [-0.55 to 0.24]	1.000
3rd jump score	0.07 [-0.34 to 0.48]	1.000
Best jump score	−0.92 [-1.30 to −0.54]	<0.001
Error present in at least 2 jumps	−0.01 [-0.41 to 0.38]	1.000

Mean of 3 jumps was set as the reference method. Abbreviations: LESS, Landing Error Scoring System; CI, confidence interval. * difference versus reference method using the Bonferroni correction.

2.3. Testing procedure

The testing procedure we used was identical to that described by the developers of the LESS (Padua et al., 2009). For the VDJ, we asked participants to jump horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately rebound for a maximal vertical height. The successful trial was defined as jumping off the box with both feet, landing in front of the designated line, jumping as high as possible straight up in the air upon landing from the box, and completing the task in a fluid motion. We did not provide any feedback on participants landing technique unless they were performing the task incorrectly. Participants used their own sport footwear for testing.

After providing instructions and allowing practice jumps for familiarization (typically 1), each participant performed three successful trials of VDJ in front of two standard video cameras capturing at 120 Hz (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8–73.3 mm (35-mm equivalent focal length of 24–200 mm). We mounted the cameras on tripods placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m. We allowed participants to rest until they felt ready to perform the task again to limit fatigue. The total testing time was typically 2 min per participant.

A qualified physiotherapist who completed over 400 LESS evaluations prior to this study replayed the videos using the Kinovea software (version 0.8.15, www.kinovea.org) and scored all trials using the 17-item LESS scoring sheet (Padua et al., 2009). The physiotherapist used the video analysis software as proposed as a mean to improve the psychometric properties of the LESS (Onate et al., 2010). The average scoring time was typically 4 min per one VDJ. The final LESS score was calculated for every participant according to the five methods reported in the scientific literature: 1) mean of 3 jumps, 2) 1st jump score, 3) 3rd jump score, 4) best jump score, and 5) sum of errors present in at least 2 jumps. The overall LESS score demonstrates good-to-excellent intra-rater (ICC = 0.82 to 0.99) and inter-rater (ICC = 0.83 to 0.92) (Hanzlíková & Hébert-Losier, 2020).

2.4. Statistical method

From our data, we assessed the effect of calculation method on: 1) estimated group mean LESS score, 2) group-level risk categorization [proportion of participants categorize at high (LESS $\geq$ 5) and low (LESS < 5) injury risk], and 3) individual-level risk categorization (consistency of high and low injury risk category and odds of being at high risk for individual participants). The mean of 3 jumps method is the most common (Beese et al., 2015; Beutler et al., 2009; DiStefano et al., 2009, 2018; Kuenze et al., 2015; Mohammadi et al., 2017; Padua et al., 2012, 2015; Pfile et al., 2016; Scarneo et al., 2017; Smith et al., 2012; Theiss et al., 2014; Welling et al., 2016; Wesley et al., 2015); therefore, we set the mean of 3 jumps as the reference method in all analyses and compared other methods to the reference method. Note that comparisons between all methods are presented in Appendix A D.

The influence of the calculation method on group mean LESS score and group-level risk categorization was estimated using a Generalized Estimating Equation (GEE) (Liang & Zeger, 1986). We selected the GEE approach as estimates consider the variation within individuals in presence of multiple observations. The GEE approach provides an estimate with its 95% confidence interval [lower, upper] of the average effect in a population, applying robust standard errors to account for within-individual correlations.

We used the GEE model with a Gaussian (normal) distribution to explore the influence of the final LESS score calculation method on the group mean LESS score. It is common in studies using a single trial for the final LESS score calculation to report LESS scores as continuous data (i.e., mean and standard deviation) (Garbenytė-Apolinskienė, Šiupšinskas, Salatkaitė, Gudas, & Radvila, 2017; Kraus et al., 2017; O'Malley et al., 2017) despite the data being ordinal in nature. This approach is fundamentally flawed; however, to be able to compare group mean LESS scores between different calculation methods, we made the assumption that the continuous outcome of the reference method (mean of three jumps) was comparable to the ordinal outcomes of the other methods. We used a GEE model with a binominal distribution to explore the influence of calculation method on group-level risk categorization, estimating the odds ratio of being at high risk of injury for a given method compared to the reference method. Both GEE models applied an exchangeable correlation structure, which assumes that all observations have the same amount of correlation over time. To have more certainty that differences between methods were not due to multiple comparisons, we decided a priori to adjust the 95% confidence intervals and p-values using the Bonferroni method in post-hoc analysis.

To explore the individual-level risk categorization, we assessed the agreement (n and %) in risk categorization with regards to the reference method using odds ratio and McNemar's tests. The odds ratio shows which one of the two methods is more likely to score individuals at high injury risk; i.e., the number of participants at high risk exclusively for a given method divided by the number of participants at high risk exclusively for the reference method. McNemar's test compares two proportions; in our case, whether the proportion of participants at high injury risk for a particular calculation method significantly differs from that of the reference method.

We set a significance level of $p \leq 0.05$ for all analysis. The statistics were computed using Microsoft® Excel for Office 365 MSO and RStudio® version 1.1.463 with R version 3.5.2. All participants finished the study and we analyzed the complete data set.

3. Results

The group mean ± standard deviation (minimum to maximum) LESS score was: 6.07 ± 1.71 errors (0.67–11.67 errors) for the reference method; 5.87 ± 1.87 errors (0–11 errors) for the 1st jump method; 6.10 ± 2.00 errors (1–13 errors) for 3rd jump method; 5.13 ± 1.75 errors (0–11 errors) for best jump score method; and 6.02 ± 1.90 errors (1–13 errors) for sum of errors present in at least 2 jumps method.

3.1. Estimated group mean LESS score

From our data, the GEE model estimated a group mean LESS score of 5.91 [5.73 to 6.10] errors for the reference method. The GEE group mean LESS score estimated from the best jump method was significantly lower than the reference method ($p < 0.001$; Table 1). Comparisons of estimated group mean LESS scores between all methods are presented in Appendix A and B.

3.2. Group-level risk categorization

Table 2 presents the number of individuals categorized at high and low risk of injury for each method. At a group-level, odds of high-risk categorization was significantly lower in the best jump score method compared to the reference method based on GEE analyses (odds ratio 0.50, $p < 0.001$, Table 2). Comparisons of odds ratios between all methods are presented in Appendix C and D.

3.3. Individual-level risk categorization

At an individual level, inconsistency in risk categorization

Table 2
Number of participants at high and low risk and Generalized Estimating Equation of the group-level risk categorization.

Method	Participants at high risk	Participants at low risk	Odds ratio* [95% CI]	p − value*
Reference method	76% ($n = 249$)	24% ($n = 79$)	–	–
1st jump score	77% ($n = 251$)	23% ($n = 77$)	1.03 [0.75 to 1.43]	1.00
3rd jump score	80% ($n = 261$)	20% ($n = 67$)	1.24 [0.90 to 1.69]	0.569
Best jump score	61% ($n = 201$)	39% ($n = 127$)	0.50 [0.39 to 0.65]	<0.001
Error present in at least 2 jumps	79% ($n = 260$)	21% ($n = 68$)	1.21 [0.94 to 1.57]	0.333

Mean of 3 jumps was set as a reference method. Abbreviations: CI, confidence interval. Odds ration greater than 1.00 indicate higher odds of high injury risk category for given method compared to the reference method. *comparing other methods with reference method using the Bonferroni correction.

compared to the reference method ranged from 8 to 15% across methods (Table 3). The individual-level risk categorization was significantly different for the best jump score compared to the reference method ($p < 0.001$, Table 3), with a greater number of individuals exclusively at high risk for the reference method.

4. Discussion

The use of clinical tools such as the Landing Error Scoring System (LESS) to assess injury risk is common in sport science and clinical practice (Dallinga, Benjaminse, & Lemmink, 2012; McCall et al., 2015). It is essential that clinical tools provide outcomes that are reproducible and comparable between practitioners and studies to improve healthcare management and scientific inference. The authors who introduced the LESS to the scientific community did not explicitly specify the method used to calculate the final LESS score (Padua et al., 2009). As a result, five different calculation methods have been reported in the literature. This paper explored the influence of these five calculation methods on estimated group mean LESS scores, group-level risk categorization, and individual-level risk categorization. We provide clinically meaningful evidence that the LESS calculation method can affect clinical outcomes and their interpretation and result in altering injury risk classification of participants and affecting injury prevention efforts.

LESS data are commonly averaged and compared between (e.g., males versus females, injured versus uninjured) or within (e.g., pre versus post intervention) groups to make clinical inferences (DiStefano et al., 2018; Pryor et al., 2017; Smith et al., 2012). When we compared estimated group mean LESS scores using different calculation methods, we found that the best jump method led to lower LESS score estimates (0.92 errors, $p < 0.001$) compared to the reference method. According to a literature review exploring the psychometric properties of the LESS (Hanzlíková & Hébert-Losier, 2020), the standard error of measurement (SEM) for intra-rater reliability is 0.19–0.52, inter-rater reliability is 0.71, and test-retest reliability is 0.81. These SEM values indicate that the magnitude of the difference in estimated group mean LESS score between the best jump and reference calculation methods is clinically meaningful. According to Padua et al. (2009), poor LESS scores are associated with decreased peak knee and hip flexion angles, and increased peak knee valgus angles and moments, all of which have been associated with high injury risk landing strategies (Hewett et al., 2005). Basing the final LESS score of individuals on their best jump (i.e., the trial with the lowest number of errors) may mask their innate risk of injury and habitual movement patterns. The greatest similarity with the reference method was the 3rd jump score and score with an error present in at least 2 jumps. To score only the 3rd jump rather than all three jumps could be beneficial for large scale screening initiatives, as it would decrease the total scoring time and associated costs, yet still reflect typical group-level performance according to our analyses.

On the other hand, when the group-level risk categorization (number of participants at high and low injury risk) is of interest, the odds of being categorized at high risk of injury was significantly lower using the best jump score method compared to the reference one (odds ratio 0.50, $p < 0.001$). This significant difference in risk classification between methods could lead to different interpretations of clinical and research outcomes. The 1st jump score calculation method was the most comparable to the reference method in terms of risk categorization at a group-level (odds ratio 1.03). The 1st jump score method could be suitable for use when the proportion of participants at high and low injury risk is of interest, and when the time available for testing and scoring is limited as it only requires completing of a single VDJ instead of three. Although not as similar in magnitude to the reference method in terms of group mean LESS scores compared to the 3rd jump score method (see Table 2), using the 1st jump score might offer the best compromise in terms of reflecting LESS data from three trials and risk categorization at a group level.

Previous literature reviews and meta-analyses provide evidence for the effectiveness of neuromuscular training programs in reducing the incidence of sport injuries (Hübscher et al., 2010; Yoo et al., 2010), including ACL. For injury prevention programs to be cost-effective and efficient, identifying individuals at high injury risk is important. In individual-level risk categorization, the method most consistent (92%) with the reference method was that of scoring errors present in at least 2 jumps, although participants were more likely to be categorized at high risk of injury exclusively for this method (19 participants) compared to exclusively for the reference method (8 participants). The advantage of the errors present in at least 2 jumps method is that it reflects the typical

Table 3
Individual-level risk categorization. Four calculation methods are compared to the reference method (mean of 3 jumps).

Method	Consistent[a]	Inconsistent[a]	High risk given method[b]	High risk reference method[b]	Odds ratio[c] [95% CI]	McNemar's test p − value*
1st jump score	85% ($n = 280$)	15% ($n = 48$)	$n = 25$	$n = 23$	1.09 [0.62 to 1.92]	0.885
3rd jump score	88% ($n = 288$)	12% ($n = 40$)	$n = 26$	$n = 14$	1.86 [0.97 to 3.56]	0.081
Best jump score	85% ($n = 280$)	15% ($n = 48$)	$n = 0$	$n = 48$	–	<0.001
Error present in at least 2 jumps	92% ($n = 301$)	8% ($n = 27$)	$n = 19$	$n = 8$	2.38 [1.04 to 5.43]	0.052

Abbreviations: CI, confidence interval. *p-value: difference in individual-level risk categorization versus reference method.
[a] Participants categorized consistently/inconsistently versus the reference method.
[b] Participants categorized at high risk exclusively for a given/reference method.
[c] The number of participants at high risk exclusively for a given method divided by the number of participants at high risk exclusively for the reference method.

errors of an individual. Practitioners can use this information to target these faulty movement patterns in individual preventative programs. The other calculation methods had a 12–15% inconsistency in risk categorization compared to the reference method, reaching statistical significance for the best jump score method ($p < 0.001$). The odds ratio for the best jump score compared to the reference method is infinity, as the best jump score (jump with the lowest number of errors) will always have a similar or lower number of participants at risk when compared to the reference method (mean of 3 jumps).

Scoring a single trial may sometimes be needed when resources (time or finance) are constrained or to answer a specific question, such as to determine the best possible performance of a person. However, it is important to note limitations in the use of a single trial to encapsulate an individual's movement patterns. Given that variability is present in all human movement, using a single trial may result in a poor representation of an individual's inherent movement variability. More specifically, a single trial protocol may by chance represent a typical performance, but also an atypical one. Using a single trial has been proposed invalid and unreliable for testing human movement (Bates, Dufek, & Davis, 1992). Previous studies have concluded that averaging a minimum of four trials is needed to achieve stability in ground reaction force variables during double-leg landing (James, Herman, Dufek, & Bates, 2007); eight to thirteen trials for stable mean ankle, knee, and hip kinetic values during double-leg jumping (Rodano & Squadrone, 2002); and twenty strides for stable kinematic and spatiotemporal values whilst running on a treadmill (Riazati, Caplan, & Hayes, 2019). Hence, the LESS calculation method using the mean of the 3 trials or sum of errors present in at least two jumps are recommended over single trial methods to represent typical movement patterns.

The main limitation of this study is that group-level and individual-level risk categorization were based on a threshold of 5 errors per Padua et al. (2015). This threshold derives from a population of young (13.9 ± 1.8 years) elite male and female soccer players and might not be appropriate for our population of predominantly young physically active adults (18.1 ± 4.3 years). Another limitation is that we set the mean of 3 jumps as a reference method given its frequent use (Beese et al., 2015; Beutler et al., 2009; DiStefano et al., 2009, 2018; Kuenze et al., 2015; Mohammadi et al., 2017; Padua et al., 2012, 2015; Pfile et al., 2016; Scarneo et al., 2017; Smith et al., 2012; Theiss et al., 2014; Welling et al., 2016; Wesley et al., 2015) even though this method is not necessarily a "gold standard" method. It is important to note that our study assessed the difference between LESS computational methods on scores and risk categorization of individual. Our study did not assess which scoring method has the greatest predictive ability, with only the mean of 3 jumps method used for this purpose to date (Padua et al., 2015; Smith et al., 2012). Moreover, the Bonferroni method used to adjust 95% confidence intervals and p-values during post-hoc comparisons is a conservative method and could inflate Type II error. However, the interpretation of our results would not be altered by changing the adjusting method given how far away our p-values were from the set significance level of $p \leq 0.05$.

5. Conclusion

This paper found that final LESS score calculation methods can influence estimated group mean LESS scores, group-level risk categorization, and individual-level risk categorization to various extents. In line with our expectations, the best jump method exhibited the greatest difference in group mean LESS score from the reference method. The significant difference of 0.92 errors in LESS score between methods is clinically meaningful based on reported psychometric properties across the scientific literature (Hanzlíková & Hébert-Losier, 2020); and therefore, interpreting results from studies or clinical practices using the best jump computational method in relation to the reference method should be done with caution. Using the mean score from the 3 DVJ trials is the most common in the scientific literature and the only one with demonstrated predictive ability (Padua et al., 2015; Smith et al., 2012), and hence, likely the most justifiable. However, when there are time or financial restrictions, scoring the 3rd jump offers a suitable option when mean group score is of interest, whereas scoring the 1st jump is a viable option when the group-level risk categorization is of interest. When both are of interest, the former option offers the best compromise. Clinicians should bear in mind that human movement is variable and that scoring a single trial only may not represent the typical performance of an individual. Selecting the mean of 3 trials or sum of errors present in at least 2 trials methods reflects typical LESS performance and individual movement errors than single trial methods. The different LESS calculation methods provide different information, outcomes, and clinical interpretations that need consideration in research and practice.

Ethical statement

The study protocol was approved by our institution's health research ethics committee [HREC(Health)#41] and adhered to the Declaration of Helsinki. All participants and their legal guardian when younger than 16 years of age signed a written informed consent document that explained the potential risks associated with testing.

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Declaration of competing interest

None declared.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2020.04.035.

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Appendix A4. *Landing Error Scoring System scores change with knowledge of scoring criteria and prior performance.*

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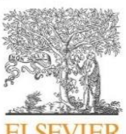

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Original Research

Landing Error Scoring System scores change with knowledge of scoring criteria and prior performance

Ivana Hanzlíková*, Kim Hébert-Losier

Division of Health, Engineering, Computing and Science, Te Huataki Waiora School of Health, University of Waikato, Adams Centre for High Performance, New Zealand

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A B S T R A C T

Objective: To examine if the knowledge of scoring criteria and prior performance influence Landing Error Scoring System (LESS) outcomes.
Design: Cross-sectional.
Setting: Laboratory.
Participants: Thirty individuals.
Main outcome measures: The LESS was tested at *Baseline* and one week later under two conditions: *Pre* and *Post* information. For the *Post* condition, LESS items were explained to participants, as were their individual *Baseline* scores. Mean LESS scores and number of individuals categorized at high and low risk were compared between *Pre* and *Post* using paired *t*-tests and McNemar's tests, respectively. McNemar's tests were also used to compare proportions of specific LESS errors between *Pre* and *Post* conditions.
Results: Mean LESS *Post* scores (4.7 ± 1.2 errors) were significantly lower than *Pre* scores (6.6 ± 2.0 errors, $p < 0.001$) as was the number of individuals at high risk (25 vs 10 participants, $p < 0.001$). A significantly lower proportion of participants scored an error for the joint displacement item of LESS *Post* compared to *Pre* condition ($p < 0.001$).
Conclusion: When using the LESS, it is important that tested individuals have no knowledge of scoring criteria or previous errors for a valid assessment of innate jump-landing movement patterns and injury risk.

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1. Introduction

Lower-extremity injuries are common in sport and are associated with health burden and socioeconomic costs (Knowles et al., 2007). Biomechanical and neuromuscular factors play an important role in non-contact lower-extremity injuries, and are potentially modifiable through preventive programs (Emery, Roy, Whittaker, Nettel-Aguirre, & Van Mechelen, 2015; Webster & Hewett, 2018). Therefore, several movement screens have been developed and are used daily to help clinicians identify individuals at high risk of non-contact injuries and inform injury prevention efforts (Cook, Burton, & Hoogenboom, 2006; Dos'Santos et al., 2019; Myer, Ford, & Hewett, 2008; Padua et al., 2009; Plisky et al., 2009).

The Landing Error Scoring System (LESS) is a movement-based injury risk screening tool that is easy to administer, suitable for testing large cohorts, and can be used both in clinics and in the field without expensive laboratory equipment (Padua et al., 2009). The LESS involves the performance of a double leg jump-landing task and relies on the use of two standard video cameras, one placed to capture frontal plane motion and the other to capture sagittal plane motion. Using the video recordings to score the LESS, an examiner visually evaluates movement patterns and notes the number of "movement errors" using a 17-item scoring sheet (Table 1). The movement errors are aberrant lower-extremity and trunk movement patterns that have been suggested as factors contributing to non-contact lower-extremity and Anterior Cruciate Ligament (ACL) injuries (Hewett, Ford, Hoogenboom, & Myer, 2010). For instance, several LESS items (items: 1 to 4, 12 to 14, and 16, Table 1) are linked to a stiff landing technique, which results in increased ground reaction forces and loading of joint structures (Laughlin et al., 2011). The magnitude of ground reaction forces has been associated with

* Corresponding author. University of Waikato, Adams Centre for High Performance, 52 Miro Street, Mount Maunganui 3116, New Zealand.
E-mail addresses: ih27@students.waikato.ac.nz (I. Hanzlíková), kim.hebert-losier@waikato.ac.nz (K. Hébert-Losier).

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Table 1
Landing Error Scoring System (LESS) specific errors.

No	Item	Definition of error	Number (percentage) of errors[a]		p-value[b]
			Pre	Post	
1.	Knee flexion at IC	Knee flexion <30° at IC	11 (37%)	13 (43%)	0.791
2.	Hip flexion at IC	Thigh is in line with the trunk (i.e., hips not flexed) at IC	0 (0%)	0 (0%)	1.000
3.	Trunk flexion at IC	Trunk is vertical or extended at the hips (i.e., not flexed) at IC	0 (0%)	0 (0%)	1.000
4.	Ankle plantar flexion at IC	Heel-to-toe or flat foot landing at IC	8 (27%)	3 (10%)	0.125
5.	Knee valgus at IC	Center of the patella is medial to the midfoot at IC	10 (33%)	14 (47%)	0.289
6.	Lateral trunk flexion at IC	Midline of the trunk is flexed to the left or the right side of the body at IC	11 (37%)	14 (47%)	0.607
7.	Stance width (wide)	Feet are positioned greater than shoulder width apart (acromion processes) at IC	7 (23%)	14 (47%)	0.065
8.	Stance width (narrow)	Feet are positioned less than shoulder width apart (acromion processes) at IC	10 (33%)	5 (17%)	0.125
9.	Foot position (toe-in)	Foot is externally rotated more than 30° between IC and MKF	0 (0%)	0 (0%)	1.000
10.	Foot position (toe-out)	Foot is internally rotated more than 30° between IC and MKF	12 (40%)	9 (30%)	0.065
11.	Symmetric foot contact at IC	One foot lands before the other foot or 1 foot lands heel to toe and the other foot lands toe to heel	21 (70%)	12 (40%)	0.064
12.	Knee flexion displacement	Knee flexes less than 45° between IC and MKF	5 (17%)	0 (0%)	0.063
13.	Hip flexion at MKF	Thigh does not flex more on the trunk between IC and MKF	1 (3%)	0 (0%)	1.000
14.	Trunk flexion at MKF	Trunk does not flex more between IC and MKF	9 (30%)	0 (0%)	0.004
15.	Knee valgus displacement	At the point of maximum medial knee position, the center of the patella is medial to the midfoot	16 (53%)	9 (30%)	0.065
16.	Joint displacement	Joint displacement: *Soft, Average, Stiff*	25 (83%)	7 (23%)	<0.001[c]
17.	Overall impression	Overall impression: *Excellent, Average, Poor*	30 (100%)	30 (100%)	1.000

Abbreviations: IC, initial contact; MKF, maximum knee flexion; No, number.
[a] Number (percentage) of participants scored error on specific LESS item. For items 1 to 15, error was marked as present when the specific LESS error was present in at least 2 of 3 trials. For items 16 and 17, error was marked as present when the "*Average*" rating was present in at least 2 of 3 trials or "*Poor/Stiff*" rating in at least 1 of 3 trials (Padua et al., 2009).
[b] McNemar's test *p*-values comparing the proportion of specific errors scored for LESS items.
[c] Significantly different between conditions based on Bonferroni-corrected p-value ≤ 0.003.

increased lower-extremity injury risk, including to the ACL (de Noronha, Refshauge, Herbert, & Kilbreath, 2006; Leppänen et al., 2017). Furthermore, knee valgus angle (items 5 and 15, Table 1) and lateral trunk flexion angle (item 6, Table 1) have been identified as strong predictors of knee ligament injuries in prospective studies (Hewett et al., 2005; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). The remaining items (items 7 to 11, Table 1) are hypothesized to contribute to ACL injury; however, stronger evidence is still needed. LESS scores range from 0 to 17 errors, where greater scores indicate more movement errors and poorer landing biomechanics (Padua et al., 2015). A prospective study has identified a 10.7 times greater relative risk of sustaining a non-contact ACL injury in presence of a LESS score ≥5 errors versus <5 errors (Padua et al., 2015).

A recent systematic review of the literature concluded that the overall LESS score has good to excellent intrarater (intraclass correlation coefficient [ICC], 0.82–0.99), interrater (ICC, 0.83–0.92), and intersession (ICC, 0.81) reliability (Hanzlíková & Hébert-Losier, 2020). Validity of the overall LESS score against 3-dimensional (3D) jump-landing biomechanics was good when individuals were divided into four quartiles based on LESS scores, although the validity of the individual LESS items was item dependent (Onate, Cortes, Welch, & Van Lunen, 2010; Padua et al., 2009). However, most of the items addressing key risk factors for ACL showed moderate-to-excellent validity versus 3D motion capture data (Onate et al., 2010). Padua et al. (2015) identified 5 errors as an optimal cutoff point for non-contact ACL injury in a prospective investigation, yielding a sensitivity of 86%, specificity of 64%, and 10.7 times greater relative risk.

For any clinical assessment, it is essential that testing methods provide outcomes that are valid and that changes in scores reflect meaningful changes in function of individuals and identify individuals with differing abilities. Previous studies showed that knowledge of scoring criteria can potentially compromise the clinical utility of the injury risk screening tool (Bryson, Arthur, & Easton, 2018; Frost, Beach, Callaghan, & McGill, 2015). Frost et al. (2015) demonstrated that professional firefighters could significantly improve their performance on the Functional Movement Screen™ (FMS) once provided with information regarding the scoring criteria. Bryson, Arthur, & Easton (2018) confirmed Frost et al. (2015) findings employing a randomized control trial design involving male professional soccer players. The FMS evaluates imbalances in mobility and stability during seven fundamental movement patterns, which are rather slow and controlled movements in nature compared to the more dynamic jump-landing task employed during the LESS.

Besides knowledge of scoring criteria, feedback on performance is able to alter movement patterns (Myer et al., 2013). A meta-analysis exploring the effect of intervention on ACL injury incidence (Sugimoto et al., 2016) highlighted the importance of plyometrics and technique feedback in intervention programs. Therefore, jump-landing technique feedback is commonly used in clinical practice and research and is also emphasized in injury prevention programs which meaningfully improved LESS scores by 2.4–3.0 errors (O'Malley, Murphy, Persson, Gissane, & Blake, 2017; Pfile, Gribble, Buskirk, Meserth, & Pietrosimone, 2016). Examples of instructions used to improve jump-landing technique include: land softly, on your toes and your knees bend; bend hips, knees, and ankles slightly and lean upper body forward; do not let your knee buckle inward; keep upper body stable (O'Malley et al., 2017; Pfile et al., 2016). All these instructions closely correspond with items assessed during LESS scoring (Table 1).

It is common in clinical practice and sport settings to explain LESS items and give feedback on individual's landing technique after the LESS test. Furthermore, jump-landing technique feedback has been shown to meaningfully improve LESS scores when integrated as part of injury prevention programs (O'Malley et al., 2017; Pfile et al., 2016). It may be that feedback on prior performance may instantly improve LESS scores regardless of adhering to a specific injury prevention program. Similar to the FMS, it is possible that participants are able to alter performance during the LESS with knowledge of scoring criteria albeit being more dynamic in nature than the FMS tasks. Therefore, our aims were to compare LESS scores, risk categorization, and specific LESS errors before and after the provision of the LESS scoring criteria and information on individuals' performance. We hypothesized that knowing the scoring

criteria and individuals' movement errors would lead to lower LESS scores, a lower number of participants being classified at high risk of injury and alter the proportion of specific errors on the LESS.

2. Methods

2.1. Participants

Sample size requirements were calculated using a G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007) from paired *t*-test two-tailed hypothesis equations using an 80% power ($\beta = 0.20$), 5% significance level ($\alpha = 0.05$), critical values of the *t* distribution, and the data from previous studies (Hanzlíková & Hébert-Losier, 2020; Padua et al., 2009). These studies indicated one error as a clinically meaningful difference in LESS scores (Padua et al., 2009) and 1.7 errors as the typical LESS standard deviation (Hanzlíková & Hébert-Losier, 2020). The equations indicated that we needed 25 individuals to identify clinically meaningful differences in LESS score before and after the provision of the scoring criteria and information on an individual's own performance. To account for 20% of potential withdrawals and missing data, we recruited 30 participants.

Thirty young adults (15 males, 15 females) volunteered to participate in the study. Age, height, and mass (mean ± standard deviation) for males were 21.8 ± 4.8 years (range 19–39 years), 179.4 ± 6.5 cm, and 81.3 ± 14.4 kg; and for females were 21.3 ± 3.7 years (range 19–32 years), 168.7 ± 7.0 cm, and 68.6 ± 9.4 kg. All participants were involved in physical activity 3 times per week (median) for on average 6.7 ± 6.3 h a week. Participants had to be free from injury, pain, or any other issues that would limit physical activity participation. Previous injuries were not an exclusion criterion. The study protocol was approved by our institution's health research ethics committee [HREC(Health)#41] and adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks associated with testing.

2.2. Procedures

We used a repeated measure study design to examine whether individuals' awareness of the LESS scoring criteria and performance would alter LESS scores, risk categorization, and specific LESS errors. Thirty participants performed 3 × 30-cm double leg jump-landing tasks (DLJL) for LESS scoring at *Baseline*. A qualified physiotherapist (IH) who completed over 400 LESS evaluations replayed the videos using the Kinovea software (version 0.8.15, www.kinovea.org) and scored all three trials using the 17-item LESS scoring sheet (Table 1). One week later, the participants performed three DLJL again, once *Pre* information and once *Post* information. Following the *Pre* condition, all 17 items used for scoring (Table 1) were explained to participants with pictures showing errors for each item. The participants were also given their individual LESS scores from *Baseline* testing that specified their own movement errors for each one of the three *Baseline* jumps. After the 20-min education session, participants performed three DLJL to obtain LESS scores *Post* information. The identical verbal instructions were given to participants in all three session, i.e. participants were not specifically instructed to change their landing technique based on their individual's errors. The same assessor (IH) collected data and scored LESS trials in all three instances. A random subsample of 10 jump-landings was scored three times by the assessor to determine the intra-rater reliability. Assessments were separated by a minimum of one week, with the assessor blinded to the previous assessment scores. The intraclass correlation coefficient was 0.96 and the standard error of the measurement was 0.23 error. The assessor was blinded to participants *Baseline* scores and to *Pre* and *Post* time points.

The original LESS protocol and scoring per Padua et al. (2009) were used in all three instances (*Baseline*, *Pre*, and *Post*). Participants jumped horizontally from a 30-cm box to a line placed at 50% of their body height, and immediately jumped upward for maximal vertical height. Participants were instructed to jump off the box with both feet, land in front of the designated line, jump as high as possible upward upon landing, and complete the task in fluid motion. No feedback on landing technique was provided unless participants were performing the task incorrectly. Participants were given as many practice trials as needed to become comfortable with the task (typically one) and were allowed to rest between trials until they felt ready to perform the DLJL again to limit fatigue. In all instances, the DLJL were recorded by two standard video cameras capturing at 120 Hz (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8–73.3 mm (35-mm equivalent focal length of 24–200 mm). We mounted the cameras on tripods placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m.

2.3. Statistical analysis

The mean LESS score from the three DLJL trials, number of individuals categorized at high (LESS $\geq$ 5 errors) and low (LESS < 5 errors) injury risk (Padua et al., 2015), and number of specific LESS errors were used for statistical analysis. Group mean LESS scores between *Pre* and *Post* conditions were compared using mean differences (MD) with 95% confidence intervals [lower, upper], two-tailed paired *t*-tests, and corresponding effect sizes (Hedge's *g*) with 95% confidence intervals. Thresholds for interpreting the magnitude of Hedge's *g* were set at 0.2, 0.5, and 0.8 for *small*, *medium*, and *large* effects (Lakens, 2013). Effect sizes <0.2 were considered *trivial* (Lakens, 2013).

McNemar's tests were used to compare the proportion of participants categorized at high and low injury risk between *Pre* and *Post* conditions. McNemar's test compares proportions; in our case, the proportion of participants at high risk exclusively for one condition compared to the proportion of participants at high risk exclusively for a second condition. McNemar's tests were also used to compare the proportion of specific LESS movement errors between *Pre* and *Post* conditions. For LESS items 1 to 15 (Table 1), an error was marked as present when the specific LESS error was present in at least 2 of 3 trials. For items 16 and 17 (Table 1), error was marked as present when the "*Average*" rating was present in at least 2 of 3 trials or "*Poor/Stiff*" rating in at least 1 of 3 trials (Padua et al., 2009).

Statistical significance level was set at $\alpha \leq 0.05$. Given the number of statistical comparisons used to compare the proportion of specific LESS movement errors between conditions ($n = 17$), the Bonferroni-corrected *p*-value ($p \leq 0.003$) was used to infer statistical significance in this analysis to reduce the likelihood of type 1 errors. The statistics were computed using Microsoft Excel® for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2.

3. Results

All participants finished the study and the complete data set was analyzed. The mean LESS scores of individuals ranged from 1.7 to 11.0 errors. *Post* information mean LESS scores were significantly lower than *Pre*, with a mean difference of −1.9 [-2.9 to -1.0] errors ($p < 0.001$, Fig. 1). The effect of condition on mean LESS scores was large (Hedge's *g* 1.2 [0.5 to 1.9]). The number of participants at high injury risk was significantly lower *Post* information compared to *Pre* information condition (McNemar's test $p < 0.001$, Fig. 2). *Post*

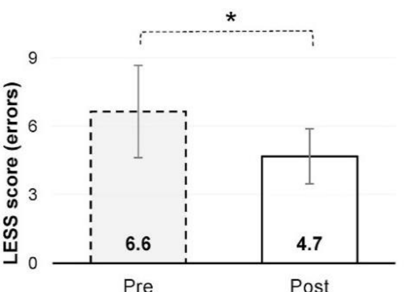

Fig. 1. Group mean Landing Error Scoring System (LESS) scores. Error bars represent standard deviations. * Indicate paired t-test $p < 0.001$.

information, 17 (57%) participants changed their injury risk categorization from high to low, 11 (37%) participants remained in the same category, and 2 (6%) participants went from low to high injury risk compared to the *Pre* information condition. Table 1 presents the proportion of specific LESS errors during the *Pre* and *Post* information conditions. Proportion was significantly lower for item 16: Joint displacement *Pre* compared to *Post* condition ($p < 0.001$).

4. Discussion

The LESS is a clinical screening tool used to identify high injury risk movement patterns from a jump-landing task. Individuals can alter their performance on movement screens with prior knowledge of scoring criteria (Bryson, Arthur, & Easton, 2018; Frost et al., 2015) or feedback on their performance (Myer et al., 2013). Our results confirm that individuals can improve their LESS scores, alter their risk category, and affect specific LESS errors after being provided with scoring criteria and information regarding their own prior performance. These results highlight how knowledge of scoring criteria and feedback can affect changes in movement patterns acutely and might be a useful training tool to raise awareness and encourage lower-risk movement patterns. However, if the innate jump-landing movement patterns and injury risk of individuals are of interest, it is recommended to abstain from providing individuals with their individualized item scores following LESS testing or explaining LESS scoring criteria for a valid assessment of risk.

Post information, mean LESS scores were 1.9 errors lower than *Pre* information. This 1.9-error difference is clinically meaningful based on Padua et al. (2009) who identified one error change in total LESS score to be clinically meaningful as associated with moderate to large differences in biomechanical variables previously linked to ACL injury. Our results are supported by previous research showing meaningful improvements in kinetic and kinematic variables after training focusing on correct technique feedback (Storberget, Grødahl, Snodgrass, van Vliet, & Heneghan, 2017). Previous literature reviews have emphasized the importance of incorporating technique feedback in ACL injury prevention programs (Sugimoto et al., 2016) and in the rehabilitation of musculoskeletal lower-extremity injuries (Storberget et al., 2017). Technique feedback has been shown effective in improving jump-landing biomechanics in a manner that would reduce ACL injury risk (Nyman & Armstrong, 2015; Storberget et al., 2017). Furthermore, Myer et al. (2013) concluded that augmented feedback targeting deficits during the tuck jump assessment was effective in improving biomechanics during a different drop vertical jump task, which supports a transfer of skills and movement pattens across tasks after provision of feedback. Altogether, these studies indicate that technique feedback is a useful tool in prevention and rehabilitation of injuries.

Within one education session, our participants were able to decrease LESS scores to a greater extent than following neuromuscular training programs for several weeks (Owens et al., 2013; Padua et al., 2012; Pryor et al., 2017). In a study conducted by Root, Trojian, Martinez, Kraemer, and DiStefano (2015), participants improved their LESS scores by 0.5 error after a single 10 to 12-min injury prevention session; however, no improvements were found after static or dynamic warm-up sessions of the same duration. Compared to static and dynamic warm-up programs, the injury prevention program included balance and plyometric exercises and concentrated on proper technique using cues, such as "land softly", "bend your knees and hips", "keep your toes facing forwards", and "keep your knees over your toes" (Root et al., 2015). These findings highlight the powerful impact of short interventions on changing

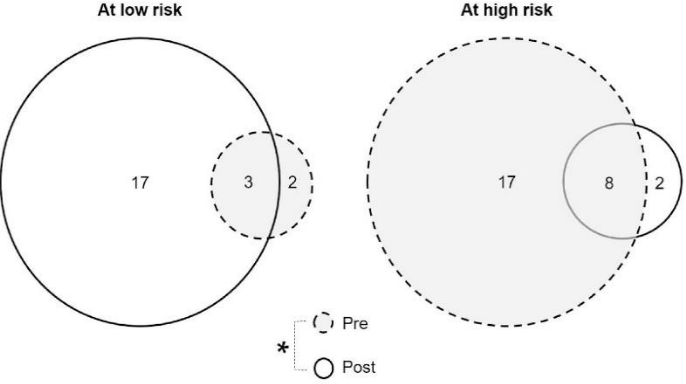

Fig. 2. Venn diagrams representing the number of participants at high (LESS ≥ 5 errors) and low (LESS < 5 errors) injury risk for each condition. The sum of all values within one circle represents the number of participants categorized at high/low injury risk for given condition. Overlapping circles show the number of participants consistently scored at high/low risk within both conditions. LESS, Landing Error Scoring System. * Indicate McNemar's test $p < 0.001$.

movement patterns acutely when interventions focus on awareness of low-risk movement mechanics and feedback. It appears that explaining scoring criteria representing low and high-risk biomechanics and specific feedback on participant's prior performance used in our study is superior to improve LESS scores in the short term compared to real-time feedback provided during injury prevention programs, such as used in Root et al. (2015). However, further targeted research is needed to confirm these speculations.

Individuals may perform better on clinical tests with knowledge of test scores and grading criteria without any long-lasting neuromuscular or physiological adaptations from training or rehabilitation and therefore reducing the screen's ability to identify individuals presenting high-risk movement patterns during jump-landing tasks. Previous study findings regarding the effect of internal and external focus instructions on the LESS indicated that instructions can significantly improve LESS scores immediately after a training session, and that improvements can persist in some – but not all – individuals one week post testing (Welling, Benjaminse, Gokeler, & Otten, 2016). It is questionable whether one education session focusing on knowledge of scoring criteria and technique feedback is able to change innate movement patterns and injury risk factors, or whether participants are simply more aware of movement biomechanics needed to perform well during this particular injury risk screening task. Examining the performance of participants at a later date (e.g., 4–8 weeks) would have provided insight into the persistence of learnings or reversion to innate movements. Padua et al. (2012) compared the effectiveness of 3 and 9-month injury prevention programs that included landing technique feedback and concluded that improved LESS scores remained 3 months post intervention only in the 9-month program group. Therefore, it seems that long-lasting intervention programs specifically designed to change movement patterns are needed to alter LESS scores in the long term. To date, there is no evidence to our knowledge that links improvements in LESS scores with changes in the innate movement patterns of individuals or changes in high-injury risk sport-specific movement patterns, such as cutting or pivoting.

When seeking to identify individuals with high injury risk movement patterns, there is arguably more value in assessing innate movement behavior as opposed to immediate movement behavior influenced by knowledge of scoring criteria or prior performance. Therefore, before more evidence is available on persistence of LESS score improvements after one technique feedback session, we recommend clinicians abstain from providing individuals with their individualized item scores following LESS or from explaining LESS scoring criteria if the test is to be used to capture habitual jump-landing patterns to assess innate injury risk, monitor rehabilitation, or assess the effects of a preventive program.

Over half of our sample were reclassified from high to low injury risk categories between *Pre* and *Post* information conditions. It is interesting to consider that two participants changed injury risk categorization from low to high between *Pre* and *Post* information conditions. For certain individuals, a greater amount of feedback can lead to maladaptive short-term responses and changes in movement patterns in part due to over-intellectualization of the task (Lee, Swinnen, & Serrien, 1994). Motor control literature has shown that certain individuals demonstrate a propensity to consciously control and correct their movement patterns more than others (Maxwell, Masters, & Poolton, 2006). Consciously controlling and monitoring one's own movement can constrain or inhibit more effective automatic control processes and lead to greater movement disruption (Masters & Maxwell, 2008). How individuals respond to feedback or consciously control their movements may explain why some participants worsen their LESS scores after being provided with feedback. Furthermore, it could be that those individuals who are unable to improve their LESS scores and remain at high risk of injury have a lesser ability to modify their movement patterns and are in fact at the greatest risk of injury and in most need of preventative programs. However, prospective studies with large cohorts are needed to confirm these speculations.

When considering the number and percentage of specific LESS errors *Post* vs *Pre* condition, most participants improved their LESS scores mostly via sagittal plane movement errors, with a significant reduction in the number of errors for item 16: Joint displacement ($p < 0.001$, Table 1). Our finding are supported by a systematic literature review showing that jump-landing training interventions combined with verbal or visual technique feedback were useful in reducing ACL injury parameters related to sagittal plane, but had little effect on frontal plane biomechanics (Neilson, Ward, Hume, Lewis, & McDaid, 2019). Externally focused instructions have been shown to impact movement behaviors to a greater extent than internally focus ones (Peh, Chow, & Davids, 2011). The LESS item number 16: Joint displacement is graded as: soft landing = 0 error, average landing = 1 error, and stiff landing = 2 errors. This item elicits a more external focused attention from individuals attempting to improve their scores. In comparison, certain items elicit more internal focus from individuals; for example, an error upon lateral trunk flexion (item 6) is attributed when the midline of the trunk is flexed to the left or to the right side of the body. It is possible that after explaining the scoring criteria, participants were more successful in using external focused cues and concentrated on overall landing more softly, which is associated with item 16: Joint displacement and also with other LESS errors in the sagittal plane. This assumption is in agreement with studies showing that participants were more successful in reducing the vertical ground reaction force during landing using instructions with an external focus (i.e., sound associated with foot impact) compared to internal focus (i.e., lower-extremity kinematics) (McNair, Prapavessis, & Callender, 2000; Onate, Guskiewicz, & Sullivan, 2001). Similarly, individuals have been shown to jump higher with external focus instructions compared to internal focus instructions or no instruction (Abdollahipour, Psotta, & Land, 2016). The only sagittal plane item that did not demonstrate a lower occurrence after education was item 1: Knee flexion at initial contact. This finding agrees with a recent meta-analysis (Lopes et al., 2018) indicating no effect of injury prevention programs on increasing knee flexion angles at initial contact during landing task.

In the studies of Frost et al. (2015) and Bryson, Arthur, & Easton (2018), participants were explained FMS scoring criteria after the first FMS testing session; however, unlike our study, participants were not aware of their specific scores, and still improved their FMS scores by 12.4%. Altogether, these studies indicate that merely knowing the screen's objectives or scoring criteria can modify results and performance. During the LESS assessment, individuals are asked to jump as high as possible after the first landing (Padua et al., 2009). This instruction is important to shift participants' focus to performance rather than landing mechanics and resemble sporting demands where performance is of primary interest. It has been shown that the verbal instructions have the ability to acutely alter the drop vertical jump biomechanics variables and influence assessment of athletic performance and injury risk (Khuu, Musalem, & Beach, 2015). Therefore, it is recommended to emphasize the maximization of jump height during LESS testing to shift attention to performance. Furthermore, clinicians could perhaps report jump height as metric to participants and address jump-landing movement errors detected by the LESS though training interventions. This solution would minimize impact of individual's awareness of the screening purpose on outcomes and

improve the ability of clinicians to monitor the impact of their intervention strategy to elicit safe landing patterns.

5. Conclusion

The LESS is clinical tool used to screen for risk of non-contact lower-extremity and ACL injuries. The knowledge of scoring criteria and performance meaningfully improved LESS scores, altered risk categorization, and changed proportions of specific LESS errors. These findings confirm the potential for feedback to acutely affect movement patterns. However, knowledge of scoring criteria and individual performance may potentially compromise the clinical utility of the LESS to assess the habitual movement patterns of individuals during the jump-landing task and identify individuals at risk of injury in practice and research. Given that it is not clear whether a single feedback session may change habitual movement behavior in the long-term, we caution against explaining the scoring criteria and individual movement errors to tested individuals when there is an intention to use the screening tool to assess innate movement patterns or use the tool again to monitor progress over time. Given that it is likely that the screening task may lose its utility to evaluate injury risk when the individual is aware of the purpose of testing, we recommend that clinicians focus on maximizing jump height after the first landing to shift an individual's attention to performance rather than landing technique. These directives are more likely to reveal innate movement patterns that have been linked with a higher risk of sustaining non-contact lower-extremity and ACL injuries. On the other hand, providing feedback on LESS performance or information regarding scoring criteria may be a useful training tool to encourage lower injury risk movement patterns during jump-landing if employed on a regular basis. In this case, the ability of the LESS to screen for innate risk of injury in athletes may be compromised and transference to sport-specific tasks are not guaranteed.

Ethical approval

The study protocol was approved by our institution's health research ethics committee [HREC(Health)#41] and adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks associated with testing.

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Declaration of competing interest

None declared.

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Appendix A5. *Which jump-landing task best represents lower extremity and trunk kinematics of unanticipated cutting manoeuvre?*

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Which jump-landing task best represents lower extremity and trunk kinematics of unanticipated cutting maneuver?

Ivana Hanzlíková [a,*], Jim Richards [b], Josie Athens [c], Kim Hébert-Losier [a]

[a] Division of Health, Engineering, Computing and Science, Te Huataki Waiora School of Health, Adams Centre for High Performance, University of Waikato, 52 Miro Street, Mount Maunganui 3116, New Zealand

[b] Allied Health Research Unit, University of Central Lancashire, Preston, Lancashire, United Kingdom

[c] Department of Preventive and Social Medicine, University of Otago, PO Box 56, Dunedin 9054, New Zealand

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ABSTRACT

Background: The double-leg jump-landing (DLJL) task is commonly used as a movement screen that can be implemented in large cohorts of athletes. However, it is debatable whether the DLJL is ecologically valid and reflects sporting requirements or injury-prone situations, such as cutting and pivoting.

Research question: Which jump-landing movement variation best represents the kinematics of unanticipated side-step cutting?

Methods: Forty-two participants (25 males and 17 females) performed unanticipated side-step cutting and four jump-landing tasks: DLJL, rotated DLJL ($DLJL_{rot}$), single-leg jump-landing (SLJL), and rotated SLJL ($SLJL_{rot}$). Ankle, knee, hip, pelvis, and trunk angles and angular velocities, and pelvic linear accelerations were collected at initial contact and during the first 100 milliseconds after initial contact (minimum, maximum, and range values) using a three-dimensional infrared camera system and inertial measurement units. Pre-contact foot-ground angles and subjective task difficulty ratings were also recorded. Intraclass correlation coefficients (ICC) between cutting and jump-landing kinematics were calculated for each participant and jump-landing variation. Friedman tests with pairwise comparisons were then used to compare the degree of association between the four different jump-landing tasks at the specified time events and to compare the difficulty ratings.

Results: Considering the ICC values across the events of interest, the kinematics of the DLJL were the least associated with those of cutting (ICC = 0.00 to 0.81), and $DLJL_{rot}$ (ICC = 0.34 to 0.81) and $SLJL_{rot}$ (ICC = 0.31 to 0.80) biomechanics the most. Participants rated the perceived challenge of the single-leg tasks in a similar manner to cutting ($p > 0.103$), and the $SLJL_{rot}$ as the most difficult task (median = "neutral", mode = "neutral").

Significance: Due to their biomechanical associations with cutting maneuver and subjectively-rated difficulty levels, both $DLJL_{rot}$ and $SLJL_{rot}$ may be more appropriate and ecologically valid for screening for risk of injury across a range of sports.

1. Introduction

The double-leg jump-landing (DLJL) task is commonly used to evaluate landing biomechanics in research and clinics [1–5], and can be implemented as a movement screen in large cohorts. However, the DLJL has limitations, including that it does not fully represent movements associated with high risk of injury in a sporting context. Athletes frequently land on one leg and injuries often involve complex movements, such as side-cutting, pivoting, or cross-cutting [6]. Krosshaug et al. [3] criticized using the DLJL as a screening task to predict anterior cruciate ligament (ACL) injury in sports, given that it is not challenging enough or reflective of common sport movements. Moreover, it has been shown that sport medicine and coaching professionals are unable to correctly identify athletes who subsequently sustain an ACL injury through visual assessment of DLJL kinematics [5].

The Landing Error Screening System (LESS) is a popular injury-risk screening tool that uses the DLJL [7]. Reliability and validity of the LESS has been established, but its predictive value is unclear [7]. The inconsistent findings relating to its predictive value may be due to the non-sport specific nature of the LESS task, supporting that the DLJL task

* Corresponding author.
E-mail addresses: ih27@students.waikato.ac.nz (I. Hanzlíková), jrichards@uclan.ac.uk (J. Richards), josie.athens@otago.ac.nz (J. Athens), kim.hebert-losier@waikato.ac.nz (K. Hébert-Losier).

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is not challenging enough to unveil 'risky' movement patterns [4]. In examining the efficiency of the LESS to identify high-risk lower extremity mechanics during a sport-specific landing task associated with ACL injury in netball, Fox et al. [8] concluded that the LESS might have low applicability in identifying netballers at high injury risk.

In recent years, other ACL injury-risk clinical screening tools have been proposed, including the Cutting Movement Assessment Score (CMAS) [9]. This tool identifies potentially high-risk movement patterns linked with greater knee valgus moments during side-step cutting [9]. The CMAS has been shown reliable and valid against three-dimensional (3D) motion capture [9]. However, its predictive value for injury has not been established, and the space and time requirements for testing are greater compared to the LESS, and may therefore be less suitable for large-scale screening [9].

There is a need for injury screening methods based on more sport-related and injury-related tasks, whilst keeping the screening task viable for large-scale screening initiatives. Incorporating single-leg landing and rotational movements within injury screening models may offer an appealing alternative to DLJL. Non-contact lower-extremity injuries, including to the ACL, result from poor whole-body movement control in all three planes of motion, rather than dysfunction or altered movement in a single joint or plane of motion [10]. Therefore, rather than considering discrete kinematic measures at specific joints, our aim was to compare the level of association between whole-body kinematics of four jump-landing tasks to a sport-specific and injury-specific unanticipated side-step cutting maneuver. The jump-landing task demonstrating the strongest association with cutting maneuver may be suitable for large-scale injury-risk screening in sports that involve cutting (e.g., soccer, field hockey) or a mix of cutting and jump-landing (e.g., netball, handball) tasks. Additionally, subjective ratings of the difficulty of each task were examined. We hypothesized that single-leg jump-landing (SLJL) would show the strongest correlations to the side-step cutting maneuver, and that $SLJL_{rot}$ would be rated as the most difficult.

2. Methods

2.1. Sample size estimation

A two-tailed hypothesis using an 80 % power (β = 0.20), 5 % significance level (α = 0.05), critical values of the *t*-distribution, and data from previous studies using a similar 3D motion capture set-up and marker set were used to determine the sample size [11,12]. Given the absence of correlation data for sample size estimations, values reporting knee flexion at initial contact (IC), coronal plane knee range of motion, and transverse plane knee range of motion were compared between the SLJL and side-step cutting tasks. It was anticipated that detecting differences between these two tasks would require the largest sample size. This analysis indicated that 33 participants were needed to identify differences between these two tasks. To account for 25 % withdrawals or missing data, 42 participants were recruited.

2.2. Participants

Inclusion criteria were: age between 16 and 35 years, free from any injury or illness that prohibited or limited physical activity participation, and regular participation in a team sport that involved cutting. A history of injury or surgery was not an exclusion criterion given that injury-risk screening is relevant to previously injured athletes. A Health Research Ethics Committee approved the study protocol [HREC(Health) 2018#27], which adhered to the Declaration of Helsinki. All participants signed a written informed consent document before participating that explained the potential risks.

2.3. Experimental procedure

Participants were familiarized with the experimental protocol and all testing was completed in one session. After completing a baseline questionnaire and the International Physical Activity Questionnaire [13], participants performed five tasks: 1) double-leg jump-landing (DLJL); 2) rotated double-leg jump-landing ($DLJL_{rot}$); 3) single-leg jump-landing (SLJL); 4) rotated single-leg jump-landing ($SLJL_{rot}$); and 5) unanticipated side-step cutting. The DLJL followed the LESS protocol [14], requiring participants to jump forward from a 30-cm high box with both feet, landing to a distance equal to half of their body height, and then immediately jump upwards for maximal height. For $DLJL_{rot}$, the protocol was similar to DLJL, but participants rotated 90° in the air before landing on both legs (Fig. 1). For SLJL, the protocol was similar to DLJL, but landing was on one leg (Fig. 1). For $SLJL_{rot}$, the protocol was similar to $DLJL_{rot}$, but landing was on one leg (Fig. 1). To begin SLJL and $SLJL_{rot}$ tasks, participants stood on one leg. Due to the difficulty of these tasks, the landing distance was reduced to 25 % of body height.

For the unanticipated side-step cutting, participants started five meters from the target cutting area. When participants moved within the target area, timing gates (Swift Performance SpeedLight™) triggered one of two pairs of lights to signal the cutting direction. During cutting, participants were required to remain between two lines taped to the floor, indicating a cutting angle of 60° to 90°. A minimum approach speed of 3.5 m/s at the penultimate foot contact was required based on previous studies to mimic a typical game setting [15]. Any trials performed at slower speeds were disregarded and repeated.

The testing order was randomized for task and then direction (i.e., left or right). After a familiarization period of typically two attempts per task, each participant completed three successful repetitions. With the exception of DLJL, all tasks were performed three times to the left and three times to the right. The Perceived Recovery Status Scale [16] was used to ensure sufficient subjective recovery between trials and tasks, with participants needing to self-report ratings ≥ 7 before proceeding to the next trial or task. On average, time between trials was 30 s, and between tasks was 3 min. Furthermore, after each task, participants were asked to evaluate the level of difficulty of the task using the following 5-point Likert scale: 1– very difficult, 2 – difficult, 3 – neutral, 4 – easy, 5 – very easy.

2.4. Instrumentation

Whole-body motion was recorded at 200 Hz during all five tasks using an 8-camera 3D motion capture system (Oqus 700+ cameras) and software (Qualisys Track Manager v.2019.1, Qualisys AB, Gothenburg, Sweden). Forty-two 12.5-mm retroreflective markers and five clusters were taped onto the skin and shoes, which were modelled using the Calibrated Anatomical System Technique [17]. An additional cluster was placed on the right side of the pelvis to improve segment tracking (Fig. 2). Three inertial measurement unit (IMU) sensors (Delsys Trigno IM sensors, Delsys Inc., MA, USA) sampling at 148 Hz were synchronized with the 3D motion capture system to assist with event determination in the absence of force plates. Two sensors were placed bilaterally 4 cm above the lateral malleoli, and one attached over the sacrum.

2.5. Data processing

Data were exported to. c3d format and processed using Visual3D Professional™ (v.6.01.36, C-Motion Inc., Germantown, Maryland, USA). A 13 rigid segment biomechanical model with six degrees of freedom at each joint was constructed. The local coordinates of all segments were derived from a static trial captured prior to the dynamic trials. Any marker data gaps less than 10 frames were interpolated using a third order polynomial fit algorithm. A fourth order low-pass Butterworth filter with a cut-off frequency of 15 Hz was then applied to the marker data [18]. IMU data were visually assessed using a range of

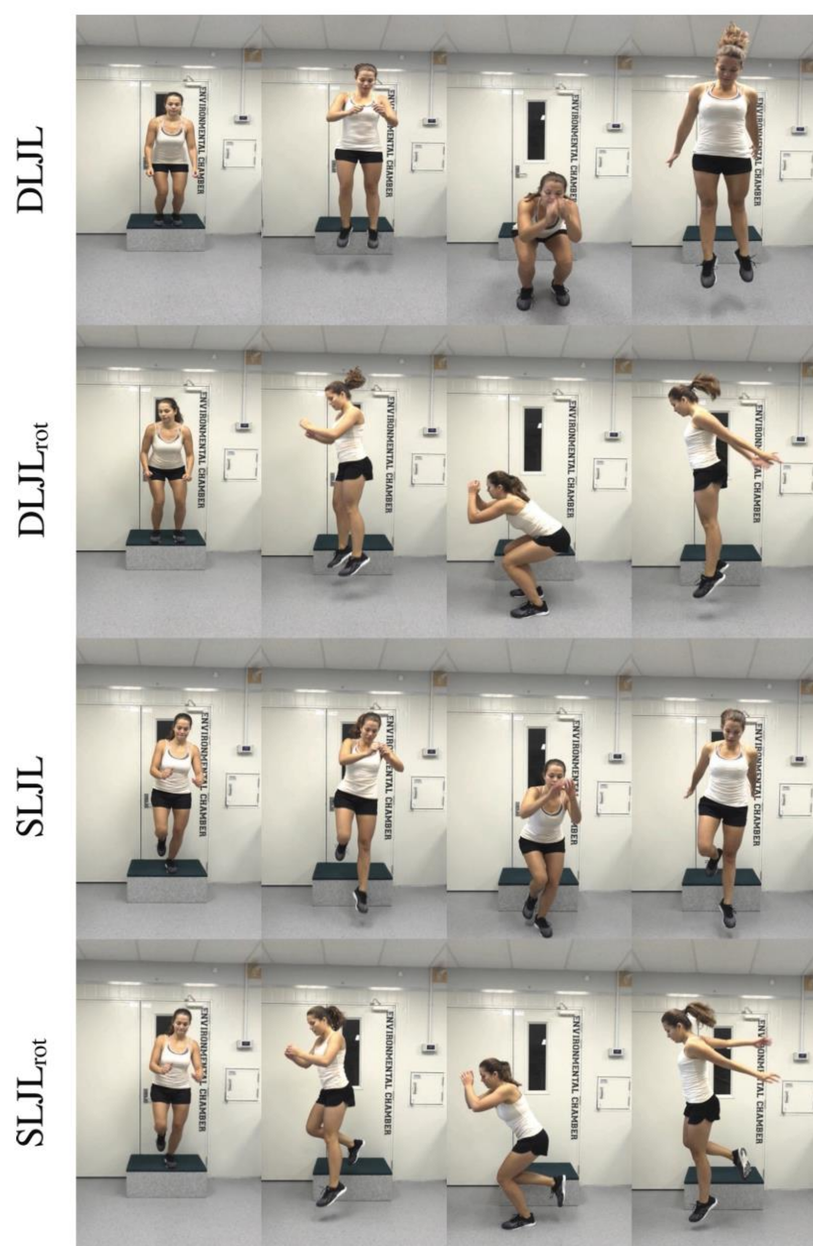

Fig. 1. Jump-landing task variations.
Abbreviations: DLJL, double-leg jump-landing; $DLJL_{rot}$, rotated double-leg jump-landing; SLJL, single-leg jump-landing; $SLJL_{rot}$, rotated single-leg jump-landing.

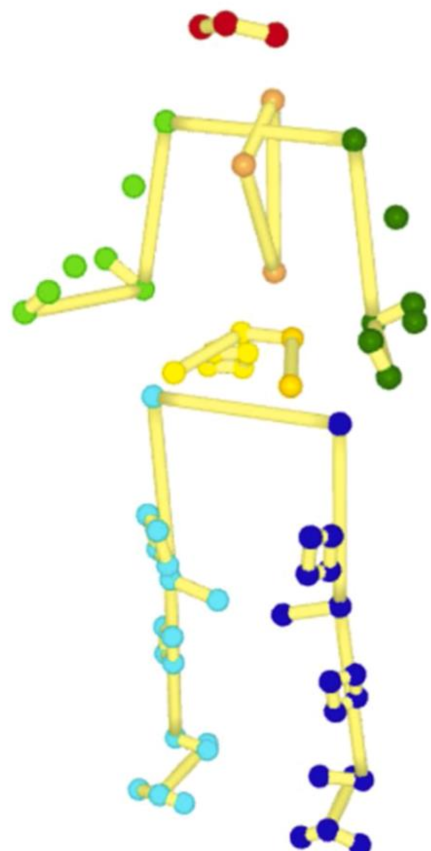

Fig. 2. Marker set.

cut-off frequencies (15–100 Hz), and 80 Hz was confirmed as the best at preserving all high-frequency signal characteristics, while also removing noise. The sacrum IMU acceleration data were corrected based on the pelvis angle in all three planes.

Kinematic parameters were calculated using an XYZ cardan sequence, equivalent to the joint coordinate system [19]. Ankle, knee, hip, pelvis, and trunk angles and angular velocities, and pelvic linear accelerations were extracted at IC and from the 100 milliseconds after IC (minimum, maximum, and range values). Additionally, foot-ground angles in all three planes were extracted one frame before IC to explore pre-landing strategies [20]. IC was defined based on the peak vertical acceleration from IMU sensors placed above the lateral malleoli for jump-landing tasks, and as the instance when the cutting-leg foot center of gravity acceleration in the vertical plane (i.e., plane perpendicular to the floor) of the lab coordinate system (z) reached a maximum value for the cutting task. The 100-millisecond timeframe was chosen as ACL injuries have been reported to occur within this period [21]. For DLJL, data from the pelvis, trunk, and both extremities were extracted. For $DLJL_{rot}$, data from the pelvis, trunk, and the extremity furthest away from the box were extracted. For single-leg tasks, data from the pelvis, trunk, and from the landing extremities were extracted. The directionality and interpretation of joint movements are presented in Table 1. Furthermore, the pelvis center of gravity velocity at IC and cutting angle during the cutting maneuver were extracted to quantify cutting performance.

2.6. Statistical analysis

Joint angle, angular velocity, and IMU data from the three trials of each task were averaged for statistical analyses. To determine which jump-landing task was the most reflective of the sport-specific unanticipated cutting maneuver, the association between the kinematic variables extracted ($n = 72$, Supplementary data) during cutting and each of the jump-landing tasks was quantified using single measurement, consistency agreement, two-way random effect intraclass correlation coefficients (ICCs) for each participant [22]. Both dominant and non-dominant lower extremities were included in the analysis to derive the ICC for each participant.

Subsequently, Friedman tests with Wilcoxon signed-rank tests during post-hoc comparisons were used to compare the strength of the associations of the kinematic variables from the different jump-landing tasks to the cutting task at IC (including pre-landing foot-ground angles) and during the 100 milliseconds after IC, Table 1. Friedman tests were used due to violated assumptions for parametric testing [23]. Subjective ratings regarding task difficulty were described using median, mode, and frequency indicators, and compared between tasks using the Friedman test with Wilcoxon signed-rank tests during post-hoc comparisons. The significance level was set at $p \leq 0.05$ for all analyses, which were performed using Microsoft® Excel (Office 365 MSO) and RStudio® (version 1.1.463) with R (version 3.5.2).

3. Results

Forty-two participants (25 males and 17 females) volunteered. Age, height, and mass (mean ± standard deviation) for males were 23.6 ± 4.1 years (range 17–32 years), 182.2 ± 6.4 cm, and 85.0 ± 11.9 kg; and for females were 22.2 ± 5.7 years (range 16–35 years), 169.1 ± 6.0 cm, and 63.7 ± 6.8 kg. Ninety-three percent of participants were right-leg dominant based on the preferred leg to kick a ball. The International Physical Activity Questionnaire indicated that activity levels were high, moderate, and low in 60 %, 38 %, and 2% of participants, respectively. Thirty-one percent of participants played soccer, 26 % rugby, 17 % ultimate-Frisbee, 14 % netball, 7 % basketball, and 5 % field hockey. Participants' level of engagement with sport was 55 % club level, 21 % recreational, 17 % national level, and 7 % school level. Participants were involved in physical activity three times per week (median) for on average 6.7 ± 4.4 h weekly. On average, our sample had participated in physical activity on a regular basis for 10.5 ± 6.2 years. In all analyses, there were no missing data.

Mean values and standard deviations of all extracted variables are presented as Supplementary data. Overall, the mean cutting angle was 58.3 ± 9.8° and cutting speed at IC was 3.4 ± 0.5 m/s. At IC, rotated tasks were more strongly ($p < 0.001$) associated with cutting kinematics than non-rotated tasks based on ICCs (Fig. 3A). The minimum values of the explored variables during all jump-landing tasks showed similar levels of associations to those of cutting, with mean ICC values ≥ 0.66 for all tasks (Fig. 3B). The maximum values of the kinematic variables during the $DLJL_{rot}$ was the most strongly associated with cutting compared to all other jump-landing tasks (ICC 0.74, $p < 0.001$), and DLJL and SLJL the least associated (Fig. 3C). The range of motion in all jump-landing tasks showed similar levels of association to those of cutting, with mean ICC values ≥ 0.80 for all tasks (Fig. 3D). Overall, when considering ICC values across the events of interest, the DLJL kinematics appeared to be the least associated with cutting, and $DLJL_{rot}$ the most followed by $SLJL_{rot}$.

Additionally, subjective ratings relating to task difficulty significantly differed between tasks ($p < 0.022$), expect for between cutting

Table 1
Joint movement in all three planes represented by minimum and maximum values.

	Sagittal plane (X)		Coronal plane (Y)		Transverse plane (Z)	
	Minimal values	Maximum values	Minimal values	Maximum values	Minimal values	Maximum values
Foot[a]	Toe landing	Heel landing	Eversion	Inversion	External rotation	Internal rotation
Ankle	Plantar flexion	Dorsiflexion	Abduction	Adduction	External rotation	Internal rotation
Knee	Extension	Flexion	Valgus	Varus	External rotation	Internal rotation
Hip	Extension	Flexion	Abduction	Adduction	External rotation	Internal rotation
Pelvis	Anteversion	Retroversion	ND pelvis drop	D pelvis drop	Rotation to D	Rotation to ND
Trunk	Extension	Flexion	Lateral flexion to ND	Lateral flexion to D	Rotation to D	Rotation to ND

Abbreviations: D, dominant side; ND, non-dominant side.
[a] Foot-ground angle one frame before initial contact.

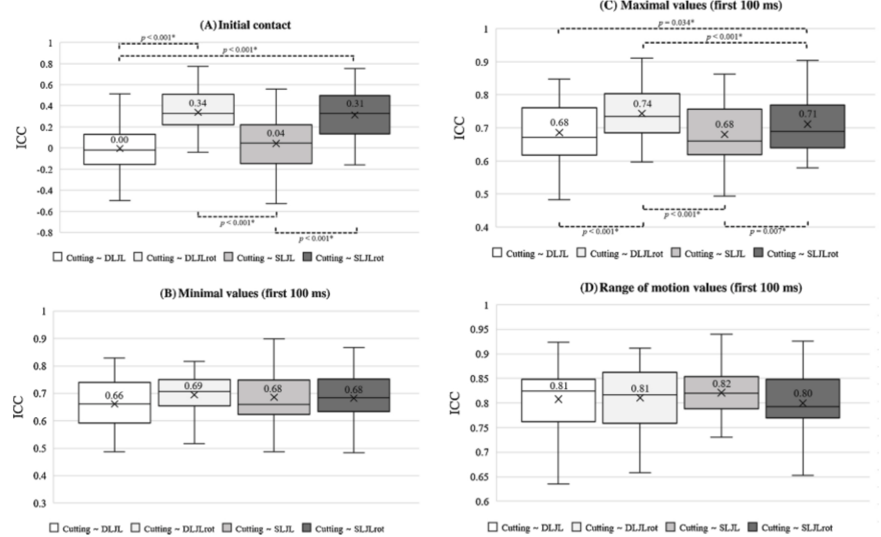

Fig. 3. Comparison of intraclass correlation coefficients (ICC) associating (A) values at initial contact (IC), (B) minimal values in the 100 milliseconds (ms) after IC, (C) maximal values in the 100 ms after IC, and (D) range of motion values in the 100 ms after IC of biomechanical variables between unanticipated side-step cutting maneuver and jump-landing tasks.
Abbreviations: DLJL, double-leg jump-landing; $DLJL_{rot}$, rotated double-leg jump-landing; SLJL, single-leg jump-landing; $SLJL_{rot}$, rotated single-leg jump-landing. Cross indicates the mean value. Horizontal line indicates the median. Error bars represent minimal and maximal values within the sample.
* Indicates significant differences between tasks based on pairwise comparison from Friedman test.

and SLJL ($p = 1.000$), cutting and $SLJL_{rot}$ ($p = 0.103$), and SLJL and $SLJL_{rot}$ ($p = 0.052$). Participants rated the DLJL as the easiest task to perform (median = "easy", mode = "very easy"), and the $SLJL_{rot}$ as the most difficult (median = "neutral", mode = "neutral"). Five percent of participants rated the $SLJL_{rot}$ as "very difficult" and 31 % as "difficult", Fig. 4.

4. Discussion

Almost two decades ago, Hewett et al. [1] suggested the DLJL could be used to screen for risk of ACL injury. The DLJL has become commonplace in the assessment of landing biomechanics. However, several studies have criticized the DLJL task, stating it is not reflective of common sport movements and injurious situations, not challenging enough, and poor for predicting ACL injury [3–5,8]. Our results support these statements and indicate the lowest association between DLJL and sport-specific cutting kinematics when compared to other jump-landing tasks. Furthermore, according to the subjective ratings, DLJL was rated as easy ($n = 19$, 45 %) and very easy ($n = 20$, 48 %), reflecting the low perceived challenge of this task. From the tasks tested, the $DLJL_{rot}$ showed the greatest biomechanical similarities to cutting based on ICC values, followed by $SLJL_{rot}$. Furthermore, single-leg landing tasks had a similar perceived challenge than cutting, with $SLJL_{rot}$ subjectively rated as the most difficult. Therefore, the two rotated jump-landing tasks ($DLJL_{rot}$ and $SLJL_{rot}$) may be more appropriate than the DLJL to reveal risky movement patterns that are more sport-specific and challenging.

Overall, single-leg landings are biomechanically more challenging for the knees than double-leg landings, with lower knee flexion at IC, lower sagittal plane knee displacement, greater frontal plane knee displacement, and greater knee abduction moments [24]. Single-leg landings are also more common in sports and during injury situations than double-leg landings [21,25]. Most athletic movements involve unilateral propulsion or stabilization (e.g., running, kicking, jumping). Video analysis of injury situations during games show that up to 80 % of non-contact ACL injuries occur during single-leg landings or cuttings [21,25]. Moreover, high injury-risk movement patterns may become more apparent during single-leg landings due to greater lower-extremity loadings, smaller bases of support, and greater motor control challenges

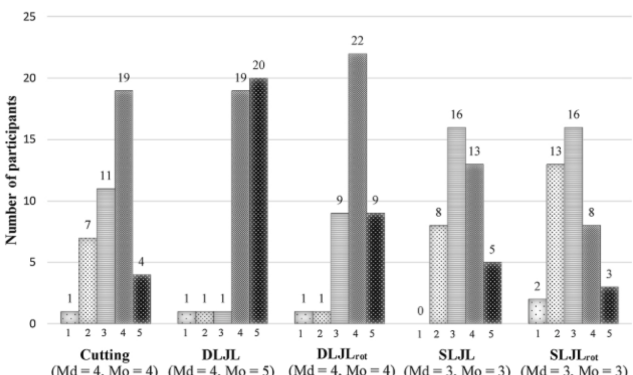

Fig. 4. Subjective ratings of the difficulty of each task.
Ratings: 1, very difficult; 2, difficult; 3, neutral; 4, easy; 5, very easy.
Abbreviations: DLJL, double-leg jump-landing; $DLJL_{rot}$, rotated double-leg jump-landing; SLJL, single-leg jump-landing; $SLJL_{rot}$, rotated single-leg jump-landing; Md, median; Mo, mode.

to stabilize the pelvis and trunk [26]. All of these variables probably contributed to the greater perceived challenge of single-leg tasks in our study. Altogether, our findings suggest that single-leg tasks may more accurately reflect the challenge associated with unanticipated cutting. However, compared to SLJL, $SLJL_{rot}$ showed stronger associations with cutting biomechanics and was rated as the most difficult task to perform. Hence, compared to SLJL, $SLJL_{rot}$ may be better suited to reveal movement patterns present during more challenging sport situations and, in turn, have a greater association with injury-risk profiles specific to ACL injuries.

Due to their subjectively-rated difficulty levels and biomechanical association with cutting movements, both $DLJL_{rot}$ and $SLJL_{rot}$ may be more appropriate screening tasks for landing (e.g., volleyball and basketball) and cutting (e.g., soccer, netball, field hockey, handball, American football, and rugby) sports than the traditional DLJL. Given that two-dimensional video assessments of double-leg and single-leg landings have been used to identify athletes with increased risk of non-contact knee injuries [2,27] and both tasks require minimal space requirements, they could be useful for large-scale screening initiatives. However, establishing what specific parameters from the $DLJL_{rot}$ or $SLJL_{rot}$ may be useful in the clinical assessment of injury risk requires further research, and prospective studies are needed to confirm the psychometric properties and predictive value of these tasks.

Noteworthy is that our study examined the association between kinematic variables, and not their comparability. The concept of kinetic chains stipulates that each joint movement and underlying muscle contraction are coupled with movements and muscle contractions in other joints [28]. For example, trunk control is closely related to the ability of the hip and pelvis to adequately respond to unexpected movements and forces generated by distal body segments [29]. For instance, weak hip abductors lead to contralateral pelvis drop (Trendelenburg position); to compensate for a Trendelenburg position, the trunk inclines laterally towards the stance leg and produces a greater lateral lever arm relative to the knee joint centre and increases the knee valgus moment and ACL strain [29]. Hence, every joint movement in each plane may contribute to non-contact lower-extremity injuries, supporting that whole-body movement patterns and control should be considered when screening for injury risk. Therefore, rather than comparing specific angles in given joints or planes of motion, this study examined the association between whole-body movement patterns during cutting and different jump-landing variations. Given that cutting was used as the sport-specific task to determine the relevance of various jump-landing movements to screen for potential risk of ACL injuries, our results might be of greater relevance for athletes and sports that involve cutting (e.g., soccer, field hockey) or cutting and jump-landing (e.g., netball, handball) rather than predominantly jump-landing (e.g., volleyball). Moreover, due to absence of force plates, we were unable to compute joint moments through inverse dynamics, which could have provided further insight into the biomechanical associations between the tasks tested.

5. Conclusion

Within the tasks explored, whole-body kinematics of $DLJL_{rot}$ were the most strongly and consistently associated with cutting kinematics, followed by $SLJL_{rot}$. The $SLJL_{rot}$ task was rated as the most difficult to perform and had similar self-reported difficulty levels to cutting. Therefore, rotated jump-landing tasks may be more appropriate than the DLJL to reveal risky movement patterns present during rapid changes of direction and landing, which could be implemented in large-scale screening as an alternative to DLJL.

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Declaration of Competing Interest

We can confirm that there is no conflict of interests for any of the authors.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2021.02.003.

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Appendix A6. *Propensity for conscious control of movement is unrelated to asymptomatic hypermobility or injury-risk scores.*

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Propensity for conscious control of movement is unrelated to asymptomatic hypermobility or injury-risk scores

Ivana Hanzlíková[1] *, Rich S.W. Masters[1], Kim Hébert-Losier[1]

[1]*Te Huataki Waiora School of Health, Division of Health, Engineering, Computing and Science, University of Waikato, New Zealand*

A R T I C L E I N F O

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A B S T R A C T

The Movement Specific Reinvestment Scale (MSRS) measures the propensity for conscious monitoring and control of movement, which can inhibit automated movement processes, potentially causing movement disruption or injury. High injury risk individuals are more likely to make movement errors during jump-landing tasks, and hypermobile individuals present with poor movement control. The link between MSRS and these characteristics remains largely unexplored. Consequently, we examined propensity for movement specific reinvestment in high injury risk and asymptomatic hypermobile participants. Sixty volunteers (35 males, 25 females) were tested using the MSRS, Landing Error Scoring System (LESS), and Beighton hypermobility scale. Spearman rank correlation coefficients were computed between MSRS, LESS, and Beighton scores. Furthermore, MSRS scores were compared between low (LESS < 5 errors) and high (LESS ≥ 5 errors) injury risk, as well as non-hypermobile and hypermobile participants. MSRS scores were not significantly related to LESS ($\rho = 0.06$, $p = 0.625$) or Beighton ($\rho = 0.09$, $p = 0.481$) scores. MSRS scores of low and high injury risk (37.8 ± 7.8 vs 38.0 ± 8.6, $p = 0.933$), and non-hypermobile and hypermobile (37.5 ± 8.9 vs 39.0 ± 7.0, $p = 0.524$) participants were comparable. Based on our results, there is no evidence that movement specific reinvestment contributes to injury risk assessed by LESS, which might be due to the phylogenetic nature of the LESS jump-landing task and/or the low psychological pressure environment of laboratory testing. The propensity for movement specific reinvestment did not vary in asymptomatic hypermobile individuals compared to non-hypermobile individuals; however, examination of the MSRS in symptomatic hypermobile individuals and individuals with well-defined syndromes is needed to fully elucidate whether or not conscious monitoring and control of movement plays a role in injury risk or movement control across the hypermobility spectrum.

1. Introduction

It is well known that human movements are influenced by various psychological factors, such as fear of movement-related pain (Meulders, Vansteenwegen, & Vlaeyen, 2011), motivation (Kadosh & Staunton, 2019), or reinvestment (Masters, 1992; Masters & Maxwell, 2008). Reinvestment is defined as 'manipulation of conscious, explicit, rule based knowledge, by working memory, to control the mechanics of one's movements during motor output' (Masters & Maxwell, 2004, p. 208). The Movement Specific Reinvestment Scale (MSRS) is a valid and reliable measure of the propensity for conscious involvement in movement (Masters, Eves, & Maxwell, 2005; Wong, Masters, Maxwell, & Abernethy, 2008). The MSRS consists of 10 statements about a person's tendency to consciously process their movements or to be self-conscious about their style of movement (Table 1). Scoring of the MSRS statements is based on a Likert-type scale ranging from strongly agree (1 point) to strongly disagree (6 points). The maximum MSRS score is 60 points, with higher scores indicating greater propensity to consciously monitor and control movements. The theory of reinvestment proposes that consciously controlling and monitoring one's own movements can constrain or inhibit more effective automatic control processes, which can potentially lead to movement disruption (Masters & Maxwell, 2008). High MSRS scores are associated with greater movement errors under psychological pressure in

*Corresponding Author: Ivana Hanzlíková, Te Huataki Waiora School of Health, University of Waikato, New Zealand, xhanzlikova@gmail.com

sport (Chell, Graydon, Crowley, & Child, 2003; Jackson, Ashford, & Norsworthy, 2006; Masters, Polman, & Hammond, 1993; Maxwell, Masters, & Poolton, 2006), slowed surgical performance by medical students under time pressure (Malhotra, Poolton, Wilson, Ngo, & Masters, 2012), higher fall incidence in older adults (Wong et al., 2008), more severe functional impairment after stroke (Orrell, Masters, & Eves, 2009), duration of Parkinson's disease (Masters, Pall, MacMahon, & Eves, 2007), and self-reported knee pain (Selfe et al., 2015).

The Landing Error Scoring System (LESS) is a reliable and valid injury risk screening tool that identifies movement patterns linked with non-contact injuries using a jump-landing task (Hanzlíková & Hébert-Losier, 2020). Clinicians evaluate frontal and sagittal plane videos from the LESS test and visually evaluate aberrant lower extremity and trunk kinematics from initial ground contact until maximal knee flexion. The LESS score consists of 17 items; movement items 1 to 15 are scored as 0 (error absent) or 1 (error present). The last two items (16 and 17) are subjective and assess the overall sagittal plane displacement and quality of landing. These two items are scored from 0 to 2 errors. The minimum (best) score is 0 and reflects the absence of movement errors, and the maximum (worst) score is 17 errors. Higher LESS scores indicate poorer jump-landing mechanics and greater risk of non-contact lower extremity injury. Padua et al. (2015) concluded that 5 errors was the optimal cut-off score for determining increased risk of non-contact Anterior Cruciate Ligament (ACL) injury incidence. The risk ratio for sustaining a non-contact ACL injury when LESS scores were 5 errors or greater (compared to lower than 5 errors) was 10.7 (Padua et al., 2015). A previous study concluded that elder fallers scored significantly higher on the MSRS compared to non-fallers (Wong et al., 2008). The authors argued that the high propensity to reinvest might contribute to cautious gait in those with fear of falling, which disrupts automaticity of walking and increases risk of falling and associated injury risk (Wong et al., 2008). Therefore, it is possible that athletes who consciously monitor their own movements may exhibit a greater number of landing errors during LESS assessment and be at greater risk of sport-related injuries.

Generalized hypermobility is an identified risk factor for injury (Dallinga, Benjaminse, & Lemmink, 2012; Donaldson, 2012; Pacey, Nicholson, Adams, Munn, & Munns, 2010), including the ACL injury (Goshima, Kitaoka, Nakase, & Tsuchiya, 2014; Sundemo et al., 2019). Generalized joint hypermobility is usually a congenital inherited disorder of connective tissue characterized by increased movement in multiple joints beyond normal physiological ranges expected in a given population (Castori et al., 2017; Malfait et al., 2017). Overall, the prevalence of generalized hypermobility reported to exist in the general population is between 10 to 20% (Remvig, Jensen, & Ward, 2007b). Generalized joint hypermobility can be categorized as individuals with asymptomatic joint hypermobility, individuals with well-defined syndrome associated with joint hypermobility, and individuals with symptomatic joint hypermobility (Castori et al., 2017). Besides a range of musculoskeletal symptoms (Hakim & Grahame, 2003), generalized hypermobility has been associated with a greater prevalence of panic disorder and anxiety (Garcia-Campayo, Asso, & Alda, 2011), attention-deficit and hyperactivity disorder (Baeza-Velasco, Sinibaldi, & Castori, 2018), fatigue (Krahe, Adams, & Nicholson, 2018), and pain hypersensitivity (Bettini, Moore, Wang, Hinds, & Finkel, 2018). Given that the propensity for movement specific reinvestment has also been linked to fear, anxiety, fatigue, and movement difficulties and disorders, there may be an association between hypermobility and conscious engagement in movement. Conscious engagement in movement may therefore be contributing to the altered movement patterns (Fatoye, Palmer, Van der Linden, Rowe, & Macmillan, 2011; Galli et al., 2011; Luder et al., 2015; Simonsen et al., 2012) and increased injury risk (Pacey et al., 2010) in hypermobile individuals.

The association between propensity for movement specific reinvestment, biomechanical control, and hypermobility has not been studied to date. The propensity for movement specific reinvestment may be an important injury risk factor to consider that may assist injury prevention efforts via the development and implementation of more targeted, multi-modal interventions for these individuals. Participants with symptomatic generalized joint hypermobility or well-defined syndromes associated with hypermobility often present with chronic pain and fatigue to various extents, which may influence the results. Several physically active individuals present with asymptomatic generalized joint hypermobility (Luder et al., 2015) and are clinically perceived at a higher risk of injury given their hypermobile status, although limited research has focused on this population specifically. Therefore, the aim of this paper was to explore the relationship between MSRS, LESS, and Beighton scores in young active asymptomatic individuals, as well as to compare MSRS scores between participants at low and high injury risk, as well as between non-hypermobile and asymptomatic generalized hypermobile participants. We hypothesized that participants at high injury risk and those presenting with asymptomatic generalized hypermobility would exhibit greater MSRS scores than low injury risk and non-hypermobile participants, respectively.

Table 1: The Movement Specific Reinvestment Scale. Adapted from Masters et al. (2005).

Conscious Motor Processing items
I remember the times when my movements have failed me.
I reflect about my movement a lot.
I try to think about my movements when I carry them out.
I am aware of the way my body works when I am carrying out a movement.
I try to figure out why my actions failed.
Movement Self-Consciousness items
If I see my reflection in a shop window, I will examine my movements.
I am self-conscious about the way I look when I am moving.
I sometimes have the feeling that I am watching myself move.
I am concerned about my style of moving.
I am concerned about what people think about me when I am moving.

2. Methods

2.1. Participants

Given that no published data exist regarding the association between MSRS, LESS, and Beighton scores, we calculated sample size requirements based on the ability to detect a correlation of moderate magnitude (i.e., 0.50) (Mukaka, 2012). Based on sample size calculations using a customizable statistical spreadsheet (Hopkins, 2006) from standard two-tailed hypothesis equations using an 90% power (β = 0.10) and 5% significance level (α = 0.05), we needed at least 38 participants to detect a moderate correlation between measures. Given that 60 individuals agreed to participate, our study sample size is powered to detect a correlation of 0.40 in magnitude.

To be included, participants needed to be involved in sport activity; and be free from injury, pain, or any other issue that would limit physical activity at the time of study participation. Previous injuries were not an exclusion criterion. This study aimed to assess only non-hypermobile and asymptomatic hypermobile participants according to the framework for the classification of joint hypermobility proposed by Castori et al. (2017). Therefore, participants with chronic pain or known diagnosis of medical syndromes associated with joint hypermobility (e.g., Ehlers Danlos and Marfan syndrome) were excluded. Sixty young adults (35 males, 25 females) fulfilled the inclusion criteria and participated in this study. Age, height, and mass (mean ± standard deviation) for males were 23.2 ± 4.7 years, 181.2 ± 6.6 cm, and 83.9 ± 3.2 kg; and 22.2 ± 5.6 years, 169.3 ± 5.8 cm, and 66.2 ± 2.6 kg for females. Participants were involved in organized sport activity 3 times per week (median), on average for 6.4 ± 4.4 hours a week. The study protocol was approved by our institution's Health Research Ethics Committee [HREC(Health)#2018-27] and adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks associated with testing before participating. Note that participants were not screened for generalized joint hypermobility prior to participation.

2.2. Procedure

All tests were completed in a single session. After self-administered MSRS completion, half of the participants completed the LESS protocol followed by the Beighton diagnostic test for hypermobility, whereas the other half completed the tests in the reverse order. The MSRS has adequate internal reliability (coefficient alpha = 0.80), teste-retest reliability (Pearson product moment correlation coefficient = 0.74), and validity (Masters et al., 2005; Masters et al., 1993). The LESS has been validated against 3D motion capture and has good-to-excellent intrarater [intraclass correlation coefficient (ICC), 0.82-0.99], interrater (ICC, 0.83-0.92), and intersession (ICC, 0.81) reliability reported in the scientific literature (Hanzlíková & Hébert-Losier, 2020). The Beighton score is a major criterion used in diagnosing joint hypermobility syndrome, and is a valid and reliable (kappa = 0.75 to 0.78) diagnostic tool for joint hypermobility (Remvig, Jensen, & Ward, 2007a). In this study, sex and age-specific cut-off scores based on Singh et al. (2017) were used to categorize hypermobility. Specifically, the cut-off score for hypermobility of ≥ 5 points was used for females, and ≥ 4 for males in our sample.

The LESS testing procedure used here was identical to the procedure described elsewhere (Padua et al., 2009). Participants jumped horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately jumped upward for maximal vertical height. Participants were instructed to jump off the box with both feet, land in front of the designated line, and jump as high as possible upward upon landing. We provided no feedback on landing technique unless participants were performing the task incorrectly. Participants were given as many practice trials as needed to become comfortable with the task (typically one). Each participant performed three trials of the double-leg jump-landing task in their own footwear. To mitigate effects of fatigue, participants were allowed to rest until they felt ready to perform the second and third trial of the task. Two tripod-mounted digital cameras (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm) captured performance of the task at 60 Hz. The cameras were placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m to capture frontal and sagittal plane motion. One investigator (IH) with experience of over 400 LESS evaluations replayed the videos using the open-source Kinovea video analysis software (version 0.8.15, www.kinovea.org). The investigator scored the first landing of the jump-landing task of all three trials (i.e., when landing from the box) using the 17-item LESS scoring criteria (Padua et al., 2009). The investigator was blinded to the MSRS and Beighton hypermobility scores.

An experienced physiotherapist (IH) recorded the Beighton scores, consisting of five components: (1) passive dorsiflexion and hyperextension of the fifth metacarpal joints (little fingers) beyond 90°, (2) passive apposition of the thumbs to the flexor aspects of the forearms, (3) passive hyperextension of the elbows beyond 10°, (4) passive hyperextension of the knees beyond 10°, and (5) active forward flexion of the trunk with the knees fully extended so that the palms of the hands rest flat on the floor (Beighton, Solomon, & Soskolne, 1973), following standard protocols and using a hand-held goniometer (Smits-Engelsman, Klerks, & Kirby, 2011). Note here that the first four elements can be given a maximum score of 2 points because these are performed bilaterally (i.e., 1 point for each hypermobile joint), whereas the last element has a maximum score of 1 point. Hence, a total score of 9 points is possible.

2.3. Statistical approach

Mean ± standard deviation, median (interquartile range), and range (minimum to maximum) values were calculated to describe variables based on variable type. Note that the mean LESS score from the three trials completed by each participant was used for statistical analysis. Statistical significance level was set at $\alpha \leq 0.05$ for all analyses. The statistics were computed using Microsoft® Excel® for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2.

To investigate the relationship between MSRS, LESS, and Beighton scores, Spearman rank correlation coefficients (ρ) were calculated given the ordinal nature of the data. The correlation coefficient values were interpreted using thresholds of 0.30, 0.50,

0.70, and 0.90 to indicate low, moderate, high, and very high correlations (Mukaka, 2012). Correlations below 0.30 were considered negligible.

Independent *t*-tests with equal variance were conducted to investigate differences in MSRS scores between low and high (LESS ≥ 5 errors) injury risk, and non-hypermobile and hypermobile (Beighton score ≥ 5 points for females and ≥ 4 points for males) participants. Mean differences and 95% confidence intervals [upper, lower] in MSRS scores between groups and corresponding effect sizes (Hedge's *g*) with 95% confidence intervals were calculated. Thresholds for interpreting the magnitude of Hedge's *g* were 0.20, 0.50, and 0.80 for small, medium, and large effects (Lakens, 2013). Effect sizes below 0.20 were considered trivial. There were no missing data, so data from all 60 participants were analyzed. Note that analysis of each MSRS subscale (Conscious Motor Processing and Movement Self-Consciousness) separately yielded similar results.

3. Results

The mean MSRS score for all participants was 37.9 ± 8.3 points (range: 19 to 54). Mean LESS score was 5.3 ± 1.5 errors (range: 2.0 to 9.7). The median and interquartile range of Beighton score for all participants was 2.5 (4.0) points (range: 0 to 9).

There was a negligible non-significant relationship between MSRS and LESS scores ($\rho = 0.06$, $p = 0.625$) and MSRS and Beighton scores ($\rho = 0.09$, $p = 0.481$). The MSRS scores between participants at low and high injury risk were similar (Table 2). There was no significant difference in MSRS scores between non-hypermobile and hypermobile participants, with a trivial effect of grouping on MSRS scores (Table 2).

4. Discussion

The purpose of our study was to investigate the relationship between MSRS, LESS, and Beighton scores, and to compare MSRS scores between high and low injury risk participants and between non-hypermobile and asymptomatic hypermobile participants. In our cohort, there was no significant relationship between MSRS, LESS, and Beighton scores, and no difference in MSRS scores between the subgroups analyzed. The results indicate that participants with greater propensity for conscious monitoring and control of their movements do not present with a greater number of high injury risk movement patterns during double-leg jump-landing as assessed by the LESS and propensity for movement specific reinvestment does not vary in asymptomatic hypermobile individuals compared to non-hypermobile individuals.

The lack of an association between injury risk according to LESS scores and movement specific reinvestment could be due to the phylogenetic nature of the LESS task, the manner in which reinvestment occurs, the low-pressure testing environment, or a combination of these factors. Unlike ontogenetic skills, which require people to learn them, phylogenetic skills (such as jumping) typically can be performed by anyone who is healthy, with minimal conscious processing (Masters & Poolton, 2012). Consequently, phylogenetic skills tend to be less susceptible to disruption by conscious control (reinvestment) than ontogenetic tasks (Masters & Poolton, 2012), which would mitigate differences between high and low MSRS scores. Previous studies have also confirmed an association between high propensity for movement specific reinvestment and poorer sport-specific task performance under psychological pressure (Chell et al., 2003; Jackson et al., 2006; Maxwell et al., 2006). Specifically, individuals with high MSRS scores displayed greater susceptibility to skill failure during soccer kicking (Chell et al., 2003), golf putting (Maxwell et al., 2006), and field-hockey dribbling (Jackson et al., 2006) under high pressure situations. These ontogenetic skills are seldom automated to the same extent as phylogenetic skills, so they require considerable concentration to be performed correctly and their execution is easily processed consciously. Psychological pressure amplifies the likelihood that performers (especially high reinventors) will process their movements consciously to ensure that their performance remains effective, but often this 'overthinking of movement' can disrupt fluid movement (Baumeister, 1984; Beilock & Carr, 2001; Gray, 2004; Masters, 1992). The double-leg jump-landing task tested by the LESS requires participants to jump horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately jump upward as high as possible upon landing. The

Table 2: Comparison of MSRS scores between groups in the sampled cohort (n = 60).

	n	MSRS scores (points)	MD [95% CI]	*t*-test	Hedge's *g* [95% CI]
At low risk [a]	21	37.8 ± 7.8	-0.2	0.933	-0.02
At high risk [a]	39	38.0 ± 8.6	[-4.7 to 4.3]		[-0.56 to 0.51]
Non-hypermobile [b]	41	37.5 ± 8.9	-1.5	0.524	-0.18
Hypermobile [b]	19	39.0 ± 7.0	[-6.1 to 3.2]		[-0.72 to 0.37]

Abbreviations: *n*, number of participants; MSRS, Movement Specific Reinvestment Scale; MD, mean difference; CI, confidence interval.
[a] At low risk Landing Error Scoring System (LESS) scores < 5 errors; at high risk LESS scores ≥ 5
[b] Hypermobile, Beighton score ≥ 5 points for females and ≥ 4 points for males; non-hypermobile, Beighton score < 5 points for females and < 4 point for males.

task involves movements that are presumably highly automated, so it requires minimal concentration and cannot easily be processed consciously. Thus, performance of the task is less likely to be influenced by movement specific reinvestment. Furthermore, the LESS testing environment imposes minimal pressure to perform well. Participants are not informed of the LESS scoring criteria when they perform the test and receive no performance feedback that might reveal innate movement patterns linked with a higher risk of sustaining non-contact lower-body and ACL injuries. As such, participants therefore are unaware of what characterizes good LESS performance or whether they are performing well (or not). Results might have been different with presence of an overhead target given that it can act as an external motivator and performance indicator, thereby altering movement patterns (Ford et al., 2005; Ford, Nguyen, Hegedus, & Taylor, 2017). Injury-risk and propensity for conscious monitoring and control of movement may be related under certain circumstances, with the association only surfacing in cases where participants are highly motivated to perform successfully (e.g., under pressure) or when they are aware of what constitutes successful or unsuccessful performance. Future research should examine this possibility by testing biomechanics during demanding high-injury risk sport-specific tasks under psychological pressure similar to the competition environment. Only once such investigations are completed will it be possible to reach conclusions about the potential role of movement specific reinvestment in sport-related injuries.

The theory of reinvestment proposes that, in addition to psychological pressure, a variety of other contingencies can cause a person to direct attention to conscious movement processing. These include instructions, novel task demands, boredom, and performance errors (Masters & Maxwell, 2008). For the purposes of LESS task standardization, participants received several instructions during testing. The instructions were to jump off the box with both feet, land in front of the designated line, and jump as high as possible upward upon landing (Padua et al., 2009). However, these instructions are unlikely to cause participants to direct their attention towards the mechanics of their movements; indeed, the instruction to jump upward for maximal vertical height is important in LESS testing because it shifts participants' focus towards performance rather than landing mechanics (Padua et al., 2009). Consequently, focusing externally on movement outcomes, in this case on the height of the jump, rather than internally on the movements is likely to have distracted attention away from the movement biomechanics, thereby reducing the likelihood of movement specific reinvestment (Maxwell et al., 2006; Wulf, Weigelt, Poulter, & McNevin, 2003).

With progressing age, degenerative changes affect all body systems and often result in pain, fatigue, muscle weakness, sensory deficits, poor balance, cognitive deficit, and other comorbidities, which are common in the elderly population (Schultz, 1992). All of these signs and symptoms impair mobility and make every movement challenging (Schultz, 1992). It may be that elderly people with movement impairment consciously process movement to avoid pain, falls, or trauma. Increased reinvestment may lead to disturbed movement patterns and greater injury risk compared to low reinvestors, similar to elder fallers who scored significantly higher than non-fallers on the MSRS (Wong et al., 2008). Therefore, it is possible that an association between MSRS scores and injury risk exists and should be further explored in the older population. Furthermore, severity of movement impairment may be positively associated with MSRS scores given that propensity for reinvestment has been shown to be greater in people with stroke compared to age-matched controls (Orrell et al., 2009), and to be positively associated with duration of Parkinson's disease (Masters et al., 2007). Disorder of connective tissue and excessive joint movement increase the likelihood of macro and micro traumas to the musculoskeletal system, which in turn lead to acute and persistent pain, early joint osteoarthrosis, and loss of function in hypermobile individuals (Castori et al., 2017; Tinkle et al., 2017). For instance, hypermobile individuals present with a higher degree of joint osteoarthrosis earlier in life compared to non-hypermobile peers (Tinkle et al., 2017). Therefore, the hypermobile population may present with greater movement impairment and associated pain earlier in life, which may lead to greater conscious processing of movements compared to non-hypermobile age-matched individuals. However, there is no supporting evidence currently available to support or refute that elder hypermobile individuals consciously process movements to a greater extent compared to age-matched non-hypermobile individuals.

The asymptomatic hypermobile participants tested in our study did not exhibit higher MSRS scores compared to non-hypermobile participants. The framework for the classification of joint hypermobility (Castori et al., 2017) used in our study suggests categorising hypermobile individuals as (1) those with asymptomatic joint hypermobility, (2) those with a well-defined syndrome associated with joint hypermobility (e.g., Ehlers Danlos syndrome and Marfan syndrome), and (3) those with symptomatic joint hypermobility. Studies exploring injury risk and anxiety in hypermobile individuals have not differentiated between joint hypermobility groups according to this classification (Dallinga et al., 2012; Donaldson, 2012; Pacey et al., 2010), with most previous studies exploring movement of hypermobile individuals involving children (Fatoye et al., 2011; Junge et al., 2015), symptomatic individuals (Simonsen et al., 2012), or individuals with well-defined disorders (Galli et al., 2011; Rombaut et al., 2011). Based on our knowledge, a single study has involved asymptomatic hypermobile individuals (Luder et al., 2015). In this study, symptomatic hypermobile females showed significantly lower EMG activity for the quadriceps during stair climbing compared to females with normal mobility; however, the EMG activity of asymptomatic hypermobile females did not differ from controls. These results indicate that there may be some clinically relevant differences in neuromuscular control and muscle recruitment patterns between asymptomatic and symptomatic hypermobile individuals that require further exploration. It is possible that our sample of asymptomatic hypermobile individuals adapt to their condition and use strategies to actively stabilize their hypermobile joints during dynamic tasks, which may explain to some extent why they do not suffer from chronic pain and other symptoms typically associated with hypermobility. Therefore, it may be that the asymptomatic hypermobile individuals tested in our study presented with similar injury risk, prevalence for anxiety, and movement control compared to our non-hypermobile individuals, which would explain the lack of significant differences between hypermobile and non-hypermobile participants in terms of MSRS scores. Furthermore, symptoms associated with symptomatic

hypermobility (e.g., chronic pain or fatigue) potentially play a more important role in injury risk and be more strongly associated with MSRS scores compared to hypermobility itself. Therefore, we recommend that future research explores the MSRS in symptomatic hypermobile individuals and individuals with well-defined syndromes associated with joint hypermobility to fully elucidate whether or not conscious monitoring and control of movement plays a role in injury risk or movement control of hypermobile individuals.

Based on our results, propensity for movement specific reinvestment was not significantly associated with injury risk assessed by the LESS, which may be due to the phylogenetic nature of the LESS task and the low-pressure testing environment. Examining the influence of reinvestment on the biomechanics of demanding sport and injury specific tasks under psychological pressure similar to a competition environment is needed to determine whether reinvestment-specific interventions may assist injury prevention efforts. Participants with asymptomatic generalized hypermobility did not present with significantly different MSRS scores compared to non-hypermobile participants. Examination of the MSRS in symptomatic hypermobile individuals and individuals with well-defined syndromes is needed to elucidate whether or not conscious monitoring and control of movement plays a role in these conditions. This information would inform clinical practice and whether implementing motor learning strategies that discourage the propensity for reinvestment is of potential benefit during the rehabilitation process in these population groups.

Conflict of Interest

The authors declare no conflict of interests.

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Appendix A7. *The 'DEEP' Landing Error Scoring System*

Article

The 'DEEP' Landing Error Scoring System

Kim Hébert-Losier [1,*], Ivana Hanzlíková [1], Chen Zheng [2], Lee Streeter [3] and Michael Mayo [2]

[1] Te Huataki Waiora School of Health, Division of Health, Engineering, Computing and Science, University of Waikato, Tauranga 3116, New Zealand; xhanzlikova@gmail.com

[2] School of Computing and Mathematical Sciences, Division of Health, Engineering, Computing and Science, University of Waikato, Hamilton 3216, New Zealand; zhengchenloot@gmail.com (C.Z.); michael.mayo@waikato.ac.nz (M.M.)

[3] School of Engineering, Division of Health, Engineering, Computing and Science, University of Waikato, Hamilton 3216, New Zealand; lee.streeter@waikato.ac.nz

* Correspondence: kim.hebert-losier@waikato.ac.nz; Tel.: +64-7-837-9476

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Featured Application: The Landing Error Scoring System, an injury-risk screening tool used in sports to detect high risk of anterior cruciate ligament injury, can be automated using deep-learning-based computer vision on 2D videos combined with machine learning methods. The successful application of this method paves the way for the automatic detection of individuals at high risk of injury using smartphone-based applications and opens doors to addressing other related injury prevention problems.

Abstract: The Landing Error Scoring System (LESS) is an injury-risk screening tool used in sports; but scoring is time consuming, clinician-dependent, and generally inaccessible outside of elite sports. Our aim is to evidence that LESS scores can be automated using deep-learning-based computer vision combined with machine learning and compare the accuracy of LESS predictions using different video cropping and machine learning methods. Two-dimensional videos from 320 double-leg drop-jump landings with known LESS scores were analysed in OpenPose. Videos were cropped to key frames manually (clinician) and automatically (computer vision), and 42 kinematic features were extracted. A series of 10 × 10-fold cross-validation experiments were applied on full and balanced datasets to predict LESS scores. Random forest for regression outperformed linear and dummy regression models, yielding the lowest mean absolute error (1.23) and highest correlation (r = 0.63) between manual and automated scores. Sensitivity (0.82) and specificity (0.77) were reasonable for risk categorization (high-risk LESS ≥ 5 errors). Experiments using either a balanced (versus unbalanced) dataset or manual (versus automated) cropping method did not improve predictions. Further research on the automation would enhance the strength of the agreement between clinical and automated scores beyond its current levels, enabling quasi real-time scoring.

Keywords: anterior cruciate ligament; automation; drop jump; injury risk; deep learning; machine learning; movement screen; OpenPose

1. Introduction

Lower-extremity injuries due to physical activities have devastating short-term and long-term consequences to the health and wellbeing of individuals [1,2] and burden societies worldwide [3,4]. Non-contact injuries account for approximately 20% of injuries in game situations and 37% of injuries in training situations [5]. Non-contact injuries in sport and recreation are the ones of most practical interest to coaches and clinicians as preventable through neuromuscular training programs [6].

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The mechanism of non-contact lower-extremity injuries and their underlying risk factors have been linked with 'risky' movement patterns [7,8], such as knee valgus and stiff landings. 3D motion analysis systems, which provide gold-standard measures for the objective quantification of human motion noninvasively, can readily identify altered movement patterns and biomechanical control. However, conventional 3D motion analysis using infrared systems requires a considerable financial outlay and an expert-user, in addition to time and space to perform the analysis. These constraints limit its practical application and use for large-scale screening of injury risk factors in physically active individuals.

As a countermeasure and to reduce technological requirements, various clinician-led movement screens have been developed [9]. Even though these clinician-led screens reduce the financial costs and space requirements compared to 3D motion analysis, they nonetheless require expert clinicians and dedicated time for testing and scoring, limiting their widespread use. For instance, the Functional Movement Screen™ takes 12 to 15 min and the Tuck jump assessment takes 12 min to administer and score for one individual [9].

The Landing Error Scoring System (LESS) is one movement screen with demonstrated reliability [10,11] and validity [11,12]. Clinicians evaluate 2D video recordings from three double-leg drop-jump landing tasks per individual to detect 'movement errors' linked to non-contact anterior cruciate ligament (ACL) and other lower-extremity injury mechanisms [10]. The LESS consists of 17 items (Table 1), with the total number or possible errors ranging from 0 (best) to 17 (worst). Greater scores hence indicate more movement errors, poorer landing biomechanics, and greater relative risk of sustaining non-contact lower-extremity injuries. In a prospective study, Padua et al. [12] determined that scoring 5 or more errors on the LESS was associated with a 10.7 times greater relative risk of sustaining a non-contact ACL injury in youth soccer players (sensitivity 0.86, specificity 0.64). The total testing time (including set up) takes ~5 min with 3 to 4 min for a trained rater to score the three drop-jump landing trials of one individual once downloaded to a computer [10].

A few of the drawbacks of the LESS is the subjective nature of the assessment, requirement for an expert-rater, and need to view videos at a later stage [13,14]. In recent years, researchers have striven to automate the LESS to streamline the process using depth sensor cameras [13,15]. Dar, Yehiel, and Cale' Benzoor [13] introduced the PhysiMax system (PhysiMax Technologies Ltd., Tel Aviv, Israel) to automate LESS scoring using a personal computer, 3D Microsoft Kinect, and motion analysis software that requires limited clinical input. Their results indicated high consensus between clinician and PhysiMax LESS scores (intra-class correlation, ICC = 0.80, mean absolute difference 1.13 errors), although the clinician manually inputted the overall impression item (no. 17, Table 1). Despite the automated quantification of the LESS using markerless motion capture using depth cameras provides time-cost saving benefits, there are still additional hardware-software expenditures to consider.

Deep-learning-based computer vision technologies enable the automatic identification and quantification of human motion without the need for depth sensor cameras. Numerous such systems are currently being developed. For example, OpenPose [16] is a system enabling real-time multi-person pose estimation in video streams captured by a camera. The system tracks both body pose as well as keypoints associated with joints and anatomical features. The same technology is also being deployed for solving other related problems, such as tracking lab animal motion in laboratory settings [17,18]. In this work, we aim to apply deep-learning techniques to LESS score estimation. Applying these approaches to 2D video recordings would improve the accessibility to end-users and pave the way to smartphone-based applications for injury risk screening. Our aim is to evidence that LESS scores can be automated from 2D videos using deep-learning-based computer vision with machine learning and compare the accuracy of LESS predictions using different video cropping and machine learning methods. Our work substantiates that: LESS automation is possible without the need for 3D motion analysis or depth sensor cameras, random forest leads to more accurate predictions than linear or dummy (ZeroR) regression models, and that cropping method (manual versus automated) does not affect predictions.

Table 1. Landing Error Scoring System operational definitions of errors. (Adapted from Padua et al. [10].)

No	Item	Definition of Error
1.	Knee flexion IC	Knee flexion < 30°
2.	Hip flexion IC	Thigh is in line with the trunk (hips not flexed)
3.	Trunk flexion IC	Trunk is vertical or extended at the hips (trunk not flexed)
4.	Ankle plantar flexion IC	Heel-to-toe or flat foot landing
5.	Knee valgus IC	The centre of the patella is medial to the midfoot
6.	Lateral trunk flexion IC	The midline of the trunk is flexed to the left or right
7.	Stance width (wide)	Feet are greater than shoulder width apart
8.	Stance width (narrow)	Feet are less than shoulder width apart
9.	Foot (toe-in)	Foot is externally rotated > 30° between IC and KF_{max}
10.	Foot (toe-out)	Foot is internally rotated > 30° between IC and KF_{max}
11.	Symmetric foot contact IC	One foot lands before the other One foot lands heel-toe and the other foot lands toe-heel
12.	Knee flexion displacement	Knee flexes < 45° between IC and KF_{max}
13.	Hip flexion at KF_{max}	Thigh does not flex more on trunk from IC to KF_{max}
14.	Trunk flexion at KF_{max}	Trunk does not flex more from IC to KF_{max}
15.	Knee valgus displacement	At max medial knee position, centre of the patella is medial to the midfoot
16.	Joint displacement	Soft, average, stiff
17.	Overall impression	Excellent, average, poor

Abbreviations: IC, initial contact; KF_{max}, maximal knee flexion.

2. Materials and Methods

2.1. Participants

A sample of 144 individuals (45 males and 99 females) volunteered to participate in this study. Age, height, mass, and body mass index (mean ± standard deviation) for males were 21.0 ± 5.9 years (range 17 to 42 years), 179.1 ± 7.2 cm, and 82.2 ± 13.6 kg; and for females were 17.1 ± 3.7 years (range 12 to 31 years), 169.2 ± 6.1 cm, and 64.8 ± 9.6 kg. All participants were involved in physical activity (34% participated in netball, 19% in rugby, 9% in field hockey, 9% in soccer, and 29% in other sports). On average, participants were involved in physical activity four times per week, 6 h a week. Participants had to be free from injury, pain, or any other issue that would limit physical activity participation. Previous injuries were not an exclusion criterion. Participants were recruited via word-of-mouth, research contacts, social media, and emails sent to local sports clubs. The study protocol was approved by our institution's health research ethics committee [HREC(Health)#41] and adhered to the Declaration of Helsinki. All participants and their legal guardian when younger than 16 years of age signed a written informed consent document that explained the potential risks associated with testing prior to participation.

2.2. Data Collection

We used the original LESS protocol for testing [10]. Participants jumped horizontally from a 30 cm high box to a line placed at 50% of their body height, and immediately jumped upward for maximal vertical height. We placed an emphasis on jumping off the box with both feet, landing in front of the designated line, jumping as high as possible straight up in the air once they landed from the box, and completing the task in a fluid motion. We did not provide any feedback on participants landing technique unless they were performing the task incorrectly. Participants used their own footwear for testing.

After task instructions and practice jumps for familiarization (typically 1), each participant performed three successful trials of the double-leg drop-jump landing task in front of two standard video cameras capturing at 120 Hz (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8 to 73.3 mm (35 mm equivalent focal length of 24–200 mm). We mounted the cameras on tripods placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m. We allowed participants to rest until they felt ready to perform the task again to limit fatigue between the three trials. Total testing time was typically 2 min per participant.

2.3. Clinical LESS

A qualified physiotherapist who completed over 400 LESS evaluations (IH) replayed the videos using the Kinovea software (version 0.8.15, www.kinovea.org), identified the two key frames of initial ground contact (IC) and maximal knee flexion (KF_{max}), and scored all trials using the 17-item LESS scoring sheet (Table 1). The clinician was blinded to the results from the automated computer-vision scoring. A total of 320 double-leg drop-jump landings from the potential 432 trials (3 jumps × 144 participants) were retained for analysis because of certain participants not completing three trials, one or both video files being not usable, or a clear misidentification of time events from the automatic cropper described in the following subsection (i.e., more than 100 ms difference with the clinician).

2.4. Automated LESS

The LESS score prediction algorithm we developed was a multistage process. Generally, the first stage consisted of processing the videos to detect the IC and KF_{max} key frames, which involved running the frontal and lateral videos for each jump through OpenPose v.1.21 [16], and then using a heuristic method to identify the key frames. Once that stage was complete, we extracted measurements from the key frames to use as features for machine learning. The final stage was the score prediction for the drop-jump landing trial from the features using a machine learning algorithm. The entire process is depicted in Figure 1. We further evaluated the predictive accuracy of the final machine learning stage using cross validation.

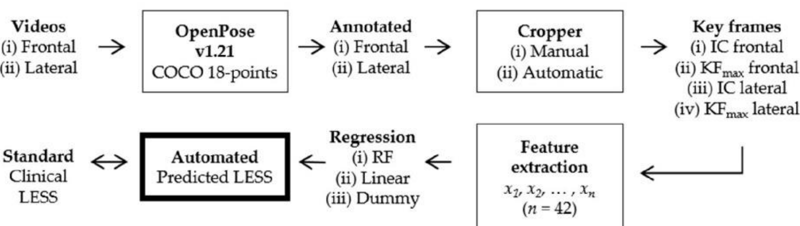

Figure 1. Flow diagram of data processing leading to comparing 'gold standard' clinical LESS scores from an expert rater to 'automated' predicted LESS scores from the automation process. *Abbreviations*: IC, initial contact; KF_{max}, maximal knee flexion; LESS, Landing Error Scoring System; RF, random forest.

In more detail, the algorithm used to detect key frames in the first stage is described in Table 2. The input to the algorithm are the frontal and lateral videos for a single drop-jump landing trial, and the output are cropped versions of the same videos where the first and last frames correspond to the IC and KF_{max} key frames, respectively.

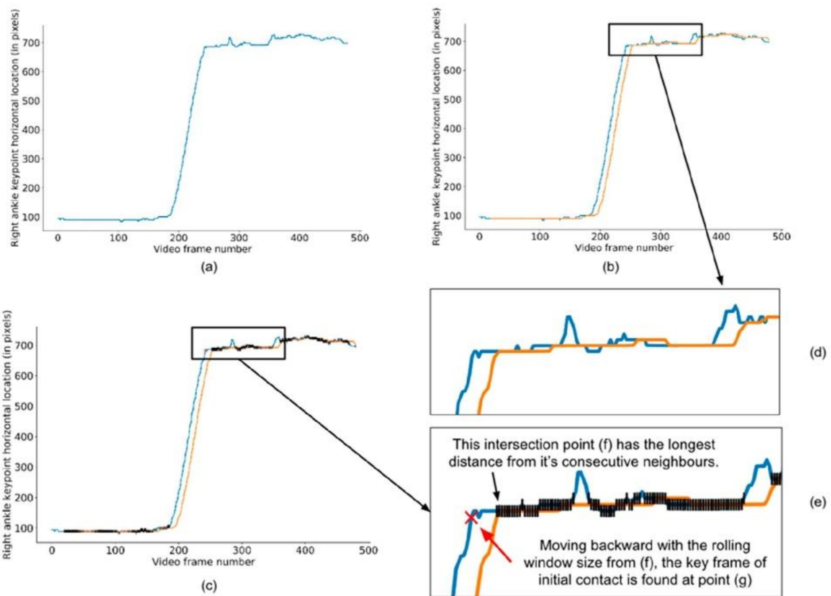

Figure 2. This figure is an example of the original (blue line) plot and rolling window (orange line) plot for the right ankle keypoint of one individual during a drop-jump landing trial taken from the lateral view video. More specifically, (**a**) the blue line depicts the distance of the right ankle to the left boarder (y-axis) in each video frame (x-axis); (**b**) the orange line is the 20-frame rolling median of the original blue line; (**c**) the black bars indicate the intersections of the two lines, whereas the red dotted line represents the distance between two consecutive intersection points. Figure (**d**) is a zoomed-in view of the intersections around the initial contact key frame. Figure (**e**) highlights the points (f) and (g) as the initial contact key frame on the rolling window plot and original plot, respectively.

The basic method is to track the location of the ankles (using OpenPose and COCO 18-points model [16]) across the frames to detect the frame in which landing occurs based on the original and rolling window plots (Figure 2), and additionally to track the body and knee keypoints so that the ankle/knee/body angle can be calculated and used to identify the point of maximum knee flexion. Once these two points are identified in both videos, then the frames before and after the key frames are cropped away. This stage generally reduces the length of the original videos from several seconds down to less than 250 ms.

Once cropping is complete, two videos in which the first frame corresponds to IC and the last frame corresponds to KF_{max} pass to the second stage. In the second stage of processing, features are extracted from both videos and merged into a single 'example' that will be used for machine learning. A total of 42 kinematic features from the two key frames in each video were generated. The features are a mixture of angles between specific OpenPose keypoints (shown in Figure 3) and ratio between distances. The specific features are listed in Table 3. A total of six angles were extracted from all four key frames with an additional eight features (mixture of angles, distances, and distance ratios) being extracted from the two frontal key frames only, for a total of 40 measurements. Two further features, being the length in frames of the cropped frontal and lateral videos, were also included.

Table 2. Algorithm used to detect key frames from the two input videos.

Step	Description
	Input: F, Frontal view video; L, Lateral view video
1.	Obtain the body part keypoints in each frame in both F and L videos using OpenPose
2.	Impute keypoint positions using linear interpolation when not recognized by OpenPose
3.	Find F key frames IC and KF_{max}
3.1.	Based on the coordinates of the left and right ankle (both visible in F), find the intersections of the original and rolling window plots [a] for each ankle
3.2.	Calculate the distances between each consecutive intersection point pairs
3.3.	Find the first point of the pair of intersection points with the longest distances for each ankle
3.4.	Identify the first point of the pair of intersection points that has the lowest x value (i.e., number of frames) as IC
3.5.	Based on the coordinates of the body keypoint, find the intersections of the original and rolling window plots [a]
3.6.	Calculate the distances between each consecutive intersection point pairs
3.7.	Identify the first point of the pair of intersection points with the longest distances as KF_{max}
4.	Find L key frames IC and KF_{max}
4.1.	Based on the coordinates of the individual's right ankle (which is closest to the camera L), find the intersections of the original and rolling window plots
4.2.	Calculate the distances between each consecutive intersection point pairs
4.3.	Identify the first point of the pair of intersection points with the longest distances as IC
4.4	Based on the coordinates of the body keypoint, find the intersections of the original and rolling window [a] plots
4.5.	Calculate the distances between each consecutive intersection point pairs
4.6.	Identify the first point of the pair of intersection points with the longest distances with upper/positive trend as KF_{max}
5.	Crop the videos (F and L) according to IC and KF_{max} key frames.
	Output: F', cropped version of frontal view video; L, cropped version of lateral view video

Notes. [a] Rolling window plot, plot of median values from a rolling 20-frame window. See Figure 2. *Abbreviations.* F, Frontal view video; IC, initial contact; L, Lateral view video KF_{max}, maximal knee flexion.

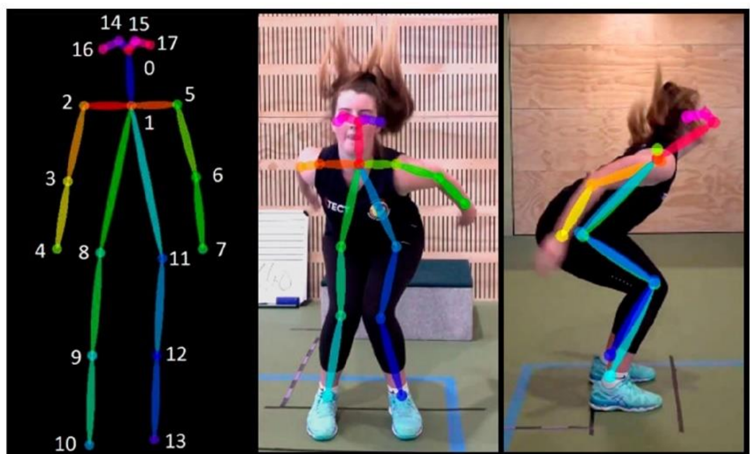

Figure 3. OpenPose's COCO 18-points model keypoint positions (left image) [16] and example of a frontal (middle image) and lateral (right image) view processed video at the maximal knee flexion key frame.

Table 3. Measurements extracted from key frames and used as kinematic features.

Key Frames and Views	Measurement (OpenPose Numbers [a])	Kinematic Features
All four key frames (two frontal key frames and two lateral key frames)	Angle (8,9,10)	Right knee angle
	Angle (9,8,1)	Right hip angle
	Angle (2,1,8)	Right trunk angle
	Angle (3,2,1)	Right shoulder angle
	Angle (4,3,2)	Right elbow angle
	Angle (2,1,0)	Right neck angle
Two key frames (two frontal key frames)	Angle (11,12,13)	Left knee angle
	Angle (1,11,12)	Left hip angle
	Angle (11,1,5)	Left trunk angle
	Angle (1,5,6)	Left shoulder angle
	Angle (5,6,7)	Left elbow angle
	Distance (9,12)	Knee distance
	Distance (2,5)	Shoulder distance
	Distance (9,12)/Distance (2,5)	Knee distance/Shoulder distance

Notes. Key frames are: (i) initial contact, (ii) maximal knee flexion. [a] Refer to Figure 3 for keypoints.

Following feature extraction, we then used a machine learning algorithm to predict the LESS score associated with the drop-jump landing videos. To evaluate the predictive effectiveness of the various machine learning algorithms, we generated features for all 320 drop-jump landings in the dataset using the approach described above. It was also noticed that the distribution of the LESS scores in the dataset was imbalanced, with the majority of LESS scores falling in the range 4–6. Given that unbalanced datasets can potentially affect the accuracy of machine learning techniques, we additionally generated a balanced version of the dataset consisting of 153 drop-jump landing trials with at most 20 trials per LESS score. All evaluations of machine learning techniques were applied to both datasets.

The machine learning techniques chosen to be evaluated were random forest regression, because it is a state-of-the-art machine learning approach and generally performs well 'out of the box' on most problems in practice; and linear regression, which is a widely understood linear modelling technique. Unlike random forest regression, linear regression produces an interpretable model, but it has the disadvantage of being unable to model interactions between features. Given that the full dataset was imbalanced, we also evaluated a dummy regressor (ZeroR) that simply predicts the mean LESS score from the training data. For the original dataset, this method was expected to have reasonably high accuracy, but lower accuracy for the balanced dataset. All machine learning methods implemented were available in WEKA 3.8.0 [19], and returned floating point numbers (i.e., decimals) that added granularity to the data.

2.5. Statistical Method

As noted in Section 2.3, 320 double-leg drop-jump landings were analysed. A series of 10×10-fold cross validation experiments were applied on full (320 videos) and balanced (153 videos, ≤ 20 videos per LESS score) to predict the scores using random forest for regression, linear regression, and dummy regression (ZeroR) models in WEKA [20]. To assess the effectiveness of the automated cropping algorithm in the context of the overall system, we additionally ran the entire pipeline with crops generated by the clinician. Mean absolute error and Pearson correlation coefficient (r) were calculated to assess the accuracy of the predictions. Predictions were then converted to a binary category and sensitivity-specificity for categorising individuals at high risk of non-contact ACL injury (LESS ≥ 5 errors [12]) were assessed for each method. The outcomes of the models were compared using paired corrected t-tests in WEKA [20], and the timestamps of the key frames IC and KF_{max} respectively compared between manual (clinician) and automated (OpenPose) cropping methods using unpaired t-tests assuming homoscedasticity. Since the LESS score was treated as a regression problem, actual (clinical LESS) versus predicted (automated LESS) and Bland-Altman [21] plots were used to allow for a visual inspection of the models. Statistical significance was set at $p \leq 0.05$.

3. Results

The mean LESS score from the 320 drop-jump landings was 5.5 ± 1.8 errors (range 0 to 12 errors) as rated by the clinician. The absolute time difference between manually identified IC and KF_{max} was 26.5 ± 17.0 (p = 0.484) and 32.8 ± 18.0 ms (p = 0.445) for the frontal videos, and 53.5 ± 16.2 (p = 0.125) and 20.8 ± 16.3 ms (p = 0.827) for the sagittal videos.

Random forest yielded the lowest mean absolute error (1.23) and greatest correlation (r = 0.63) between actual and predicted scores based on results from the cross validation experiments (Table 4). Sensitivity (0.82) and specificity (0.77) were reasonable for high (LESS ≥ 5 errors) and low (LESS < 5 errors) injury risk categorisation. Experiments using a balanced (versus unbalanced) dataset or manually (versus automated) cropping methods did not improve predictions. An actual versus predicted plot from the random forest regression is depicted in Figure 4, and two Bland-Altman plots on the same dataset in Figure 5. Note that both conventional (mean difference ± 1.96 standard deviation) and regression-based (regressed difference between methods on the mean of the two methods ± 2.46 standard deviation of the residual) Bland-Altman plots were generated given the non-uniform differences in mean [21].

Table 4. Results from machine learning experiments.

Cropper	Dataset	Mean Absolute Error (n Errors)			Correlation (r)		
		RF	Linear	Dummy	RF	Linear	Dummy
(i) Manual	(i) Full	1.23 ± 0.18	1.39 ± 0.20 *	1.44 ± 0.20 *	0.52 ± 0.15	0.39 ± 0.14 *	0.0 ± 0.0 *
	(ii) Balanced	1.57 ± 0.27	1.90 ± 0.61	2.08 ± 0.34 *	0.60 ± 0.15	0.48 ± 0.21 *	0.0 ± 0.0 *
(ii) Automatic	(i) Full	1.23 ± 0.18	1.32 ± 0.20 *	1.44 ± 0.20 *	0.53 ± 0.15	0.44 ± 0.16 *	0.0 ± 0.0 *
	(ii) Balanced	1.56 ± 0.29	1.63 ± 0.32	2.08 ± 0.32 *	0.63 ± 0.17	0.51 ± 0.20 *	0.0 ± 0.0 *
Cropper	**Dataset**	**Sensitivity [a]**			**Specificity [a]**		
		RF	Linear	Dummy	RF	Linear	Dummy
(i) Manual	(i) Full	0.80 ± 0.09	0.75 ± 0.09	1.0 ± 0.0 *	0.50 ± 0.18	0.51 ± 0.18	0.0 ± 0.0 *
	(ii) Balanced	0.77 ± 0.13	0.73 ± 0.13	1.0 ± 0.0 *	0.73 ± 0.18	0.63 ± 0.21	0.0 ± 0.0 *
(ii) Automatic	(i) Full	0.82 ± 0.07	0.77 ± 0.09 *	1.0 ± 0.0 *	0.52 ± 0.19	0.52 ± 0.18	0.0 ± 0.0 *
	(ii) Balanced	0.76 ± 0.15	0.77 ± 0.13	1.0 ± 0.0 *	0.77 ± 0.19	0.70 ± 0.21	0.0 ± 0.0 *

Notes. Values are means ± standard deviations. *Abbreviations*. RF, random forest. * Significant difference versus random forest ($p \leq 0.05$) using paired-corrected t-tests. [a] Categorising high (LESS ≥ 5 errors) and low (LESS < 5 errors) injury risk individuals [12].

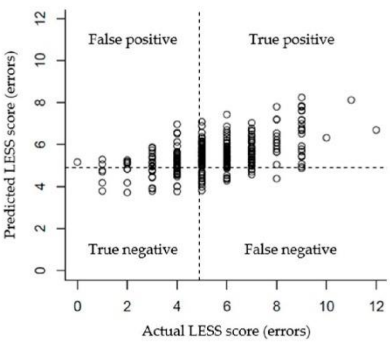

Figure 4. Actual (clinical) versus predicted (automated) LESS score plots from the random forest regression using full dataset (n = 320) and automatic cropping method. Dashed lines represent the 5-error threshold that defines high risk of injury (i.e., scoring 5 or more errors during LESS has been associated with a 10.7 times greater relative risk of sustaining a non-contact anterior cruciate ligament injury [12]). Note that the clinical scores are integers and predicted scores are decimals, which adds granularity. *Abbreviations*: LESS, Landing Error Scoring System.

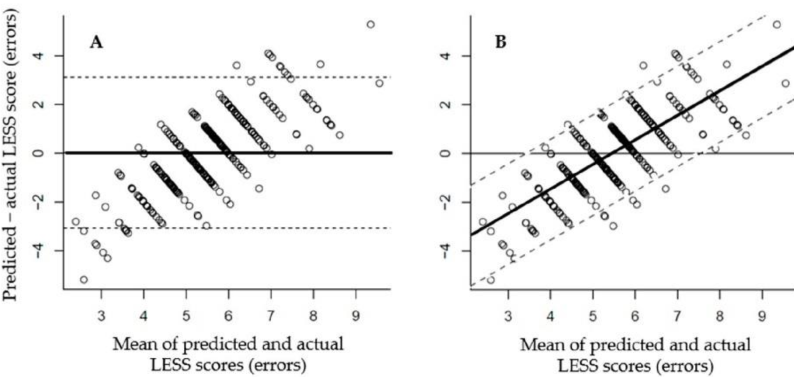

Figure 5. Bland-Altman [21] plots depicting the difference in predicted (automated) and actual (clinical) LESS scores versus the mean scores with (**A**) conventional 95% limits of agreement (mean difference ± 1.96 standard deviation), and (**B**) regression-based limits of agreement (regressed difference between methods on the mean of the two methods ± 2.46 standard deviation of the residual).

4. Discussion

The use of the LESS to assess injury risk is common in sport science and clinical practice [9,22], but scoring is time consuming, clinician-dependent, and generally inaccessible for large-scale screening outside of elite sports. This study provides evidence that the LESS can be automated using deep-learning-based computer vision combined with machine learning methods without the need for 3D motion analysis or depth sensor cameras. A clear benefit of automating LESS scoring is immediate feedback to end-users. The successful application of this method paves the way for the automatic detection of individuals at high risk of injury using smartphone-based applications of LESS videos (Video S1: https://youtu.be/q1wiGt4K8MU).

The characteristics of an ideal injury risk screening tool are good reliability, validity, and predictive value for injury incidence. In practical or field settings, an ideal screening method is easy to administer without an expert, and has minimal financial, spatial, and temporal requirements. Ideally, the screening tool provides immediate results and is accessible to everyone, from the recreational to elite athlete, as well as novice to expert rater. Overall, the LESS responds to most of these stated requirements. The test demonstrates acceptable reliability and validity [10,11,23], as well as predictive value for non-contact ACL injury using a threshold of 5 errors [12]. The inter-rater reliability of the total LESS score is good to excellent, with ICC ranging from 0.83 to 0.92 [10,11,23] and typical errors at 0.71 LESS errors [10]. The results from the current study indicate that the typical errors from the automated processing and scoring of the LESS through computer vision when applying the random forest model (Table 2) are less than half an error greater than scores taken from two expert clinicians. In fact, certain individual LESS items yield suboptimal psychometric properties between raters and 3D motion analysis [23]. More specifically, no significant agreement between raters was found for knee and trunk flexion at IC, and poor agreement between rater and 3D motion capture analysis was found for knee flexion at IC, lateral trunk flexion at IC, and symmetric foot contact at IC [23]. As such, a certain level of disagreement between clinical ratings and computerised ratings is expected.

As seen in Figures 4 and 5, the estimated error is not uniform across the range of LESS scores, but depends on the target. For example, trials with a low actual LESS score tend to have a positive error (the prediction is an overestimation) and trials with a higher actual LESS score tend to have a negative error (the prediction is an underestimation). If these biases stemmed from the over representation of the mid-range LESS values (i.e., majority of LESS scores falling in the range 4–6), the balanced dataset should have provided more accurate predictions, which was not the case. It might be possible

to attempt correcting predictions to improve accuracy in future work using probability calibration methods, such as Platt Scaling and Isotonic Regression. The large errors in LESS score predictions were attributed to inaccurate foot and IC key frame detection. The newest body model in OpenPose (Body 25) contains 25 points, including coordinates that define the feet and enable computations of angles at the ankles [24]. Improving the LESS score automation relies on either refining body part detection or training a new system specifically to solve this problem.

In previous research, depth sensor technology has been used to automate LESS scoring [13,15]. Comparisons between automated and expert clinicians indicate a mean difference of 1.20 errors [15], mean absolute difference of 1.13 errors [13], intra-class correlation of 0.80 [16], and percentage agreement of the individual items ranging from 55–100% [13,15]. These research findings are comparable to our lowest mean absolute error (1.23), greatest correlation (r = 0.63), and agreement in risk classification (sensitivity 0.82, specificity 0.77) between actual and predicted scores from the cross validation experiments using random forest regression. In contrast to the PhysiMax system [13,15], our approach did not require the clinician to add the overall impression manually (no. 17 in Table 1) given that the LESS items were not scored one-by-one. Although the lack of individual-item scores might be perceived as a limitation of the deep LESS approach; no subjective rating from the clinician or hardware other than a handheld camera or smart portable device are required. Furthermore, only the final LESS score has shown predictive value in terms of injury risk [12]; hence, the individual items are of lesser clinical value.

The better accuracy achieved by random forest can be explained by the fact that the features (angles, distances, and ratios) are likely correlated and related in a non-linear manner. Decision tree ensembles in general are better able to cope with correlated variables and model non-linear patterns [25]. Linear regression, on the other hand, achieves optimal results when the predictor variables are independent and do not interact. We also foresee a possibility of processing the raw video images themselves and attempting direct deep learning-based classification with minimal pre-processing. Such an approach would obviate the need to use OpenPose or a similar pose-tracking tool. However, taking such an approach would be challenging because of the lack of training data relative to size of datasets usually used to train deep image recognisers. Another significant disadvantage of the proposed approach is that deep learning needs GPU-based acceleration hardware, and is therefore currently unable to process videos independently on consumer smartphones. That said; the rapidly increasing computational power of consumer smartphones and the current trend in research of compressing deep models [26] so that they run efficiently on mobile devices should solve this problem in the next few years.

One of the main concerns in clinical screening tools are their subjective nature and reliance on visual observations to estimate angles, which are challenging to quantify accurately [27,28]. During the LESS, a small kinematic difference (e.g., knee angle 29°, 1—error present; knee angle 30°, 0—error absent) can result in poor agreement between raters and between clinical LESS scores and motion capture scores. Recent technological advances have allowed the more objective quantification of human motion using wearable technology [29,30]. Inertial measurement units are able to measure linear and angular motion of individual body segments and centre of mass, and are proposed as more accurate means of identifying risky movement patterns than through visual observations [31]. Although inertial measurement units are relatively inexpensive; they are not commonly used in clinical environments and an expert is still needed to process and interpret data signals. The automated scoring process here developed using standard video recordings offers an alternative solution that can possibly improve consistency of LESS ratings, removing the subjective interpretation of the task. Moving forward, the reliability of deep LESS scores, validity of OpenPose derived data during the dynamic double-leg drop-landing task, and predictive ability of the method need empirical support.

An indisputable advantage of automated scoring using deep-learning-based computer vision combined with machine learning methods or markerless methods from depth sensor cameras is immediate results and feedback to patients, athletes, coaches, or healthcare professionals.

Our developed method that automates LESS scores provides a viable solution to decreasing scoring time, increasing accessibility to non-expert raters, and delivering immediate results without any additional expenditure other than conventional video recordings. Conventional 2D video recordings are adequate for quantifying kinematics [32–34] and are readily accessible through tablets or smartphones. The successful application of this method would pave the way for the automatic detection of individuals at high risk of injury using smartphone-based applications of LESS and 2D video footage (Video S1: https://youtu.be/q1wiGt4K8MU). Other than expediting mass injury risk screening initiatives in youth or team sports, LESS automation could be a valuable and convenient tool to track injury risk factors over time and to assess the effectiveness of intervention programs at improving landing mechanics (Video S2: https://youtu.be/Ve_QJu0fuLs). The proposed method could be extended to other injury risk screening methods based on 2D camera recordings to decrease manual labour and time required for screening initiatives; e.g., the Cutting Movement Assessment Scale [35] and Tuck jump assessment [36].

This preliminary investigation provides evidence that it is feasible to automate the LESS from 2D video recordings alone. Further research could lead to improved automation outcomes and enhance the strength of the agreement between clinical and automated LESS scores beyond its current levels. The newest body model in OpenPose (Body 25) contains 25 points, including coordinates that define the feet and enable computations of angles at the ankles [24]. Although the timestamped IC key frame in frontal and sagittal videos were comparable between the clinician and scripted process (mean difference: 32.8 ms, $p = 0.445$ and 20.8 ± 16.3 ms, $p = 0.827$), using the foot coordinates rather than ankle and body coordinates would certainly enhance precision. A number of videos from the available dataset were not used because of a clear misidentification of time events from the automatic cropper (i.e., more than 100 ms). We were unable to determine the reason underlying the mislabelling of these videos upon visual inspection. We speculate that rerunning the current experiment using the COCO + Foot model might lead to the correct identification of key events in a greater number of our database videos, increasing the number of eligible videos for analysis. The increased number of coordinates from the 25-point Body rather than 18-point COCO model would also allow us to extract a greater number of features from the processed videos and use these as input in the subsequent regression experiments.

5. Conclusions

We provide evidence that the Landing Error Scoring System (LESS)—an injury-risk screening tool—can be automated using deep-learning-based computer vision combined with machine learning methods. Further research on the automation would enhance the strength of the agreement between clinical (gold standard) and automated (predicted) LESS scores, and risk classification beyond its current levels. Automation of the LESS using standard 2D recordings would facilitate mass injury-risk screening initiatives with quasi real-time feedback, without the need of depth cameras or expert clinicians. The successful application of this method would pave the way for the automatic detection of individuals at high risk of injury using smartphone-based applications of LESS and 2D video footage (Video S1: https://youtu.be/q1wiGt4K8MU), increasing accessibility of injury-risk assessment methods beyond elite athletes and removing depth-sensor camera requirements. It may also open doors to other related injury prevention problems. Future work includes updating the framework using the newest body model in OpenPose (Body 25) to extract a greater number of features and more accurately detect key frames.

Supplementary Materials: The following are available online: https://youtu.be/q1wiGt4K8MU. Video S1: LESS demonstration. https://youtu.be/Ve_QJu0fuLs. Video S2: The 'DEEP' Landing Error Scoring System.

Author Contributions: Conceptualization, K.H.-L.; methodology, K.H.-L.; formal analysis, K.H.-L., L.S., M.M.; investigation, K.H.-L., I.H.; data curation, I.H., C.Z.; writing—original draft preparation, K.H.-L., I.H.; writing—review and editing, K.H.-L., I.H., C.Z., L.S., M.M.; supervision, K.H.-L., M.M.; project administration, K.H.-L.; funding acquisition, K.H.-L., L.S., M.M. Authorship must be limited to those who have contributed substantially to the work reported. All authors have read and agreed to the published version of the manuscript.

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Appendix B. Conference presentations arising from this thesis.

Appendix B1. *Landing Error Scoring System: Injury risk screening tool.*

LANDING ERROR SCORING SYSTEM
Injury risk screening tool

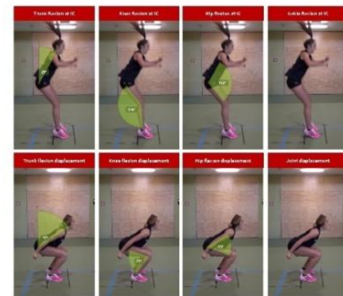
Ivana Hanzlíková, Kim Hébert-Losier

xhanzlikova@gmail.com, heblos@waikato.ac.nz

Faculty of Health, Sport and Human Performance, Adams Centre for High Performance, The University of Waikato, New Zealand

INTRODUCTION

Neuromuscular and biomechanical factors are often highlighted as important factors to address prevention of non-contact injuries, as these are potentially modifiable factors through training. The Landing Error Scoring System (**LESS**) is a 17-item clinical-based assessment tool to identify individuals displaying potentially high-risk biomechanics patterns during a drop-jump task. The **LESS** is scored by clinicians who evaluate aberrant lower extremity and trunk kinematics based on frontal and sagittal plane videos. This work systematically reviews the literature using the **LESS** as main outcome to address the psychometric properties and influencing factors of **LESS** scores.



METHODS

Three electronic databases were searched in March 2018 using "Landing Error Scoring System". All peer-reviewed English language articles using the **LESS** as main outcome were included (n = 38).

RESULTS

- 🙂 **LESS** scores demonstrate good-to-excellent reliability, but concurrent validity of individual items against 3D motion capture is item dependent.
- ☹️ The association between **LESS** scores and other screening tools is poor.
- 🤔 The value of the **LESS** for predicting anterior cruciate ligament (ACL) injury incidence is unclear.
- 🧐 Sex, previous ACL injury, and training program influence **LESS** scores (Figure).

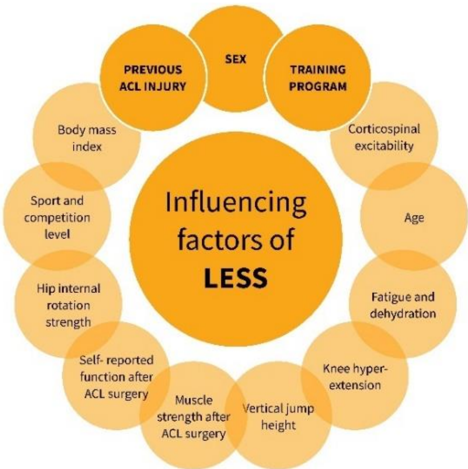


Figure. Factors proposed to influence **LESS** scores. The three factors with strong evidence are bolded.

CONCLUSION

Literature supports that the **LESS** is a reliable and generally valid screening tool for assessing movement patterns linked with injury risk with low financial, spatial, and temporal costs. Further work is needed to improve its concurrent and predictive validity for non-contact lower-extremity injuries.

Appendix B2. *Comparing two Landing Error Scoring System protocols: Same but different!*

17.Comparing two Landing Error Scoring System protocols: Same but different!

Hébert-Losier, K; **Hanzlíková, I**; Beaven, CM

University of Waikato

Introduction: The Landing Error Scoring System (LESS) screens for risk of non-contact lower-extremity injuries. The original LESS requires individuals to jump down from a 30-cm box to 50% of body height. However, clinicians and scientists often do not dictate landing distance during LESS assessment. This study examines whether landing distance influences LESS score and risk categorisation. **Method**: Seventy volunteers (34 males, 36 females) performed 3 x 30-cm drop-jumps under two landing conditions: (1) 50% of body height, (2) no set distance. The average LESS score and proportion of individuals categorised at high (LESS ≥ 5) and low (LESS < 5) risk were

compared. **Results:** LESS scores (difference: -0.01 ± 1.49, paired t-test p = 0.947) and proportion of individuals at high and low risk (odds ratio: 1.09, McNear test p = 1.00) were similar between conditions. However, risk categorisation was inconsistent for 23 participants (33%). **Discussion:** At a group-level, LESS score and risk categorisation was similar between the two landing distances examined. However, at an individual-level, landing distance influenced risk categorisation in one-third of the sample. **Take home message:** When tracking changes in movement patterns linked with injury risk, using a consistent LESS protocol is recommended.

Appendix B3. *Landing Error Scoring System calculation method can make an important difference!*

Appendix B4. *The deep Landing Error Scoring System.*

The Deep Landing Error Scoring System

Kim Hébert-Losier*, Ivana Hanzlíková, Chen Zheng, Lee Streeter, Michael Mayo

*Email: heblos@waikato.ac.nz

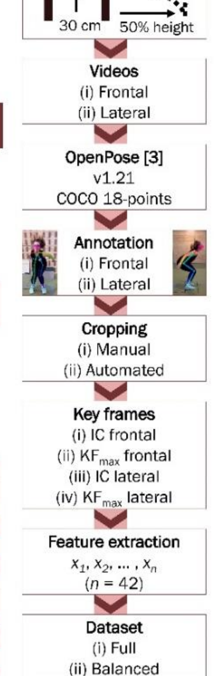
Division of Health, Science, Computing and Engineering, University of Waikato, New Zealand

INTRODUCTION

The **LESS** (Landing Error Scoring System) is a reliable and valid injury-risk screening tool [1,2]; but scoring is clinician-dependent and time consuming. **DEEP LEARNING** methods now enable the automatic quantification of human motion. Our **AIMS** were to evidence that LESS scores can be **AUTOMATED** using **DEEP LEARNING** based computer vision combined with **MACHINE LEARNING**, and compare LESS predictions between cropping (manual vs automated) and machine learning (random forest, linear, dummy regression) methods.

METHODS

Videos from **320** drop-jump landings with LESS scores (range: 0–12 errors) from an expert clinician were analysed (Fig 1). Validation experiments (10 x 10-fold cross validation) on full (n = 320) and balanced (n = 153, $n \leq 20$ per score) datasets were applied to predict LESS scores using three regression models.



RESULTS & DISCUSSION

RANDOM FOREST outperformed linear and dummy regression (Table), yielding the lowest **MEAN ABSOLUTE ERROR** and highest **CORRELATION** between clinical (gold standard) and predicted (automation) scores, reaching reasonable **SENSITIVITY** and **SPECIFICITY**. Using a balanced dataset or manually cropped videos did not improve predictions.

		Mean absolute error			Pearson correlation		
Cropping	**Dataset**	**Random forest**	**Linear**	**Dummy**	**Random forest**	**Linear**	**Dummy**
(i) Manual	(i) Full	1.23 ± 0.18	1.39 ± 0.20*	1.44 ± 0.20*	0.52 ± 0.15	0.39 ± 0.14*	0.0 ± 0.0*
	(ii) Balanced	1.57 ± 0.27	1.90 ± 0.61	2.08 ± 0.34*	0.60 ± 0.15	0.48 ± 0.21*	0.0 ± 0.0*
(ii) Automated	(i) Full	1.23 ± 0.18*	1.32 ± 0.20*	1.44 ± 0.20*	0.53 ± 0.15	0.44 ± 0.16*	0.0 ± 0.0*
	(ii) Balanced	1.56 ± 0.29	1.63 ± 0.32	2.08 ± 0.32*	0.63 ± 0.17	0.51 ± 0.20*	0.0 ± 0.0*
		Sensitivity§			Specificity§		
Cropper	**Dataset**	**Random forest**	**Linear**	**Dummy**	**Random forest**	**Linear**	**Dummy**
(i) Manual	(i) Full	0.80 ± 0.09	0.75 ± 0.09	1.0 ± 0.0*	0.50 ± 0.18	0.51 ± 0.18	0.0 ± 0.0*
	(ii) Balanced	0.77 ± 0.13	0.73 ± 0.13	1.0 ± 0.0*	0.73 ± 0.18	0.63 ± 0.21	0.0 ± 0.0*
(ii) Automated	(i) Full	0.82 ± 0.07	0.77 ± 0.09*	1.0 ± 0.0*	0.52 ± 0.19	0.52 ± 0.18	0.0 ± 0.0*
	(ii) Balanced	0.76 ± 0.15	0.77 ± 0.13	1.0 ± 0.0*	0.77 ± 0.19	0.70 ± 0.21	0.0 ± 0.0*

*Significant difference versus random forest ($p < 0.05$). §For identifying high-risk individuals (LESS ≥ 5 errors).

TAKE HOME

THE LESS CAN BE AUTOMATED USING DEEP LEARNING BASED COMPUTER VISION COMBINED WITH MACHINE LEARNING

[1] Padua DA et al. (2015). *J Athl Train*, **50**: 589-95. [2] Onate et al. (2010). *J Sport Rehabil*, **19**: 41-46. [3] Cao Z et al. (2018) CVPR; arXiv:1611.08050v2.

This work was funded by a University of Waikato Strategic Investment Fund 2018 Medium Research Grant.

Appendix B5. *Landing Error Scoring System (LESS): LESS knowledge, more useful!*

Landing Error Scoring System (LESS): LESS knowledge, more useful

Kim Hébert-Losier*, Ivana Hanzlíková

*Email: heblos@waikato.ac.nz, xhanzlikova@gmail.com

Division of Health, Science, Computing and Engineering, University of Waikato, New Zealand

ADAMS CENTRE FOR HIGH PERFORMANCE

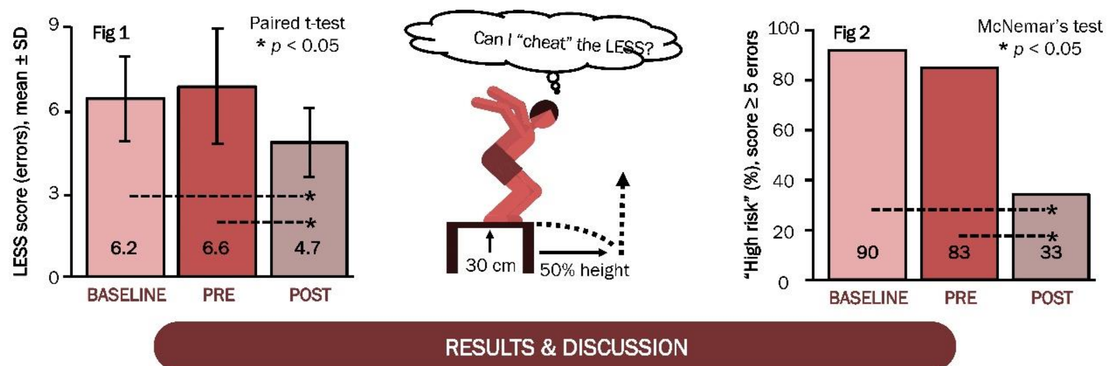
INTRODUCTION

Clinicians use **MOVEMENT SCREENS** daily to identify individuals at high risk of injury. The **LESS** (Landing Error Scoring System) is a valid and reliable injury risk screening tool [1,2]. Clinicians score the number of "movement errors" (0 to 17 errors) seen during drop-jump landings [3], where more errors (≥ 5) indicate a greater risk of injury.

Performance of individuals on the FMS™ movement screen can change with **KNOWLEDGE** of scoring criteria [4]. Conscious alterations in movement can mask innate injury risk and movement abilities. Our **AIMS** were to compare **LESS** scores and **RISK** category before and after providing LESS score information.

METHODS

THIRTY volunteers (50% female) completed 3 x 30-cm drop-jumps for LESS scoring three times [4] with 120 Hz videos: (1) **BASELINE** and 1-week later (2) **PRE** information and (3) **POST** information. Before the Post condition, an expert clinician explained all 17 LESS items to volunteers and their baseline LESS scores (i.e., errors).



RESULTS & DISCUSSION

LESS scores (Fig 1) and percentage of the cohort "at **RISK**" (Fig 2) were significantly **LOWER** in **POST** than **BASELINE** and **PRE** conditions. **LESS** scores (Fig 1) and percentage "at **RISK**" (Fig 2) were **SIMILAR** between **PRE** and **BASELINE**.

When the **LESS** is used to assess injury **RISK** or track changes in movement patterns, it is important that individuals have no prior **KNOWLEDGE** of the scoring criteria for valid assessment of innate movement abilities and injury risk.

TAKE HOME

PEOPLE CAN "CHEAT" THE LESS TEST KNOWING HOW IT IS SCORED, NULLIFYING ITS CLINICAL UTILITY IN INJURY PREVENTION EFFORTS.

[1] Padua DA et al. (2015) *J Athl Train*, **50**: 589-95. [2] Onate et al. (2010) *J Sport Rehabil*, **19**: 41-46. [3] Padua DA et al. (2009) *Am J Sports Med*, **37**: 1996-2002. [4] Frost et al. (2015) *J Strength Cond Res*, **29**: 3037-44.

The authors acknowledge Akshatha Ananth for her assistance during data collection. This work was funded (in part) by a University of Waikato Strategic Investment Fund 2018 Medium Research Grant.

Appendix B6. *Propensity for conscious control of movement is unrelated to hypermobility or injury-risk scores.*

tactical principles is derived from interactions between multiple players highlighting that, in high level netball, turnovers typically result from the team dynamics rather than from individual player behaviours (i.e., a poorly executed pass). Therefore, when using game statistics to assess performance it is important to acknowledge that errors and successes are the result of the interactions of multiple players on court, and not solely a reflection of individual players' tactical ability. In this context, the (TPG) has been incorporated into a Netball NZ player profiling tool as it is seen to be the first step in enhancing the effectiveness of coach and player communication, tactical behaviour assessment, as well as informing selection processes.

Use of a brake power meter to quantify skill in mountain biking

Fink, P.[1], & Miller, M.[1]

[1]*School of Sport, Exercise, and Nutrition, Massey University*

Power meters for measuring pedalling power have become widely used in the sport of cycling. Here, we use a similar technology to measure the power taken away from the bicycle through braking. We have developed and patented a brake power meter, which was subsequently validated by comparison to reductions in kinetic energy during braking events. The current research is designed to identify differences between skill levels in regards to braking.

Participants completed two laps of a mountain bike course at a "race pace". The brake power meter recorded instantaneous braking power. The downhill portions of the course were then analysed to find correlations between different braking variables and the time to complete the downhills. The highest correlations (R^2=.93) were found between time and a normalized brake power, where power was divided by the instantaneous kinetic energy of the rider and bicycle and then integrated over the downhill section.

The brake power meter is a valid method for measuring braking during mountain biking. Moreover, differences in skill levels and performance can be determined using the normalized brake power. This technology could be used in the future to provide feedback during training and competitions to improve descending performance.

(Thres)Hold my beer while I use executive functions as a talent identification tool in football

Fransen, J.[1], Beaven, A. [1,2,3,8], Chin, V. [4,5], Ryan, L. [4,6,7]

[1] *Institute of Sports and Preventive Medicine, Saarland University, Saarbrücken, Germany.*
[2] *Sport and Exercise Discipline Group, Faculty of Health, University of Technology, Sydney, Australia.*
[3] *Think Tank, DFB-Akademie (Deutscher Fußball-Bund), Frankfurt, Germany.*
[4] *Australian Research Council Centre of Excellence for Mathematical & Statistical Frontiers, The University of Melbourne, Victoria, Australia.*
[5] *School of Mathematics and Statistics, University of New South Wales, Sydney, Australia.*
[6] *School of Mathematical and Physical Sciences, University of Technology Sydney, Sydney, Australia.*
[7] *Harvard T.H. Chan School of Public Health, Harvard University, Cambridge, USA.*
[8] *TSG 1899 Hoffenheim, Zuzenhausen, Germany.*

Executive functions (EF), such as response inhibition, working memory updating, attention shifting and action planning, are higher-level cognitive functions for regulating attention, thoughts and action, which have previously been associated with performance in football (Vestberg et al., 2017). However, no study has investigated longitudinal changes in EF in a cohort of elite athletes to examine if increased exposure to high level training is related to superior EF performance. This study used 1-6 observations of EF in 304 German football players aged between 10-21 years. Individual and age-cohort specific segmented linear models were developed using a Bayesian approach to structural equation modelling to describe the 'breakpoints' associated with the development of domain-generic and domain-specific EF measured using a battery of five EF assessments.

The results revealed that the slopes for domain-generic and domain-specific EF decreased with increasing age (domain-generic: late childhood 29.4 (22.6-36.8), adolescence 24.8 (21.3-28.0), post adolescence 6.4 (2.9-9.9), adulthood 8.71 (5.1-12.0); domain-specific: late childhood 0.5 (0.1-0.9), adolescence 1.1 (0.9-1.3), post adolescence 0.1 (0.0-0.2), adulthood 0.1 (0.0-0.3) arbitrary units). Furthermore, no consistent influence of field position was observed, with only goalkeepers scoring worse than on-field players.

Despite previous research showing a positive relationship between EF and sporting expertise (i.e., the higher the EF the more expert the performer, Sakamoto et al., 2018), this study showed that in elite populations, just like in a general population, improved EF are likely a result of the maturation of the central nervous system (Zelazo et al., 2004), rather than a result of increased exposure to high level sport. Additionally, EF likely adhere to the 'threshold hypothesis', where increases in EF are only related to performance below a certain EF threshold. Therefore, their use as a prognostic tool in talent identification and development in high level athletes is questionable.

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Propensity for conscious control of movement is unrelated to hypermobility or injury-risk scores

Hanzlíková, I.[1], Masters, R.S.W.[1], Hébert-Losier, K.[1]

[1]*Te Huataki Waiora School of Health, University of Waikato*

The Movement Specific Reinvestment Scale (MSRS) measures the propensity for conscious control of movement. Conscious control can inhibit automated movement processes, potentially causing movement disruption or injury. Hypermobile individuals present with poor movement control or clumsiness, and high injury risk individuals make more movement errors during jump-landing tasks. Consequently, we examined propensity for movement specific reinvestment in hypermobile and high injury risk participants.

Sixty volunteers (35 males, 25 females) were tested using the MSRS, Beighton hypermobility scale, and Landing Error Scoring System (LESS). Spearman rank correlation coefficients were computed between MSRS, Beighton, and LESS scores. Furthermore, MSRS scores were compared between non-hypermobile and hypermobile, as well as high (LESS ≥ 5) and low (LESS < 5) injury risk participants.

MSRS was not significantly related to Beighton ($\rho = 0.09$, $p = 0.481$) or LESS ($\rho = 0.06$, $p = 0.625$) scores. MSRS scores between non-hypermobile and hypermobile (37.55 ± 9.10 vs 38.59 ± 6.86, $p = 0.619$), and low and high injury risk (37.81 ± 7.84 vs 38.00 ± 8.64, $p = 0.931$) participants were comparable.

The origin of poor movement control in hypermobile individuals stems from genetic alterations in connective tissue and proprioceptive deficits, with propensity for movement specific reinvestment not appearing to be a relevant factor. Based on our results, there is also no evidence that movement specific reinvestment contributes to injury risk, which might be due to the phylogenetic and dynamic nature of the LESS jump-landing task.

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Innate injury risk scores change with knowledge of the grading criteria

Hebert-Losier, K.[1]

[1]*Te Huataki Waiora School of Health, University of Waikato*

Clinicians examine movement patterns during dynamic tasks to identify athletes at high risk of injury. The Landing Error Scoring System (LESS) is one clinical tool used for this purpose. In less dynamic movement screen assessments than the LESS, individuals with knowledge of scoring criteria are able to alter their innate movement patterns during testing to 'better' their score. We compared LESS scores and risk categorisation before and after providing scoring criteria and information on performance to thirty volunteers. Participants performed 3 x 30-cm drop-jumps for LESS scoring at Baseline and one week later under two conditions: Pre and Post knowledge of scoring criteria and performance. Baseline and Pre errors were similar (6.2 ± 2.5 versus 6.6 ± 2.0, $p = 0.186$), as was the percentage of individuals at high risk (90 vs 83%, p = 0.688). In contrast, LESS errors (4.7 ± 1.2, $p < 0.001$) and percentage of individuals at high risk (33%, $p < 0.001$) were significantly lower after individuals were provided with scoring criteria compared to Baseline and Pre. The clinical utility of LESS to identify high injury-risk biomechanics and athletes is compromised with prior knowledge of scoring criteria and performance.

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Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E., Jr., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *The American Journal of Sports Medicine*, 37(10), 1996-2002. doi:10.1177/0363546509343200

Padua, D. A., DiStefano, L. J., Beutler, A. I., de la Motte, S. J., DiStefano, M. J., & Marshall, S. W. (2015). The Landing Error Scoring System as a screening tool for an anterior cruciate ligament injury-prevention program in elite-youth soccer athletes. *Journal of Athletic Training*, 50(6), 589-595. doi:10.4085/1062-6050-50.1.10

Action deception in combat sports – the case of *muay thai*

Hjortborg, SK.[1]

[1]*Department of Cognitive Science, Faculty of Human Sciences, Macquarie University*

This paper examines deceptive actions in combat sports. The research uses a cognitive ethnographic approach to address questions on the nature of deceptive actions and the coregulative interaction processes that underlie behavioural dynamics in unique performance settings. I make my key points through ethnographic research on specialised martial arts practices that I have conducted throughout the last six months and particularly zoom in on a decisive moment at the *Yokkao muay thai* fight event 2019 in Sydney. In this moment *muay thai* fighter Singpayak skilfully feints and badly cuts his opponent Lloyd Dean on the forehead and close to settles the fight. I use this example to look into the strategies that fighters employ to make skilful decisions in temporally narrow and constrained settings. I will explore and investigate: 1) philosophical and socio-psychological definitions of deceptive actions including the feint; 2) the semiotics or "grammar" that fighters rely on during competitive fighting in *muay thai*; 3) entrainment and pattern detection as tools in deceptive actions; and 4) the breaking of those patterns in the pivotal moment of the feint.

Appendix B7. *Do generalised hypermobility and knee hypermobility influence Landing Error Scoring System scores?*

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1. Do generalized hypermobility and knee hypermobility influence Landing Error Scoring System scores?

Hanzlíková, I.[1], Hébert-Losier, K.[1]

[1]*University of Waikato*

Introduction: The Landing Error Scoring System (LESS) is a reliable and valid injury risk screening tool used to identify potentially high injury risk movement patterns. These patterns may be altered in participants with hypermobility or knee hyperextension. **Method**: Eighty-five young active individuals (37 females, 48 males) were tested using LESS and Beighton hypermobility tests. Spearman rank correlation coefficient was calculated to investigate relationship between LESS and Beighton scores. Furthermore, a *t*-test was performed to explore differences in LESS scores between non-hypermobile and hypermobile participants, as well as between participants with passive knee extension $< 10°$ and passive knee extension $\geq 10°$. **Results**: The mean LESS score was 5.4 ± 1.4 errors and median (interquartile range) Beighton score was 2 (4) points. No significant relationship was found between LESS and Beighton scores ($\rho = -0.08$, $p = 0.490$). The LESS scores between non-hypermobile (5.2 ± 1.5 errors) and hypermobile (5.5 ± 1.3 errors) participants and between participants with knee extension $< 10°$ (5.6 ± 1.5 errors) and knee extension $\geq 10°$ (5.3 ± 1.4 errors) were comparable ($p > 0.05$). **Discussion**: Generalized hypermobility and knee hyperextension do not influence LESS scores. **Take home message**: Despite LESS scores, Beighton scores, and knee hyperextension being identified risk factors for non-contact anterior cruciate ligament injuries in the scientific literature; the latter two aspects did not influence LESS, indicating that these tests assess different constructs and injury risk factors.

Appendix B8. *The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics.*

18. The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics.

[1]Hanzlíková, I.; [2]Richards, J.; [1]Hébert-Losier, K.

[1] *University of Waikato*
[2] *University of Central Lancashire*

Introduction: Limited dorsiflexion range of motion (ROM) has been related to Anterior Cruciate Ligament (ACL) injury risk during landings. However, the influence of dorsiflexion ROM on cutting kinematics is unknown despite high incidence of knee injuries during such tasks. **Method**: Dorsiflexion ROM was measured for each leg using the Weight-Bearing Lunge Test (WBLT) in 42 participants. Participants subsequently performed unanticipated side-step cutting. Ankle, knee, hip, and trunk angles and pelvis linear accelerations in all planes were collected at initial contact (IC) and between IC and maximum knee flexion using a three-dimensional motion analysis system and inertial measurement units. Pre-contact foot-ground angles were also extracted. Multiple linear regressions with sex as a confounder were used to explore relationships between cutting kinematics and WBLT dorsiflexion ROM for both dominant and non-dominant extremities. When non-significant, the sex confounder was removed from analyses. **Results**: Mean and standard deviation dorsiflexion ROM values from the WBLT were 51.33° ± 6.48° and 50.21° ± 7.00° on dominant and non-dominant legs, respectively. For dominant leg cutting, transverse plane knee ROM increased 0.20° ($p = 0.037$), sagittal plane trunk ROM increased 0.16° ($p = 0.044$), and trunk flexion at IC decreased 0.39° ($p = 0.009$) for each degree of WBLT dorsiflexion ROM recorded. Males had 5.89° greater trunk flexion at IC compared to females. For non-dominant leg cutting, peak lateral trunk flexion towards the stance leg, as well as sagittal and coronal plane hip ROM increased 0.36° ($p = 0.039$), 0.24° ($p = 0.017$), and 0.21° ($p = 0.005$) for each degree of WBLT dorsiflexion ROM, respectively. **Discussion**: It seems that both limited and excessive dorsiflexion ROM may influence cutting kinematics and contribute to ACL injury risk. **Take home message:** The use of clinical measures of dorsiflexion ROM for screening purposes may be useful in cutting sports.

Appendix C. Chapter 3: Summary of the study designs, levels of evidence, and quality scores of the studies reviewed (n = 10). The number of stars (*) allocated for each quality assessment item is provided.

Study	Year	Design[a]	Evidence[b]	Quality[c] (category)	Representativeness of the sample (max 1*)	Sample size (max 1*)	Non-respondents (max 1*)	Ascertainment of the exposure (max 2*)	Comparability (max 2*)	Assessment of the outcome (max 2*)	Statistical test (max 1*)
Padua et al.	2009	Cross-sectional	2	6 stars (Moderate)	*			**	*	**	
Onate et al.	2010	Cross-sectional	3	4 stars (Moderate)				**	**		
Smith et al.	2012a	Case-control	4	8 stars (Strong)	*			**	**	**	*
Padua et al.	2015	Prospective cohort	3	8 stars (Strong)	*			**	**	**	*
Beese et al.	2015	Cross-sectional	2	8 stars (Strong)	*	*		**	**	**	
Wesley et al.	2015	Cross-sectional	3	7 stars (Moderate)	*	*		**	**		*

James et al.	2016	Prospective cohort	3	6 stars (Moderate)	*	*		**	**		
Fox et al.	2017	Cross-sectional	3	6 stars (Moderate)	*			**	**		*
Scarneo et al.	2017	Cross-sectional	2	9 stars (Strong)	*	*		**	**	**	*
Dar et al.	2018	Cross-sectional	2	8 stars (Strong)	*			**	**	**	*

[a] Study design based on Parab & Bhalerao (Parab & Bhalerao, 2010)

[b] Level of evidence based on the Oxford Centre for Evidence-Based Medicine 2011 table; 5, lowest level of evidence; 1, highest level of evidence (Mukaka, 2012).

[c] Methodology quality assessment score based on Newcastle – Ottawa Quality Assessment Scale adapted for cross-sectional studies, weak (0 to 3 stars), moderate (4 to 6 stars), and strong (7 to 10 stars) (Modesti et al., 2016)

Appendix D. Appendices for Chapter 4.

Appendix D1. *Summary of the reviewed studies, including their design, level of evidence, and risk of bias.*

Study	Year	Design[a]	Evidence[b]	Overall NOS score (out of 10*)	Representatives of the sample (*)[c]	Sample size (*)[c]	Non-respondents (*)[c]	Ascertainment of the exposure (**)[c]	Comparability (**)[c]	Assessment of the outcome (**)[c]	Statistical test (*)[c]
Padua et al.	2009	Cohort	2	6*	*			**	*	**	
Beutler et al.	2009	Cross-sectional	3	6*	*			**	**		*
Smith et al.	2012a	Case-control	4	8*	*			**	**	**	*
Lepley et al.	2013	Cross-sectional	3	5*	*			**	**		
Bell et al.	2014	Cross-sectional	2	8*	*	*		**	**	**	
Lam & McLeod	2014	Cross-sectional	3	5*	*			**		**	
Theiss et al.	2014	Cross-sectional	3	5*	*			**	**		
Padua et al.	2015	Prospective cohort	3	8*	*			**	**	**	*
Beese et al.	2015	Cross-sectional	2	8*	*	*		**	**	**	

Wesley et al.	2015	Cross-sectional	3	7*	*	*		**	**		*
James et al.	2016	Prospective cohort	3	6*	*	*		**	**		
de la Motte et al.	2016	Cross-sectional	3	4*	*			*	**		
Fox et al.	2017	Cross-sectional	3	6*	*			**	**		*
Everard et al.	2017	Cross-sectional	3	4*	*				**		*
Mohammadi et al.	2017	Cross-sectional	3	6*		*		**	**		*
DiFabio et al.	2018	Cross-sectional	3	2*	*				*		
DiStefano et al.	2018	Cross-sectional	2	9*	*	*		**	**	**	*
Everard et al.	2018	Prospective cohort	3	8*	*			**	**	**	*
Jacobs et al.	2018	Cross-sectional	3	7*	*			**	**	**	
Kuenze et al.	2018	Cross-sectional	3	6*	*			**	**		*
Welling et al.	2018	Prospective cohort	3	6*	*	*		**	**		
Kraus et al.	2019	Cross-sectional	3	4*				**	**		
Dar et al.	2019	Cross-sectional	2	8*	*			**	**	**	*
Arslan et al.	2019	Cross-sectional	3	4*	*		*	**			

Biese et al.	2019	Cross-sectional	3	8*		*		**	**	**	*
Herman et al.	2019	Cross-sectional	3	5*	*			**	**		
John et al.	2019	Cross-sectional	3	2*				**			
Kraus et al.	2019	Cross-sectional	3	5*	*			**	**		
Scarborough et al.	2019	Cross-sectional	3	5*	*			**	**		
Šiupšinskas et al.	2019	Prospective cohort	3	6*	*			**	**		*
van Melick et al.	2019	Cross-sectional	3	6*	*	*		**	**		
Hébert-Losier et al.	2020	Cross-sectional	3	6*				**	*	**	*
Tran et al.	2020	Cohort	3	5*	*		*	**	*		

Study	**Year**	**Design**[a]	**Evidence**[b]	**Overall RoB 2 score**	**Rob from the randomisation process**	**Rob due to deviations from the intended interventions (effect of assignment)**	**Rob due to deviations from the intended interventions (adhering to intervention)**	**Rob due to missing outcome data**	**Rob in measurement of the outcome**	**Rob in selection of the reported result**
DiStefano et al.	2009	Randomised controlled trial	2	High	**L**	**L**	**H**	**H**	**L**	**L**

DiStefano et al.	2013 a	Randomised controlled trial	2	High	**SC**	**SC**	**H**	**L**	**L**	**SC**
DiStefano et al.	2016	Randomised controlled trial	2	High	**H**	**SC**	**SC**	**H**	**L**	**L**
Welling et al.	2016	Randomised controlled trial	2	Some concerns	**SC**	**L**	**L**	**L**	**L**	**L**
O'Malley et al.	2017	Randomised controlled trial	2	High	**L**	**L**	**H**	**H**	**L**	**SC**
Parsons et al.	2017	Randomised controlled trial	2	Some concerns	**SC**	**L**	**SC**	**L**	**L**	**L**
Pryor et al.	2017	Randomised controlled trial	2	High	**SC**	**L**	**SC**	**H**	**L**	**L**
Akbari et al.	2019	Randomised controlled trial	2	High	**SC**	**SC**	**H**	**L**	**H**	**L**
Parsons et al.	2019	Randomised controlled trial	2	Some concerns	**SC**	**SC**	**H**	**L**	**L**	**L**

Study	Year	Design[a]	Evidence[b]	Overall ROBINS-I score	Rob due to confounding	Rob in selection of participants	Rob in classification of intervention	Rob due to deviations from intended interventions	Rob due to missing data	Rob in measurement of outcomes	Rob in selection of the reported result
Padua et al.	2012	Cohort	2	Serious	**S**	**S**	**L**	**L**	**NI**	**L**	**M**
DiStefano et al.	2013b	Case-series	3	Moderate	**M**	**L**	**L**	**L**	**NI**	**L**	**M**
Owens et al.	2013	Case-series	3	Serious	**S**	**L**	**L**	**L**	**L**	**NI**	**M**
Gokeler et al.	2014	Case-control	4	Serious	**S**	**L**	**L**	**L**	**S**	**NI**	**M**
Kuenze et al.	2015	Case-control	4	Moderate	**M**	**L**	**L**	**L**	**NI**	**NI**	**M**
Stiffler et al.	2015	Case-control	4	Serious	**S**	**M**	**S**	**L**	**L**	**NI**	**S**
Bell et al.	2016	Case-series	3	Serious	**M**	**M**	**L**	**L**	**L**	**S**	**M**
Pfile et al.	2016	Case-series	4	Moderate	**M**	**L**	**L**	**L**	**L**	**NI**	**M**
Scarneo et al.	2017	Case-series	4	Moderate	**M**	**L**	**L**	**L**	**L**	**NI**	**M**

Garbenytė-Apolinskienė et al.	2018	Case-series	4	Serious	**M**	**L**	**L**	**L**	**L**	**NI**	**S**

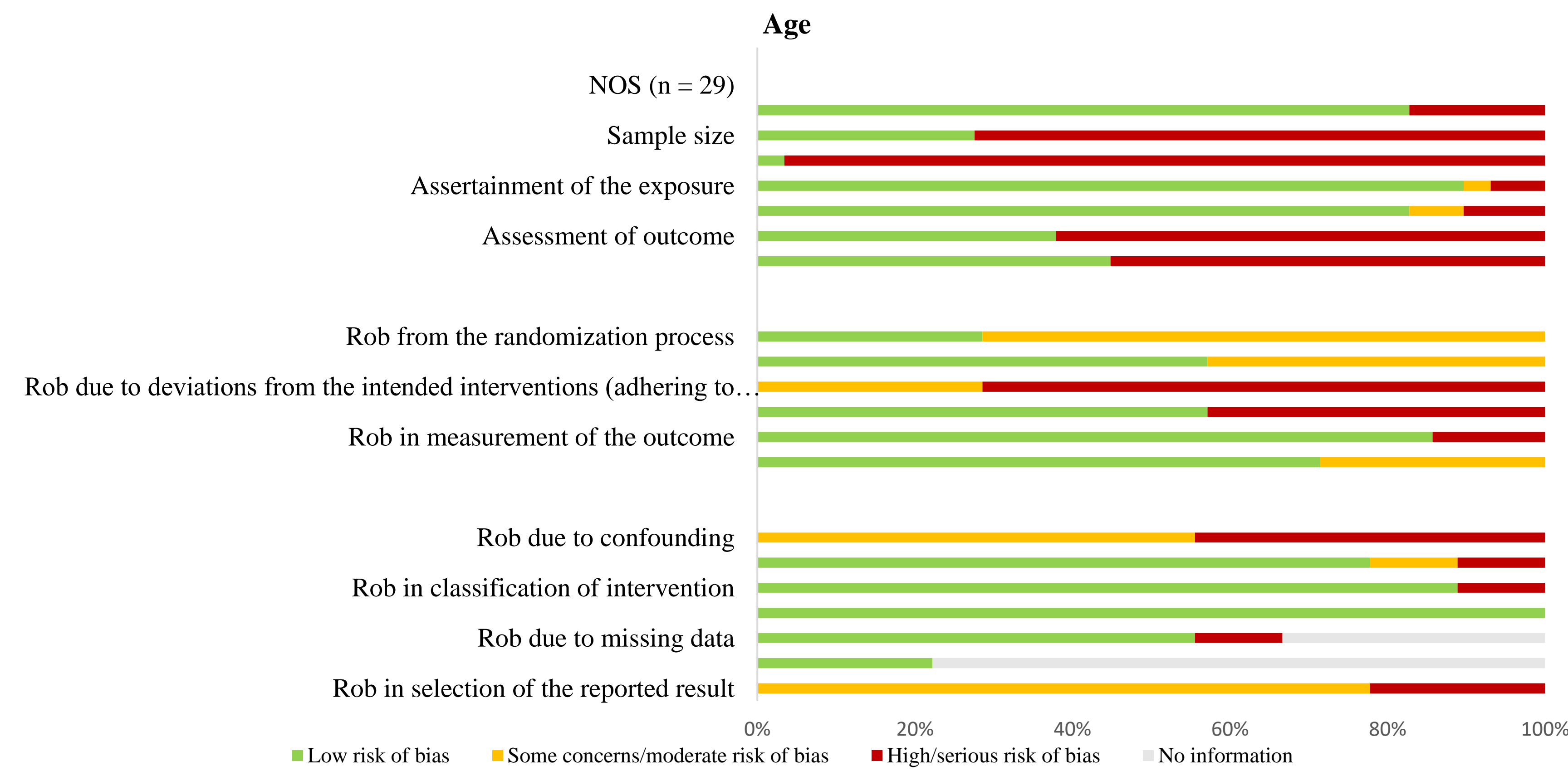
Abbreviations: Rob, risk of bias; L, low; SC, some concerns; H, high; M, moderate, S, strong; NI, no information; NOS, Newcastle – Ottawa Assessment Scale adapted for cross-sectional studies(Modesti et al., 2016); RoB 2; Revised Cochrane Risk-of-bias Tool For Randomised Trials(Sterne et al., 2019); ROBINS-I, Risk Of Bias In Non-randomised Studies Of Interventions(Sterne et al., 2016).

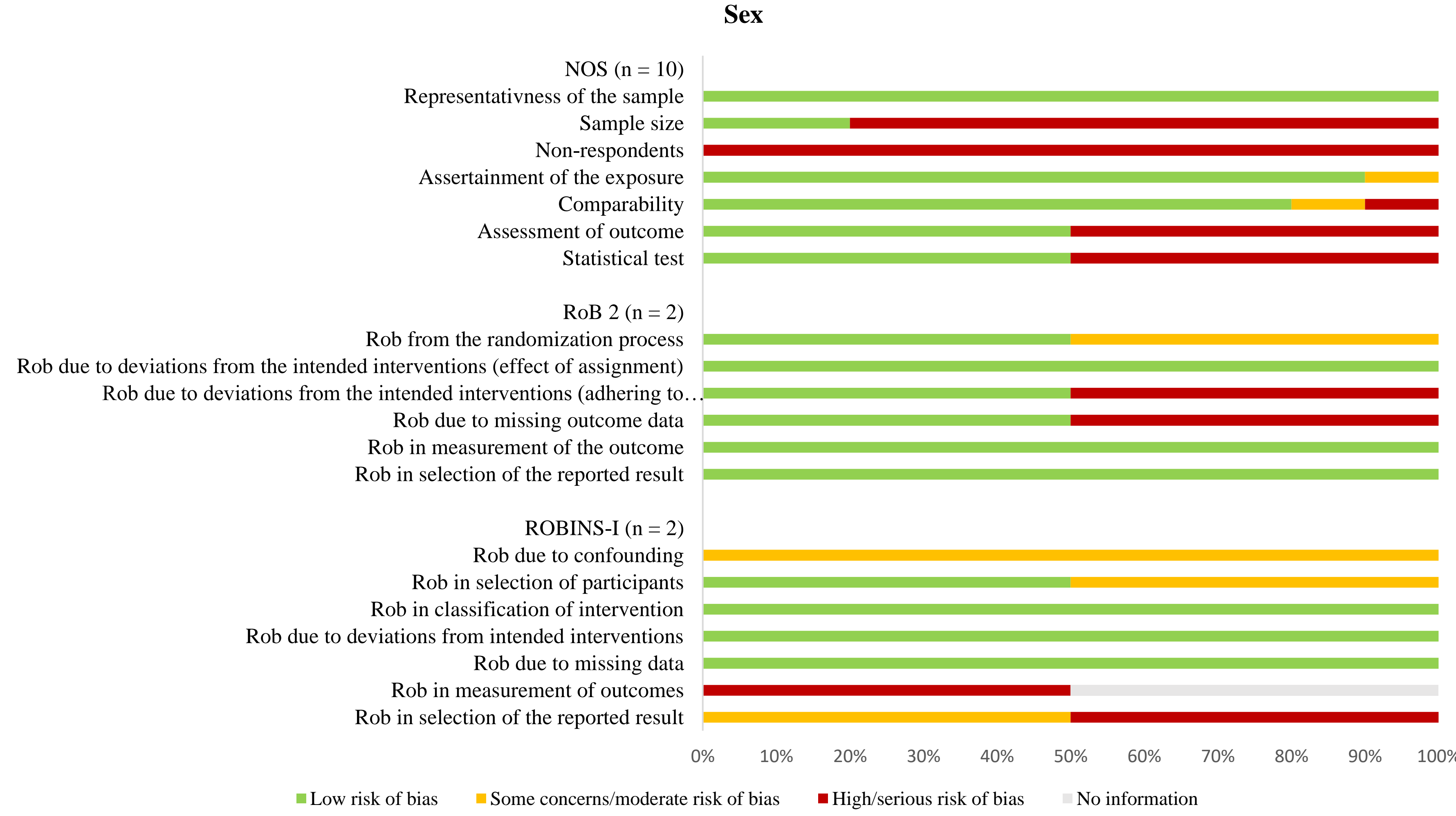
[a]Study design according to Parab & Bhalerao(Parab & Bhalerao, 2010).

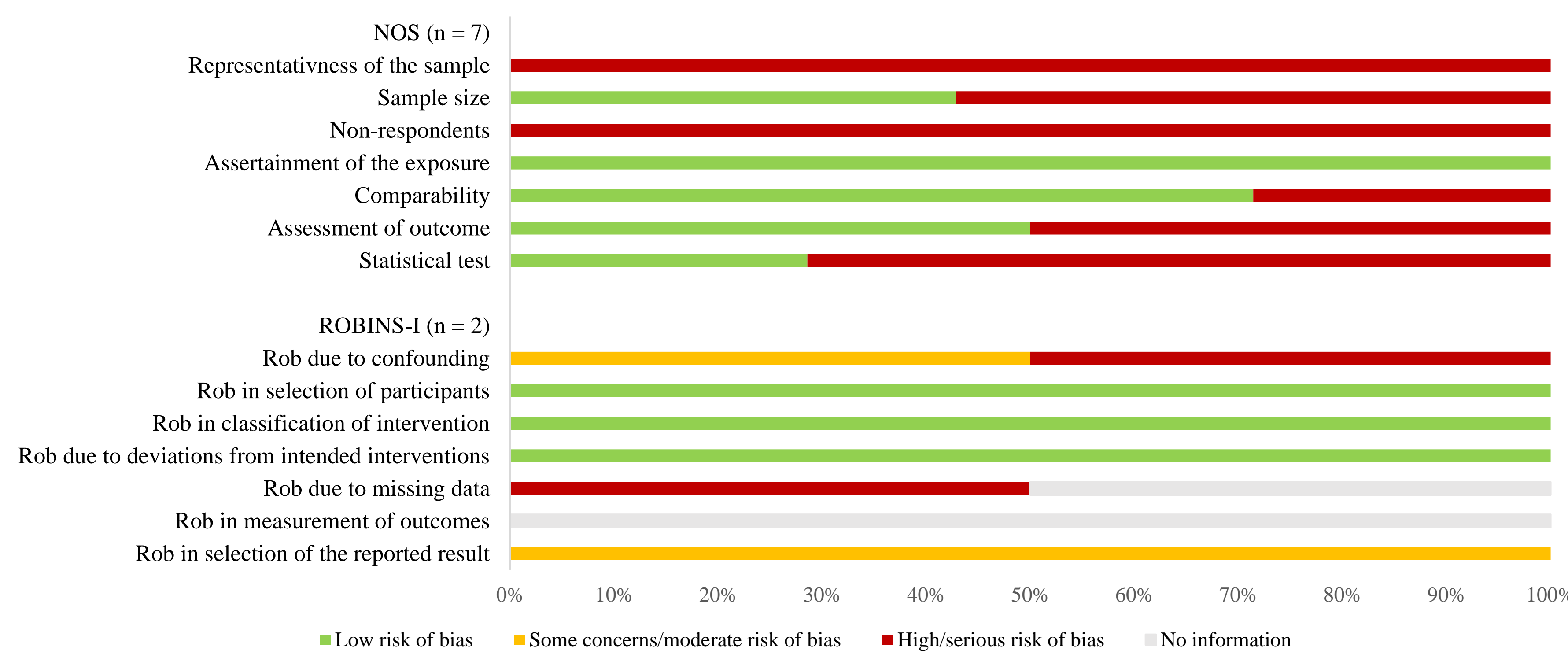
[b]Level of evidence based on the Oxford Centre for Evidence-Based Medicine 2011 table.

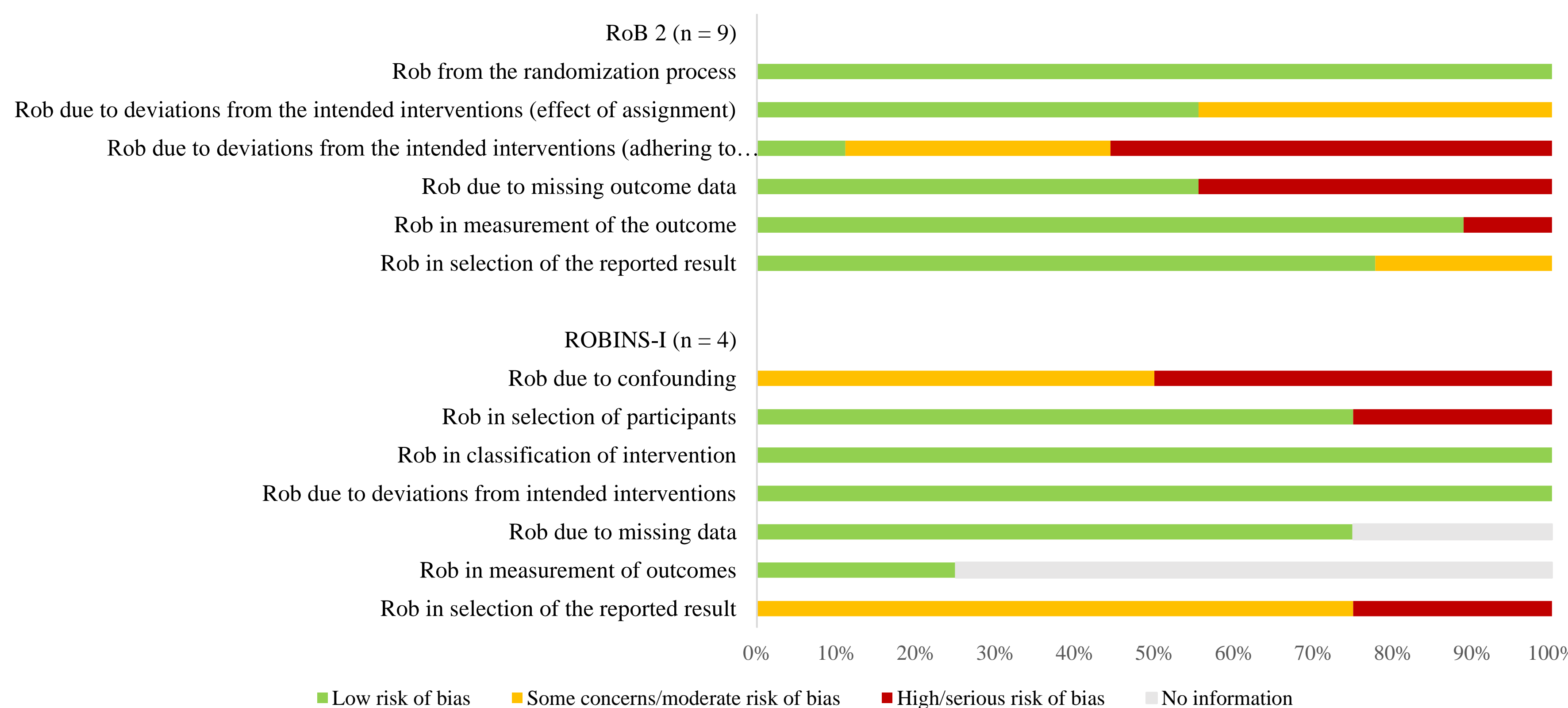
[c]Maximum number of stars possible.

Appendix D2. *Risk of bias (Rob) for each influencing factor according Newcastle – Ottawa Assessment Scale (NOS), Revised Cochrane Risk-of-bias Tool for Randomised Trials (RoB2), and Risk Of Bias In Non-randomised Studies of Interventions (ROBINS-I).*

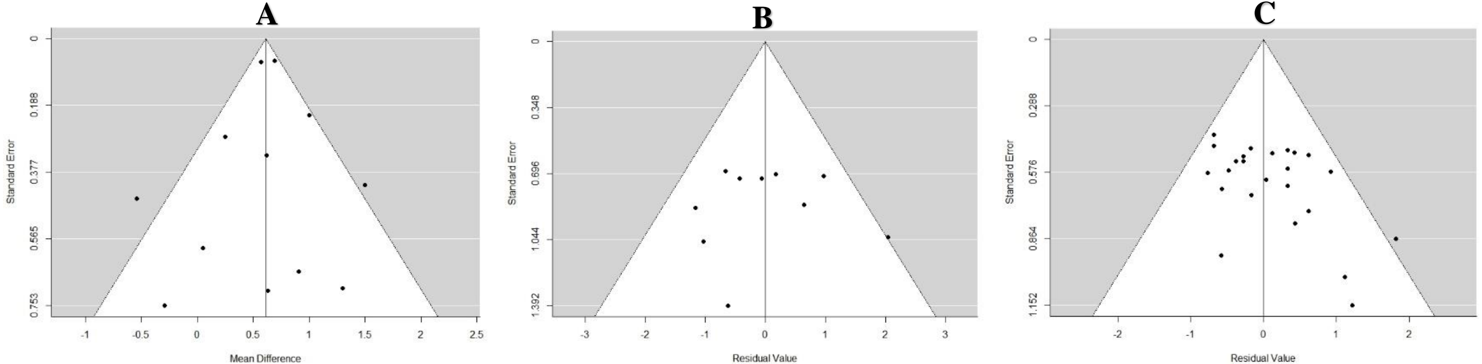



Sex
NOS (n = 10)
Representativness of the sample
Sample size
Non-respondents
Assertainment of the exposure
Comparability
Assessment of outcome
Statistical test
RoB 2 (n = 2)
Rob from the randomization process
Rob due to deviations from the intended interventions (effect of assignment)
Rob due to deviations from the intended interventions (adhering to…
Rob due to missing outcome data
Rob in measurement of the outcome
Rob in selection of the reported result
ROBINS-I (n = 2)
Rob due to confounding
Rob in selection of participants
Rob in classification of intervention
Rob due to deviations from intended interventions
Rob due to missing data
Rob in measurement of outcomes
Rob in selection of the reported result
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Low risk of bias
Some concerns/moderate risk of bias
High/serious risk of bias
No information


Previous injury
NOS (n = 7)
Representativness of the sample
Sample size
Non-respondents
Assertainment of the exposure
Comparability
Assessment of outcome
Statistical test
ROBINS-I (n = 2)
Rob due to confounding
Rob in selection of participants
Rob in classification of intervention
Rob due to deviations from intended interventions
Rob due to missing data
Rob in measurement of outcomes
Rob in selection of the reported result
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Low risk of bias
Some concerns/moderate risk of bias
High/serious risk of bias
No information


Intervention program
RoB 2 (n = 9)
Rob from the randomization process
Rob due to deviations from the intended interventions (effect of assignment)
Rob due to deviations from the intended interventions (adhering to…
Rob due to missing outcome data
Rob in measurement of the outcome
Rob in selection of the reported result
ROBINS-I (n = 4)
Rob due to confounding
Rob in selection of participants
Rob in classification of intervention
Rob due to deviations from intended interventions
Rob due to missing data
Rob in measurement of outcomes
Rob in selection of the reported result
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Low risk of bias
Some concerns/moderate risk of bias
High/serious risk of bias
No information

Appendix D3. *Funnel plots for meta-analyses exploring influence of (A) sex, (B) previous injury, and (C) intervention programme on Landing Error Scoring System scores.*



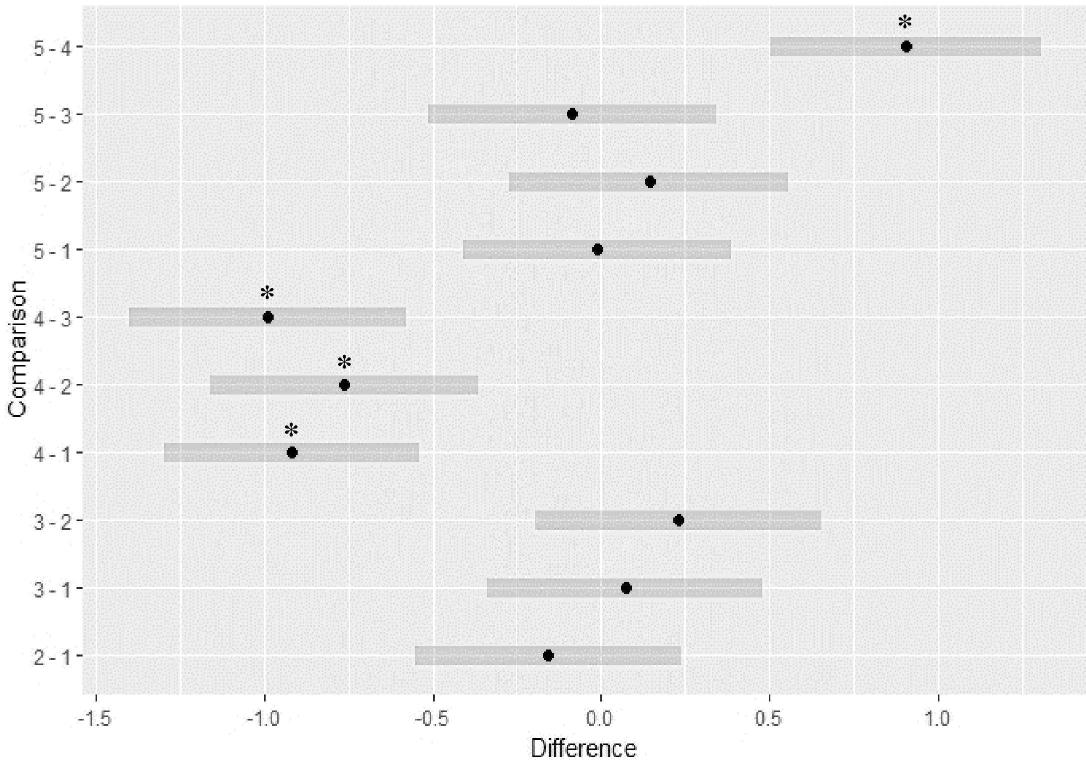
Appendix E. Appendices for Chapter 5.

Appendix E1. *Comparison of the group mean Landing Error Scoring System scores between calculation methods using Generalised Estimating Equations.*

Methods	Mean difference in LESS scores (error) [95% CI]	*p* – value*
2 vs 1	-0.16 [-0.55 to 0.24]	1.000
3 vs 1	0.07 [-0.34 to 0.48]	1.000
4 vs 1	-0.92 [-1.30 to -0.54]	< 0.001
5 vs 1	-0.01 [-0.41 to 0.38]	1.000
3 vs 2	0.23 [-0.20 to 0.65]	1.000
4 vs 2	-0.76 [-1.16 to -0.37]	< 0.001
5 vs 2	0.14 [-0.27 to 0.56]	1.000
4 vs 3	-0.99 [-1.40 to -0.58]	< 0.001
5 vs 3	-0.09 [-0.51 to 0.34]	1.000
5 vs 4	0.91 [0.51 to 1.31]	< 0.001

Abbreviations: LESS, Landing Error Scoring System; CI, confidence interval; 1, Mean of 3 jumps; 2, 1st jump score; 3, 3rd jump score; 4, Best jump score; 5, Error present in at least two jumps. **p*-value: difference between methods using the Bonferroni correction.

Appendix E2. *Comparison of the group mean Landing Error Scoring System scores between calculation methods using Generalised Estimating Equations.*



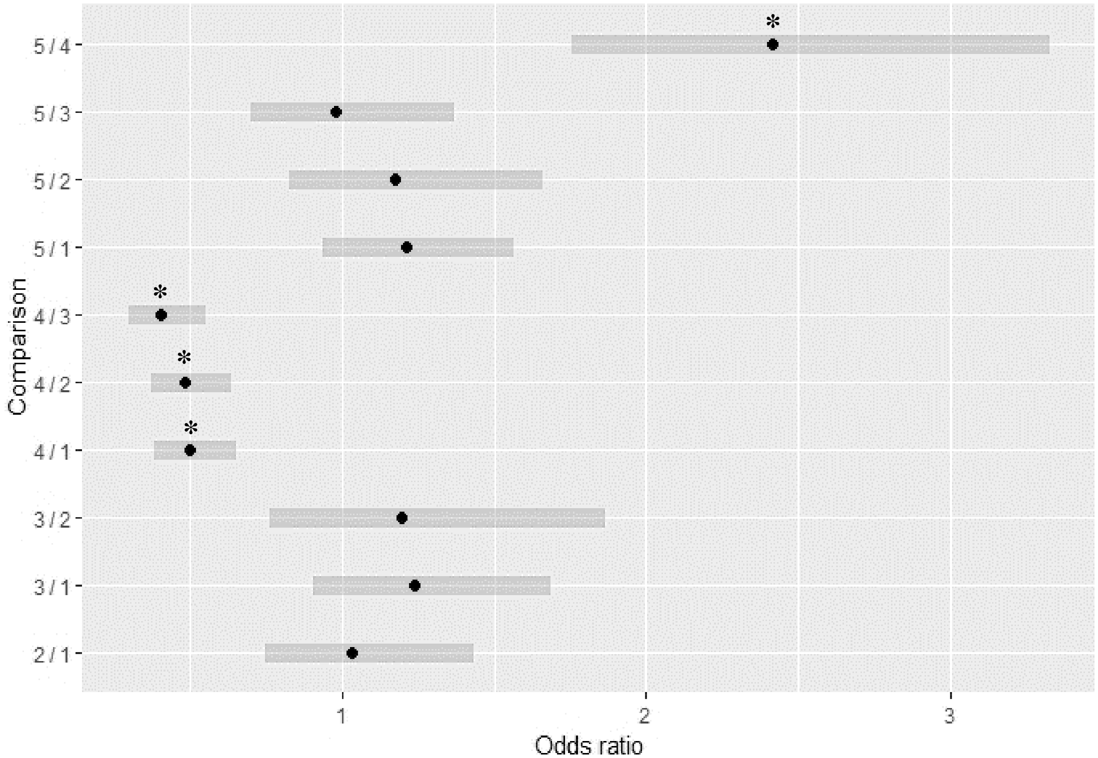
1, Mean of 3 jumps; 2, 1st jump score; 3, 3rd jump score; 4, Best jump score; 5, Error present in at least two jumps. Dots represent the mean difference between methods, bands represent 95% confidence intervals, and asterisk significant difference between methods.

Appendix E3. *Comparison of the odds ratio of being at high risk between calculation methods using Generalised Estimating Equations.*

Methods	**Odds ratio [95% CI]**	***p* – value***
2 vs 1	1.03 [0.75 to 1.43]	1.000
3 vs 1	1.24 [0.90 to 1.69]	0.569
4 vs 1	0.50 [0.39 to 0.65]	< 0.001
5 vs 1	1.21 [0.94 to 1.57]	0.333
3 vs 2	1.20 [0.76 to 1.87]	1.000
4 vs 2	0.49 [0.37 to 0.64]	< 0.001
5 vs 2	1.17 [0.83 to 1.66]	1.000
4 vs 3	0.41 [0.30 to 0.56]	< 0.001
5 vs 3	0.98 [0.70 to 1.37]	1.000
5 vs 4	2.42 [1.76 to 3.33]	< 0.001

Abbreviations: CI, confidence interval; 1, Mean of 3 jumps; 2, 1st jump score; 3, 3rd jump score; 4, Best jump score; 5, Error present in at least two jumps. Odds ration greater than 1.00 indicate higher odds of high injury risk compared to the other method. * *p*-value: difference between methods the Bonferroni correction.

Appendix E4. *Comparison of the odds ratio of being at high risk between calculation methods using Generalised Estimating Equations.*



1, Mean of 3 jumps; 2, 1st jump score; 3, 3rd jump score; 4, Best jump score; 5, Error present in at least two jumps. Dots represent the mean difference between methods, bands represent 95% confidence intervals, and asterisk significant difference between methods.

Appendix F. Appendices for Chapter 8.

Appendix F1. *Mean values and standard deviations of extracted variables.*

	Dominant-leg variables at 100ms: Minimal Values									
	Mean Cutting	SD Cutting	**Mean DLJL**	SD DLJL	**Mean DLJLrot**	SD DLJLrot	**Mean SLJL**	SD SLJL	**Mean SLJLrot**	SD SLJLrot
Dominant-leg Ankle Angle_X	**-10.8**	10.8	**-13.1**	7.9	**-14.7**	8.3	**-16.7**	9.6	**-18.8**	7.4
Dominant-leg Ankle Angle_Y	**17.2**	6.8	**0.1**	3.0	**11.7**	5.6	**-7.0**	3.2	**2.7**	4.3
Dominant-leg Ankle Angle_Z	**-12.6**	11.7	**-11.1**	6.8	**-11.3**	6.0	**-13.4**	6.2	**-14.1**	5.8
Dominant-leg Ankle Angular Velocity_X	**-58.0**	225.8	**59.5**	54.3	**9.9**	56.0	**54.7**	54.7	**41.8**	45.9
Dominant-leg Ankle Angular Velocity_Y	**-155.7**	115.1	**-396.1**	195.4	**-186.7**	99.1	**-357.2**	149.7	**-225.2**	110.7
Dominant-leg Ankle Angular Velocity_Z	**-495.5**	259.7	**-417.2**	220.7	**-436.8**	264.7	**-450.7**	203.7	**-407.8**	186.8
Dominant-leg Hip Angle_X	**26.5**	12.2	**38.8**	13.1	**31.1**	11.8	**26.8**	11.4	**24.3**	10.4
Dominant-leg Hip Angle_Y	**-17.6**	6.8	**-11.6**	5.8	**-16.3**	6.5	**-13.7**	4.9	**-17.4**	5.9
Dominant-leg Hip Angle_Z	**-10.0**	9.2	**-12.4**	7.9	**-11.8**	8.1	**-13.0**	8.6	**-10.3**	7.9
Dominant-leg Hip Angular Velocity_X	**-270.2**	79.2	**37.7**	96.8	**32.3**	83.5	**-104.1**	95.5	**-80.8**	83.1
Dominant-leg Hip Angular Velocity_Y	**-231.7**	139.5	**-274.7**	153.6	**-205.1**	121.2	**-149.0**	94.1	**-88.9**	68.3
Dominant-leg Hip Angular Velocity_Z	**-533.7**	204.8	**-203.9**	107.4	**-219.1**	95.4	**-222.9**	121.2	**-222.6**	115.2
Dominant-leg Knee Angle_X	**26.8**	5.8	**33.7**	8.3	**27.6**	7.5	**18.9**	7.2	**18.3**	5.6
Dominant-leg Knee Angle_Y	**-12.6**	7.3	**-8.5**	7.3	**-8.0**	6.7	**-6.1**	5.8	**-6.9**	5.9
Dominant-leg Knee Angle_Z	**-3.6**	6.7	**-3.0**	4.6	**-3.8**	5.5	**-5.0**	5.9	**-3.6**	5.9
Dominant-leg Knee Angular Velocity_X	**-38.8**	99.4	**200.3**	86.4	**199.8**	89.0	**76.0**	84.1	**96.9**	97.7
Dominant-leg Knee Angular Velocity_Y	**-312.7**	181.6	**-368.7**	232.5	**-343.2**	252.8	**-284.9**	173.2	**-281.8**	180.1
Dominant-leg Knee Angular Velocity_Z	**-400.5**	232.5	**-238.0**	179.0	**-281.3**	168.2	**-315.1**	192.8	**-309.6**	160.2
Dominant-leg Pelvis Angle_X	**-18.0**	8.1	**-5.5**	9.2	**15.2**	10.0	**0.5**	8.2	**7.1**	8.0
Dominant-leg Pelvis Angle_Y	**-11.6**	7.9	**-0.9**	4.2	**-5.7**	4.7	**2.5**	7.2	**3.5**	4.3
Dominant-leg Pelvis Angle_Z	**14.8**	13.5	**-2.2**	4.6	**-7.9**	5.7	**0.2**	15.4	**-7.6**	9.3
Dominant-leg Pelvis Angular Velocity_X	**-199.5**	80.3	**-189.3**	77.4	**133.5**	90.1	**-136.7**	115.3	**67.9**	61.4
Dominant-leg Pelvis Angular Velocity_Y	**-166.0**	71.2	**-83.0**	46.9	**-99.5**	58.9	**-215.7**	98.3	**-197.9**	72.5
Dominant-leg Pelvis Angular Velocity_Z	**-139.4**	85.4	**-96.0**	52.9	**-98.2**	54.0	**-173.2**	78.7	**-107.9**	65.0
Dominant-leg Trunk Angle_X	**3.4**	8.2	**12.5**	7.6	**29.0**	9.7	**3.5**	7.2	**15.3**	8.6
Dominant-leg Trunk Angle_Y	**-3.1**	7.4	**-1.5**	3.1	**-1.5**	4.1	**3.7**	5.3	**6.9**	4.7
Dominant-leg Trunk Angle_Z	**3.4**	12.1	**-0.3**	2.9	**-9.3**	7.5	**-6.1**	15.3	**-16.1**	14.5
Dominant-leg Trunk Angular Velocity_X	**-13.5**	36.6	**22.6**	57.9	**210.9**	87.9	**23.8**	36.5	**180.5**	64.0
Dominant-leg Trunk Angular Velocity_Y	**-42.4**	38.9	**-20.3**	16.6	**-34.5**	29.2	**-7.7**	40.8	**-14.4**	24.9
Dominant-leg Trunk Angular Velocity_Z	**47.7**	85.8	**-23.0**	14.6	**7.7**	38.7	**-35.3**	30.4	**-6.8**	41.4
Dominant-leg Pelvis Linear Acceleration_Vertical	**-11.6**	2.8	**-10.2**	3.1	**-8.2**	2.9	**-11.8**	2.9	**-13.3**	2.0
Dominant-leg Pelvis Linear Acceleration_Medio-lateral	**-2.6**	2.2	**-2.0**	1.2	**-1.1**	1.0	**-3.2**	2.0	**-1.7**	1.7
Dominant-leg Pelvis Linear Acceleration_Anterio-posterior	**-1.5**	1.6	**-1.3**	1.4	**-0.4**	1.4	**-1.4**	1.6	**-1.0**	1.6

Note , that the directionality and interpretation of joint movements are presented in Table 13

Abbreviations: DLJL, double-leg jump-landing; DLJLrot, rotated double-leg jump-landing; SLJL, single-leg jump-landing; SLJLrot, rotated single-leg jump-landing; SD, standard deviation

** Foot-ground angle one frame before initial contact*

	Non-dominant-leg variables at 100ms: Minimal Values									
	Mean Cutting	SD Cutting	**Mean DLJL**	SD DLJL	**Mean DLJLrot**	SD DLJLrot	**Mean SLJL**	SD SLJL	**Mean SLJLrot**	SD SLJLrot
Non-dominant-leg Ankle Angle_X	**-12.5**	6.3	**-12.0**	8.0	**-14.0**	7.1	**-16.9**	7.4	**-16.9**	6.6
Non-dominant-leg Ankle Angle_Y	**15.9**	5.7	**1.2**	3.2	**12.3**	4.8	**-7.6**	2.6	**3.0**	3.6
Non-dominant-leg Ankle Angle_Z	**-10.5**	8.5	**-8.5**	6.8	**-9.2**	7.1	**-11.2**	6.6	**-11.2**	6.9
Non-dominant-leg Ankle Angular Velocity_X	**-125.0**	218.9	**32.7**	93.5	**18.9**	57.1	**36.2**	61.4	**41.7**	49.7
Non-dominant-leg Ankle Angular Velocity_Y	**-133.5**	121.5	**-345.1**	176.9	**-165.4**	76.4	**-348.1**	154.3	**-207.1**	109.3
Non-dominant-leg Ankle Angular Velocity_Z	**-467.1**	273.0	**-435.0**	212.0	**-400.2**	187.5	**-453.4**	193.6	**-402.2**	191.5
Non-dominant-leg Hip Angle_X	**24.7**	15.4	**38.6**	12.3	**29.1**	11.6	**24.1**	12.4	**18.2**	12.8
Non-dominant-leg Hip Angle_Y	**-19.4**	7.0	**-14.0**	6.0	**-18.0**	5.8	**-14.5**	5.9	**-18.1**	6.7
Non-dominant-leg Hip Angle_Z	**-19.4**	12.6	**-19.2**	10.3	**-18.7**	8.5	**-19.0**	10.5	**-15.7**	9.4
Non-dominant-leg Hip Angular Velocity_X	**-288.8**	111.3	**23.8**	98.9	**40.0**	102.1	**-132.5**	89.7	**-77.1**	84.3
Non-dominant-leg Hip Angular Velocity_Y	**-229.2**	149.8	**-335.4**	152.6	**-259.0**	142.4	**-195.0**	92.7	**-102.4**	56.6
Non-dominant-leg Hip Angular Velocity_Z	**-582.4**	215.8	**-247.2**	119.2	**-296.2**	132.1	**-278.3**	176.7	**-222.1**	127.1
Non-dominant-leg Knee Angle_X	**25.5**	4.9	**34.2**	7.9	**28.0**	7.2	**18.2**	4.3	**17.6**	5.4
Non-dominant-leg Knee Angle_Y	**-15.3**	7.7	**-12.3**	8.8	**-10.8**	7.4	**-9.2**	7.2	**-9.4**	7.1
Non-dominant-leg Knee Angle_Z	**-2.9**	8.2	**-3.0**	5.8	**-2.6**	6.6	**-3.5**	7.3	**-2.1**	6.8
Non-dominant-leg Knee Angular Velocity_X	**-32.7**	94.3	**187.8**	95.0	**191.9**	96.3	**30.7**	91.8	**62.5**	97.8
Non-dominant-leg Knee Angular Velocity_Y	**-308.7**	179.2	**-395.0**	253.5	**-330.5**	217.7	**-325.7**	226.7	**-301.4**	207.7
Non-dominant-leg Knee Angular Velocity_Z	**-426.3**	224.2	**-295.4**	171.6	**-287.5**	165.1	**-360.7**	191.3	**-289.7**	192.6
Non-dominant-leg Pelvis Angle_X	**-18.7**	9.9	**-3.0**	9.2	**6.1**	9.9	**-5.9**	9.9	**-7.1**	8.9
Non-dominant-leg Pelvis Angle_Y	**5.8**	8.2	**-0.9**	4.2	**-7.5**	5.8	**-11.0**	6.3	**0.3**	6.2
Non-dominant-leg Pelvis Angle_Z	**-22.2**	15.2	**-2.5**	4.5	**0.4**	7.0	**-8.1**	7.2	**5.8**	8.9
Non-dominant-leg Pelvis Angular Velocity_X	**-278.8**	127.2	**-186.9**	77.9	**-101.4**	78.3	**-167.2**	85.7	**-81.5**	60.8
Non-dominant-leg Pelvis Angular Velocity_Y	**-92.0**	51.8	**-83.6**	47.1	**-132.6**	71.8	**-64.2**	90.4	**-291.0**	85.9
Non-dominant-leg Pelvis Angular Velocity_Z	**-200.2**	95.4	**-96.1**	52.8	**-176.1**	86.3	**-69.8**	66.8	**-133.7**	49.3
Non-dominant-leg Trunk Angle_X	**2.6**	9.2	**12.6**	7.6	**6.6**	9.8	**5.4**	7.7	**1.2**	7.4
Non-dominant-leg Trunk Angle_Y	**-2.2**	6.8	**-1.5**	3.1	**0.3**	4.8	**-9.1**	5.3	**7.0**	5.5
Non-dominant-leg Trunk Angle_Z	**-13.1**	15.6	**-0.3**	3.0	**3.3**	7.6	**1.5**	5.5	**14.4**	15.2
Non-dominant-leg Trunk Angular Velocity_X	**-3.8**	40.4	**23.0**	60.5	**96.5**	98.9	**16.5**	43.4	**39.0**	70.4
Non-dominant-leg Trunk Angular Velocity_Y	**-32.0**	39.1	**-20.2**	16.6	**-26.4**	35.9	**-54.2**	33.3	**-16.2**	30.7
Non-dominant-leg Trunk Angular Velocity_Z	**-150.3**	92.2	**-22.7**	14.2	**-89.8**	44.3	**-39.2**	28.8	**-82.7**	44.7
Non-dominant-leg Pelvis Linear Acceleration_Vertical	**-12.5**	2.6	**-10.1**	3.1	**-12.7**	2.8	**-10.8**	2.6	**-10.1**	2.8
Non-dominant-leg Pelvis Linear Acceleration_Medio-lateral	**-7.1**	3.2	**-2.0**	1.2	**-3.5**	1.8	**-5.1**	2.4	**-5.4**	2.5
Non-dominant-leg Pelvis Linear Acceleration_Anterio-posterior	**-1.1**	1.0	**-1.2**	1.4	**-0.1**	1.3	**-1.1**	1.5	**-0.8**	1.3

Note , that the directionality and interpretation of joint movements are presented in Table 13

Abbreviations: DLJL, double-leg jump-landing; DLJLrot, rotated double-leg jump-landing; SLJL, single-leg jump-landing; SLJLrot, rotated single-leg jump-landing; SD, standard deviation

** Foot-ground angle one frame before initial contact*

	Dominant-leg variables at 100ms: Maximum Values									
	Mean Cutting	SD Cutting	**Mean DLJL**	SD DLJL	**Mean DLJLrot**	SD DLJLrot	**Mean SLJL**	SD SLJL	**Mean SLJLrot**	SD SLJLrot
Dominant-leg Ankle Angle_X	**18.8**	9.9	**23.9**	3.6	**29.1**	3.2	**19.7**	3.9	**26.3**	3.3
Dominant-leg Ankle Angle_Y	**32.3**	6.6	**8.0**	3.8	**22.0**	4.1	**2.6**	3.9	**11.8**	3.5
Dominant-leg Ankle Angle_Z	**-2.1**	12.0	**-0.9**	6.1	**-2.3**	6.3	**-0.6**	6.3	**-3.1**	6.5
Dominant-leg Ankle Angular Velocity_X	**669.0**	273.5	**1254.2**	368.9	**1297.3**	299.7	**1308.0**	387.8	**1324.4**	261.5
Dominant-leg Ankle Angular Velocity_Y	**795.7**	392.8	**166.9**	96.2	**467.9**	221.6	**173.5**	87.8	**370.9**	190.8
Dominant-leg Ankle Angular Velocity_Z	**351.3**	196.0	**198.0**	191.8	**244.2**	219.6	**181.7**	148.7	**166.2**	168.4
Dominant-leg Hip Angle_X	**36.8**	11.0	**64.3**	14.4	**59.7**	14.5	**42.3**	12.7	**41.3**	11.3
Dominant-leg Hip Angle_Y	**-10.9**	6.6	**-6.9**	5.5	**-10.1**	6.5	**0.9**	6.2	**-2.7**	5.7
Dominant-leg Hip Angle_Z	**7.6**	9.1	**-2.7**	8.4	**-2.1**	8.0	**-2.3**	7.9	**-0.7**	7.8
Dominant-leg Hip Angular Velocity_X	**190.9**	132.9	**494.9**	102.1	**573.2**	147.9	**412.8**	114.9	**429.2**	111.2
Dominant-leg Hip Angular Velocity_Y	**313.5**	126.4	**243.5**	92.6	**279.3**	113.3	**362.1**	141.8	**334.6**	126.4
Dominant-leg Hip Angular Velocity_Z	**244.3**	135.8	**253.6**	129.3	**223.5**	127.1	**415.4**	143.1	**387.0**	134.8
Dominant-leg Knee Angle_X	**55.8**	7.2	**89.4**	8.4	**79.8**	7.9	**59.8**	6.7	**59.8**	6.5
Dominant-leg Knee Angle_Y	**-2.7**	5.2	**2.5**	5.1	**1.9**	4.8	**1.9**	4.2	**0.1**	4.0
Dominant-leg Knee Angle_Z	**8.6**	6.8	**6.8**	4.8	**6.2**	6.3	**5.9**	6.0	**6.6**	7.3
Dominant-leg Knee Angular Velocity_X	**720.6**	184.1	**961.1**	178.1	**870.8**	180.3	**769.8**	165.9	**737.2**	156.1
Dominant-leg Knee Angular Velocity_Y	**341.3**	218.9	**290.8**	184.7	**284.8**	179.1	**269.7**	157.4	**232.9**	144.3
Dominant-leg Knee Angular Velocity_Z	**539.7**	214.5	**412.0**	163.6	**437.3**	184.4	**444.3**	158.1	**392.2**	156.4
Dominant-leg Pelvis Angle_X	**8.5**	7.9	**17.0**	8.8	**17.3**	9.3	**19.0**	7.7	**17.4**	7.3
Dominant-leg Pelvis Angle_Y	**-5.4**	7.8	**2.9**	4.5	**-1.9**	4.0	**11.1**	5.6	**11.8**	4.3
Dominant-leg Pelvis Angle_Z	**22.6**	14.1	**0.8**	4.1	**-2.5**	6.3	8.8	6.6	**-1.2**	9.2
Dominant-leg Pelvis Angular Velocity_X	**134.9**	68.5	**102.2**	60.0	**-122.0**	76.5	**64.1**	70.7	**-107.6**	72.0
Dominant-leg Pelvis Angular Velocity_Y	**111.9**	78.2	**118.4**	60.7	**85.6**	48.7	**76.6**	91.5	**22.7**	45.2
Dominant-leg Pelvis Angular Velocity_Z	**221.1**	99.9	**72.4**	40.6	**121.2**	64.3	**84.3**	66.3	**141.0**	68.9
Dominant-leg Trunk Angle_X	**23.4**	8.1	**28.2**	7.9	**17.5**	9.3	**23.5**	9.3	**13.4**	6.6
Dominant-leg Trunk Angle_Y	**1.1**	6.5	**0.4**	3.1	**1.4**	4.1	**8.0**	5.4	**10.6**	5.0
Dominant-leg Trunk Angle_Z	**14.1**	12.5	**1.5**	3.0	**-3.6**	6.9	-0.3	5.3	**-10.7**	13.7
Dominant-leg Trunk Angular Velocity_X	**130.9**	58.4	**175.0**	56.0	**102.1**	83.3	**205.1**	54.4	**47.3**	73.4
Dominant-leg Trunk Angular Velocity_Y	**35.9**	38.4	**26.9**	17.9	**20.5**	29.3	**59.8**	36.4	**74.2**	47.1
Dominant-leg Trunk Angular Velocity_Z	**151.7**	90.3	**22.4**	15.7	**87.2**	36.7	**35.6**	31.8	**80.2**	45.7
Dominant-leg Pelvis Linear Acceleration_Vertical	**10.5**	1.1	**4.7**	1.3	**3.9**	1.1	**7.6**	0.8	**4.4**	2.1
Dominant-leg Pelvis Linear Acceleration_Medio-lateral	**7.8**	3.5	**2.1**	1.1	**4.0**	2.2	**5.1**	2.5	**5.6**	2.8
Dominant-leg Pelvis Linear Acceleration_Anterio-posterior	**4.8**	1.8	**5.3**	1.8	**4.1**	1.5	**4.5**	1.9	**3.9**	1.7

Note , that the directionality and interpretation of joint movements are presented in Table 13
Abbreviations: DLJL, double-leg jump-landing; DLJLrot, rotated double-leg jump-landing; SLJL, single-leg jump-landing; SLJLrot, rotated single-leg jump-landing; SD, standard deviation
** Foot-ground angle one frame before initial contact*

	Non-dominant-leg variables at 100ms: Maximum Values									
	Mean Cutting	SD Cutting	**Mean DLJL**	SD DLJL	**Mean DLJLrot**	SD DLJLrot	**Mean SLJL**	SD SLJL	**Mean SLJLrot**	SD SLJLrot
Non-dominant-leg Ankle Angle_X	**14.6**	8.1	**23.6**	3.4	**28.4**	4.1	**20.1**	3.0	**24.9**	4.8
Non-dominant-leg Ankle Angle_Y	**32.2**	7.5	**7.9**	3.9	**22.5**	4.0	**1.8**	3.6	**11.6**	3.6
Non-dominant-leg Ankle Angle_Z	**0.3**	8.3	**2.5**	7.0	**0.0**	7.4	**2.3**	6.3	**-0.1**	6.6
Non-dominant-leg Ankle Angular Velocity_X	**606.9**	233.3	**1219.0**	372.7	**1234.5**	294.9	**1355.6**	338.9	**1259.0**	319.1
Non-dominant-leg Ankle Angular Velocity_Y	**860.4**	457.7	**173.7**	94.4	**508.6**	198.0	**191.6**	100.4	**403.4**	216.5
Non-dominant-leg Ankle Angular Velocity_Z	**335.9**	171.8	**222.2**	204.3	**203.3**	165.2	**169.9**	144.2	**144.1**	159.4
Non-dominant-leg Hip Angle_X	**36.9**	14.3	**63.2**	14.1	**56.3**	14.2	**40.9**	13.9	**37.1**	14.6
Non-dominant-leg Hip Angle_Y	**-12.2**	7.5	**-7.7**	5.5	**-10.9**	5.6	**2.8**	6.8	**-1.5**	6.8
Non-dominant-leg Hip Angle_Z	**1.2**	10.7	**-8.2**	11.0	**-6.7**	8.8	**-7.3**	10.7	**-6.1**	9.4
Non-dominant-leg Hip Angular Velocity_X	**143.8**	96.8	**495.8**	90.1	**524.0**	133.6	**454.9**	132.6	**484.1**	140.6
Non-dominant-leg Hip Angular Velocity_Y	**376.4**	137.4	**294.6**	116.9	**276.8**	121.4	**473.9**	167.6	**412.9**	156.5
Non-dominant-leg Hip Angular Velocity_Z	**296.0**	157.8	**237.6**	130.0	**209.7**	114.2	**429.3**	166.4	**331.3**	152.6
Non-dominant-leg Knee Angle_X	**55.1**	6.7	**87.9**	8.1	**78.2**	7.9	**58.0**	5.2	**57.1**	10.4
Non-dominant-leg Knee Angle_Y	**-3.8**	5.5	**0.1**	5.4	**-0.6**	5.3	**0.2**	4.4	**-1.6**	4.7
Non-dominant-leg Knee Angle_Z	**9.7**	8.7	**7.3**	6.4	**7.2**	6.7	**7.0**	8.1	**7.1**	7.8
Non-dominant-leg Knee Angular Velocity_X	**725.2**	206.2	**959.7**	198.5	**837.5**	170.7	**786.4**	184.9	**702.0**	179.3
Non-dominant-leg Knee Angular Velocity_Y	**283.8**	168.4	**241.8**	177.3	**244.8**	139.7	**240.8**	136.6	**211.6**	144.3
Non-dominant-leg Knee Angular Velocity_Z	**583.1**	270.9	**446.3**	161.1	**411.6**	140.1	**472.3**	196.6	**365.8**	161.9
Non-dominant-leg Pelvis Angle_X	**10.9**	9.0	**19.4**	9.0	**24.7**	10.7	**22.8**	9.4	**19.6**	9.6
Non-dominant-leg Pelvis Angle_Y	**12.8**	8.4	**2.8**	4.6	**-2.2**	4.4	**12.2**	5.4	**0.5**	6.2
Non-dominant-leg Pelvis Angle_Z	**-14.7**	15.2	**0.6**	4.2	**6.8**	6.7	**11.6**	9.0	-1.8	7.2
Non-dominant-leg Pelvis Angular Velocity_X	**104.8**	53.1	**105.9**	59.1	**130.5**	86.4	**121.5**	85.0	**98.8**	58.0
Non-dominant-leg Pelvis Angular Velocity_Y	**203.8**	100.7	**118.3**	60.5	**95.5**	45.9	**34.3**	48.8	**295.3**	109.8
Non-dominant-leg Pelvis Angular Velocity_Z	**109.4**	77.6	**75.3**	41.0	**77.8**	57.5	**76.1**	54.5	**138.9**	53.4
Non-dominant-leg Trunk Angle_X	**17.5**	9.3	**28.2**	7.8	**31.6**	11.0	**16.2**	9.6	**21.6**	8.8
Non-dominant-leg Trunk Angle_Y	**2.2**	7.6	**0.4**	3.1	**3.6**	5.1	**12.1**	6.0	**-5.0**	5.0
Non-dominant-leg Trunk Angle_Z	**-2.5**	14.9	**1.8**	2.9	**9.6**	7.8	**20.0**	15.3	5.5	5.2
Non-dominant-leg Trunk Angular Velocity_X	**138.6**	65.3	**174.9**	55.8	**206.9**	87.4	**181.5**	66.1	**205.6**	51.2
Non-dominant-leg Trunk Angular Velocity_Y	**50.1**	42.4	**26.9**	18.1	**42.1**	42.7	**97.9**	50.8	**19.7**	28.9
Non-dominant-leg Trunk Angular Velocity_Z	**-34.7**	87.5	**22.4**	15.9	**-8.4**	43.8	**10.8**	43.1	**39.6**	26.3
Non-dominant-leg Pelvis Linear Acceleration_Vertical	**4.9**	0.9	**4.7**	1.3	**4.9**	0.8	**1.5**	0.7	**2.0**	1.0
Non-dominant-leg Pelvis Linear Acceleration_Medio-lateral	**2.8**	2.2	**2.1**	1.1	**1.4**	1.3	**2.4**	2.5	**3.4**	2.4
Non-dominant-leg Pelvis Linear Acceleration_Anterio-posteri	**4.6**	1.4	**5.3**	1.8	**4.1**	1.4	**4.2**	1.7	**4.7**	2.0

Note , that the directionality and interpretation of joint movements are presented in Table 13

Abbreviations: DLJL, double-leg jump-landing; DLJLrot, rotated double-leg jump-landing; SLJL, single-leg jump-landing; SLJLrot, rotated single-leg jump-landing; SD, standard deviation

** Foot-ground angle one frame before initial contact*

	Dominant-leg variables at 100ms: Range of Values									
	Mean Cutting	SD Cutting	**Mean DLJL**	SD DLJL	**Mean DLJLrot**	SD DLJLrot	**Mean SLJL**	SD SLJL	**Mean SLJLrot**	SD SLJLrot
Dominant-leg Ankle Angle_X	**29.5**	8.8	**37.0**	7.1	**43.7**	8.4	**36.4**	9.0	**45.1**	7.5
Dominant-leg Ankle Angle_Y	**14.3**	6.6	**7.9**	3.6	**10.3**	3.8	**9.6**	3.5	**9.1**	2.8
Dominant-leg Ankle Angle_Z	**10.6**	3.6	**10.3**	3.6	**9.0**	4.2	**12.8**	3.5	**11.0**	3.8
Dominant-leg Ankle Angular Velocity_X	**727.0**	329.9	**1194.7**	389.9	**1287.4**	330.1	**1253.3**	401.0	**1282.6**	279.3
Dominant-leg Ankle Angular Velocity_Y	**951.4**	434.1	**563.0**	234.6	**654.5**	256.0	**530.7**	202.1	**596.1**	222.2
Dominant-leg Ankle Angular Velocity_Z	**846.8**	423.0	**615.3**	380.0	**681.0**	460.9	**632.4**	330.9	**574.0**	336.1
Dominant-leg Hip Angle_X	**10.3**	4.3	**25.5**	6.0	**28.6**	6.6	**15.5**	4.6	**17.1**	4.3
Dominant-leg Hip Angle_Y	**6.7**	2.2	**4.6**	1.9	**6.1**	2.5	**14.6**	4.7	**14.7**	3.9
Dominant-leg Hip Angle_Z	**17.6**	6.6	**9.7**	4.1	**9.7**	3.7	**10.7**	4.2	**9.6**	3.7
Dominant-leg Hip Angular Velocity_X	**461.1**	174.0	**457.2**	149.2	**540.9**	177.0	**516.9**	173.4	**509.9**	163.3
Dominant-leg Hip Angular Velocity_Y	**545.2**	217.9	**518.1**	223.9	**484.4**	194.1	**511.1**	194.9	**423.5**	163.7
Dominant-leg Hip Angular Velocity_Z	**778.1**	279.3	**457.5**	215.1	**442.6**	193.1	**638.3**	228.7	**609.6**	221.5
Dominant-leg Knee Angle_X	**29.0**	5.6	**55.7**	7.2	**52.2**	6.1	**40.9**	5.9	**41.5**	5.0
Dominant-leg Knee Angle_Y	**9.8**	3.9	**11.0**	4.2	**9.9**	3.6	**8.0**	3.3	**7.1**	2.7
Dominant-leg Knee Angle_Z	**12.3**	4.0	**9.8**	3.4	**10.0**	4.1	**10.9**	3.5	**10.2**	3.3
Dominant-leg Knee Angular Velocity_X	**759.4**	210.8	**760.7**	173.6	**671.0**	209.7	**693.8**	180.5	**640.3**	206.3
Dominant-leg Knee Angular Velocity_Y	**654.0**	375.2	**659.5**	364.4	**628.0**	407.6	**554.6**	294.6	**514.8**	300.4
Dominant-leg Knee Angular Velocity_Z	**940.2**	394.7	**650.0**	313.0	**718.6**	320.4	**759.3**	316.4	**701.8**	293.1
Dominant-leg Pelvis Angle_X	**26.6**	2.7	**22.5**	2.4	**13.6**	2.1	**18.6**	2.6	**19.9**	2.6
Dominant-leg Pelvis Angle_Y	**6.6**	3.5	**3.8**	1.7	**4.1**	1.7	**8.6**	3.7	**8.6**	3.1
Dominant-leg Pelvis Angle_Z	**5.9**	14.7	**1.0**	14.1	**5.4**	1.9	**4.4**	14.3	**6.4**	2.5
Dominant-leg Pelvis Angular Velocity_X	**334.4**	116.5	**291.5**	94.3	**273.4**	87.9	**230.1**	104.4	**192.7**	76.0
Dominant-leg Pelvis Angular Velocity_Y	**277.9**	111.0	**201.4**	85.9	**195.7**	81.0	**291.0**	111.0	**229.5**	97.2
Dominant-leg Pelvis Angular Velocity_Z	**360.5**	142.8	**168.5**	80.4	**219.4**	86.2	**257.5**	111.0	**248.9**	95.8
Dominant-leg Trunk Angle_X	**20.0**	3.1	**15.7**	4.4	**21.6**	4.5	**19.7**	4.0	**22.1**	4.0
Dominant-leg Trunk Angle_Y	**4.2**	2.0	**1.9**	0.7	**3.5**	1.9	**4.6**	2.0	**4.3**	2.1
Dominant-leg Trunk Angle_Z	**9.3**	13.7	**-0.2**	14.1	**5.6**	2.0	**1.8**	14.2	**5.4**	2.9
Dominant-leg Trunk Angular Velocity_X	**144.4**	53.4	**152.4**	53.3	**122.5**	50.2	**179.3**	49.3	**152.9**	40.2
Dominant-leg Trunk Angular Velocity_Y	**78.3**	30.4	**47.2**	18.0	**65.5**	19.6	**72.5**	24.6	**97.6**	39.6
Dominant-leg Trunk Angular Velocity_Z	**104.0**	33.3	**45.4**	14.1	**79.5**	28.9	**70.9**	28.9	**87.0**	34.4
Dominant-leg Pelvis Linear Acceleration_Vertical	**22.1**	3.4	**14.9**	3.9	**12.0**	3.6	**19.4**	3.5	**17.7**	2.9
Dominant-leg Pelvis Linear Acceleration_Medio-lateral	**10.4**	4.4	**4.1**	2.0	**5.1**	2.4	**8.3**	3.8	**7.3**	3.5
Dominant-leg Pelvis Linear Acceleration_Anterio-posterior	**6.3**	2.9	**6.6**	2.8	**4.5**	2.5	**5.8**	3.1	**4.9**	3.1

Note , that the directionality and interpretation of joint movements are presented in Table 13

Abbreviations: DLJL, double-leg jump-landing; DLJLrot, rotated double-leg jump-landing; SLJL, single-leg jump-landing; SLJLrot, rotated single-leg jump-landing; SD, standard deviation

** Foot-ground angle one frame before initial contact*

	Non-dominant-leg variables at 100ms: Range of Values									
	Mean Cutting	SD Cutting	**Mean DLJL**	SD DLJL	**Mean DLJLrot**	SD DLJLrot	**Mean SLJL**	SD SLJL	**Mean SLJLrot**	SD SLJLrot
Non-dominant-leg Ankle Angle_X	**27.1**	6.6	**35.7**	7.2	**42.3**	7.6	**37.1**	7.2	**41.8**	9.0
Non-dominant-leg Ankle Angle_Y	**16.3**	7.3	**6.8**	3.4	**10.2**	3.6	**9.4**	3.2	**8.6**	3.2
Non-dominant-leg Ankle Angle_Z	**10.8**	3.8	**11.0**	2.9	**9.2**	3.5	**13.5**	3.1	**11.1**	3.5
Non-dominant-leg Ankle Angular Velocity_X	**731.9**	298.2	**1186.3**	390.3	**1215.6**	320.7	**1319.4**	361.1	**1217.2**	333.3
Non-dominant-leg Ankle Angular Velocity_Y	**993.9**	541.3	**518.8**	234.4	**674.0**	214.8	**539.7**	225.3	**610.5**	251.2
Non-dominant-leg Ankle Angular Velocity_Z	**803.1**	417.8	**657.2**	388.8	**603.5**	324.0	**623.3**	312.5	**546.3**	325.1
Non-dominant-leg Hip Angle_X	**12.2**	4.4	**24.6**	6.0	**27.2**	7.0	**16.8**	5.0	**19.0**	5.3
Non-dominant-leg Hip Angle_Y	**7.2**	3.3	**6.3**	2.5	**7.0**	3.3	**17.2**	4.8	**16.5**	5.2
Non-dominant-leg Hip Angle_Z	**20.6**	7.6	**11.1**	4.1	**12.0**	4.3	**11.7**	4.7	**9.6**	3.6
Non-dominant-leg Hip Angular Velocity_X	**432.6**	137.0	**472.0**	132.5	**484.0**	174.4	**587.5**	182.7	**561.2**	180.5
Non-dominant-leg Hip Angular Velocity_Y	**605.6**	241.7	**630.0**	237.4	**535.8**	193.9	**669.0**	212.8	**515.3**	177.6
Non-dominant-leg Hip Angular Velocity_Z	**878.3**	300.6	**484.8**	213.8	**505.8**	203.2	**707.6**	305.7	**553.5**	239.1
Non-dominant-leg Knee Angle_X	**29.5**	6.2	**53.7**	7.1	**50.3**	6.0	**39.8**	4.3	**39.5**	7.9
Non-dominant-leg Knee Angle_Y	**11.5**	4.2	**12.4**	4.9	**10.2**	3.4	**9.3**	4.6	**7.8**	4.1
Non-dominant-leg Knee Angle_Z	**12.7**	4.1	**10.3**	3.8	**9.7**	3.6	**10.5**	3.6	**9.2**	3.9
Non-dominant-leg Knee Angular Velocity_X	**757.9**	253.2	**771.9**	218.7	**645.6**	208.6	**755.7**	248.5	**639.4**	230.8
Non-dominant-leg Knee Angular Velocity_Y	**592.6**	306.5	**636.9**	351.2	**575.3**	319.1	**566.5**	314.4	**513.0**	326.4
Non-dominant-leg Knee Angular Velocity_Z	**1009.4**	438.2	**741.7**	307.9	**699.1**	273.0	**832.9**	342.8	**655.5**	323.5
Non-dominant-leg Pelvis Angle_X	**29.6**	4.3	**22.4**	2.3	**18.8**	2.4	**25.5**	3.0	**30.3**	1.9
Non-dominant-leg Pelvis Angle_Y	**7.0**	3.0	**3.8**	1.7	**5.6**	2.3	**11.5**	3.3	**11.8**	2.9
Non-dominant-leg Pelvis Angle_Z	**5.3**	13.8	**1.0**	14.1	**6.3**	2.9	**4.1**	14.1	**5.8**	2.2
Non-dominant-leg Pelvis Angular Velocity_X	**383.6**	138.8	**292.8**	92.0	**255.6**	80.4	**269.3**	100.3	**219.4**	74.5
Non-dominant-leg Pelvis Angular Velocity_Y	**295.8**	113.3	**201.9**	85.7	**225.6**	84.2	**356.1**	102.4	**325.3**	102.7
Non-dominant-leg Pelvis Angular Velocity_Z	**309.6**	107.8	**171.4**	80.2	**253.9**	112.2	**208.7**	78.5	**209.9**	70.6
Non-dominant-leg Trunk Angle_X	**14.9**	4.0	**15.5**	4.4	**26.6**	4.4	**15.8**	4.0	**16.4**	4.2
Non-dominant-leg Trunk Angle_Y	**4.4**	2.4	**1.9**	0.7	**3.4**	1.6	**4.5**	1.8	**5.1**	2.4
Non-dominant-leg Trunk Angle_Z	**8.4**	13.2	**-0.1**	14.1	**6.4**	2.7	**1.8**	13.9	**5.6**	2.4
Non-dominant-leg Trunk Angular Velocity_X	**142.4**	54.8	**151.9**	52.9	**121.1**	56.2	**187.2**	50.7	**162.0**	40.1
Non-dominant-leg Trunk Angular Velocity_Y	**82.2**	25.0	**47.1**	18.0	**70.7**	25.7	**75.8**	23.0	**114.1**	50.0
Non-dominant-leg Trunk Angular Velocity_Z	**115.6**	47.8	**45.2**	12.4	**81.5**	25.1	**78.8**	26.3	**93.5**	40.8
Non-dominant-leg Pelvis Linear Acceleration_Vertical	**17.4**	3.1	**14.7**	3.9	**17.6**	3.5	**12.8**	3.0	**11.6**	3.2
Non-dominant-leg Pelvis Linear Acceleration_Medio-lateral	**9.9**	3.6	**4.1**	2.0	**4.9**	1.8	**8.5**	4.0	**7.8**	3.1
Non-dominant-leg Pelvis Linear Acceleration_Anterio-posterior	**5.7**	2.2	**6.5**	2.8	**4.2**	2.1	**5.8**	3.1	**5.0**	2.6

Note , that the directionality and interpretation of joint movements are presented in Table 13

Abbreviations: DLJL, double-leg jump-landing; DLJLrot, rotated double-leg jump-landing; SLJL, single-leg jump-landing; SLJLrot, rotated single-leg jump-landing; SD, standard deviation

** Foot-ground angle one frame before initial contact*

	Dominant-leg variables at Initial Contact									
	Mean Cutting	SD Cutting	**Mean DLJL**	SD DLJL	**Mean DLJLrot**	SD DLJLrot	**Mean SLJL**	SD SLJL	**Mean SLJLrot**	SD SLJLrot
Dominant-leg Ankle Angle_X	**-10.5**	10.9	**-13.1**	7.9	**-14.7**	8.3	**-16.7**	9.6	**-18.8**	7.5
Dominant-leg Ankle Angle_Y	**18.3**	6.7	**7.1**	4.8	**13.3**	6.3	**1.8**	4.6	**5.4**	5.5
Dominant-leg Ankle Angle_Z	**-5.1**	11.5	**-1.7**	5.6	**-3.8**	6.4	**-1.0**	6.3	**-4.1**	6.6
Dominant-leg Ankle Angular Velocity_X	**57.5**	328.6	**1035.7**	370.4	**993.6**	250.8	**1019.4**	236.9	**933.0**	276.3
Dominant-leg Ankle Angular Velocity_Y	**673.8**	417.6	**-307.3**	211.2	**384.7**	191.8	**-154.2**	179.5	**282.4**	158.7
Dominant-leg Ankle Angular Velocity_Z	**-169.1**	218.5	**-238.9**	154.4	**-230.4**	199.8	**-140.5**	193.1	**-169.0**	136.1
Dominant-leg Hip Angle_X	**35.1**	10.5	**38.9**	13.1	**31.2**	11.7	**27.8**	11.0	**25.2**	9.9
Dominant-leg Hip Angle_Y	**-12.8**	7.0	**-9.7**	5.6	**-14.4**	6.0	**-13.1**	4.9	**-16.9**	6.1
Dominant-leg Hip Angle_Z	**4.0**	9.9	**-9.0**	8.8	**-5.9**	9.3	**-10.1**	9.1	**-6.0**	8.9
Dominant-leg Hip Angular Velocity_X	**-134.2**	91.9	**167.4**	81.1	**137.9**	93.2	**-0.9**	82.9	**12.2**	61.3
Dominant-leg Hip Angular Velocity_Y	**-7.0**	137.6	**-52.8**	63.9	**8.7**	60.6	**-47.3**	91.3	**3.0**	50.6
Dominant-leg Hip Angular Velocity_Z	**-73.3**	157.5	**-33.7**	73.7	**-31.7**	83.0	**29.9**	112.4	**-24.2**	90.9
Dominant-leg Knee Angle_X	**27.2**	5.8	**33.7**	8.3	**27.6**	7.5	**18.9**	7.2	**18.3**	5.6
Dominant-leg Knee Angle_Y	**-5.3**	5.3	**1.4**	4.6	**-0.1**	4.3	**-0.1**	3.6	**-1.6**	3.8
Dominant-leg Knee Angle_Z	**0.9**	8.3	**0.7**	5.9	**-0.6**	7.1	**-2.1**	8.0	**-0.1**	8.4
Dominant-leg Knee Angular Velocity_X	**224.6**	195.8	**740.1**	179.4	**605.0**	172.1	**502.3**	132.2	**418.6**	148.0
Dominant-leg Knee Angular Velocity_Y	**-64.5**	100.0	**172.6**	153.4	**66.7**	122.6	**100.2**	130.1	**55.0**	91.0
Dominant-leg Knee Angular Velocity_Z	**95.7**	258.9	**218.7**	135.8	**200.5**	140.0	**185.9**	217.4	**162.1**	161.5
Dominant-leg Pelvis Angle_X	**-2.9**	7.8	**13.4**	7.9	**15.7**	8.7	**17.7**	7.4	**19.8**	7.6
Dominant-leg Pelvis Angle_Y	**-7.8**	7.9	**0.1**	3.7	**-2.9**	4.0	**9.5**	8.3	**11.8**	4.3
Dominant-leg Pelvis Angle_Z	**15.9**	12.3	**-0.3**	4.0	**-6.4**	6.5	6.9	7.2	**-5.6**	10.0
Dominant-leg Pelvis Angular Velocity_X	**-16.4**	66.8	**-104.5**	49.9	**-44.6**	70.0	**-93.0**	39.2	**-51.1**	40.9
Dominant-leg Pelvis Angular Velocity_Y	**5.1**	73.1	**19.9**	37.0	**-6.7**	44.1	**25.8**	43.2	**-14.0**	31.2
Dominant-leg Pelvis Angular Velocity_Z	**126.9**	111.5	**9.9**	35.7	**66.9**	73.5	**9.6**	50.4	**85.8**	73.4
Dominant-leg Trunk Angle_X	**9.8**	8.6	**16.4**	7.5	**16.1**	6.8	**9.7**	7.2	**4.5**	5.6
Dominant-leg Trunk Angle_Y	**-0.1**	5.7	**-0.7**	2.9	**1.1**	4.1	**4.1**	4.0	**7.3**	4.7
Dominant-leg Trunk Angle_Z	**3.8**	10.9	**0.5**	2.7	**-8.7**	8.4	-1.6	5.3	**-15.6**	15.6
Dominant-leg Trunk Angular Velocity_X	**5.3**	43.7	**34.2**	45.1	**113.8**	50.4	**35.7**	31.6	**47.5**	30.1
Dominant-leg Trunk Angular Velocity_Y	**-16.0**	41.5	**1.6**	17.3	**-22.1**	26.1	**13.4**	18.5	**-8.7**	22.0
Dominant-leg Trunk Angular Velocity_Z	**87.0**	86.8	**-3.9**	19.5	**72.5**	48.4	**8.1**	26.2	**57.7**	52.5
Dominant-leg Pelvis Linear Acceleration_Vertical	**3.5**	0.7	**-0.1**	0.6	**0.9**	0.5	**-2.8**	0.4	**-0.9**	0.2
Dominant-leg Pelvis Linear Acceleration_Medio-lateral	**-0.6**	0.8	**0.0**	0.2	**-0.1**	0.4	**0.2**	0.3	**0.0**	0.2
Dominant-leg Pelvis Linear Acceleration_Anterio-posterior	**0.2**	1.1	**0.7**	0.8	**1.1**	0.6	**0.6**	0.7	**0.5**	0.4
Dominant-leg Foot-ground Contact_X*	**4.0**	6.5	**-11.9**	5.7	**-22.9**	6.2	**-18.2**	5.9	**-23.7**	7.1
Dominant-leg Foot-ground Contact_Y*	**-11.3**	9.4	**9.6**	5.6	**3.3**	5.7	**9.3**	5.2	**6.0**	6.7
Dominant-leg Foot-ground Contact_Z*	**4.1**	11.5	**-14.3**	5.6	**-26.9**	7.7	**-7.9**	6.2	**-24.6**	9.2

Note , that the directionality and interpretation of joint movements are presented in Table 13

Abbreviations: DLJL, double-leg jump-landing; DLJLrot, rotated double-leg jump-landing; SLJL, single-leg jump-landing; SLJLrot, rotated single-leg jump-landing; SD, standard deviation

** Foot-ground angle one frame before initial contact*

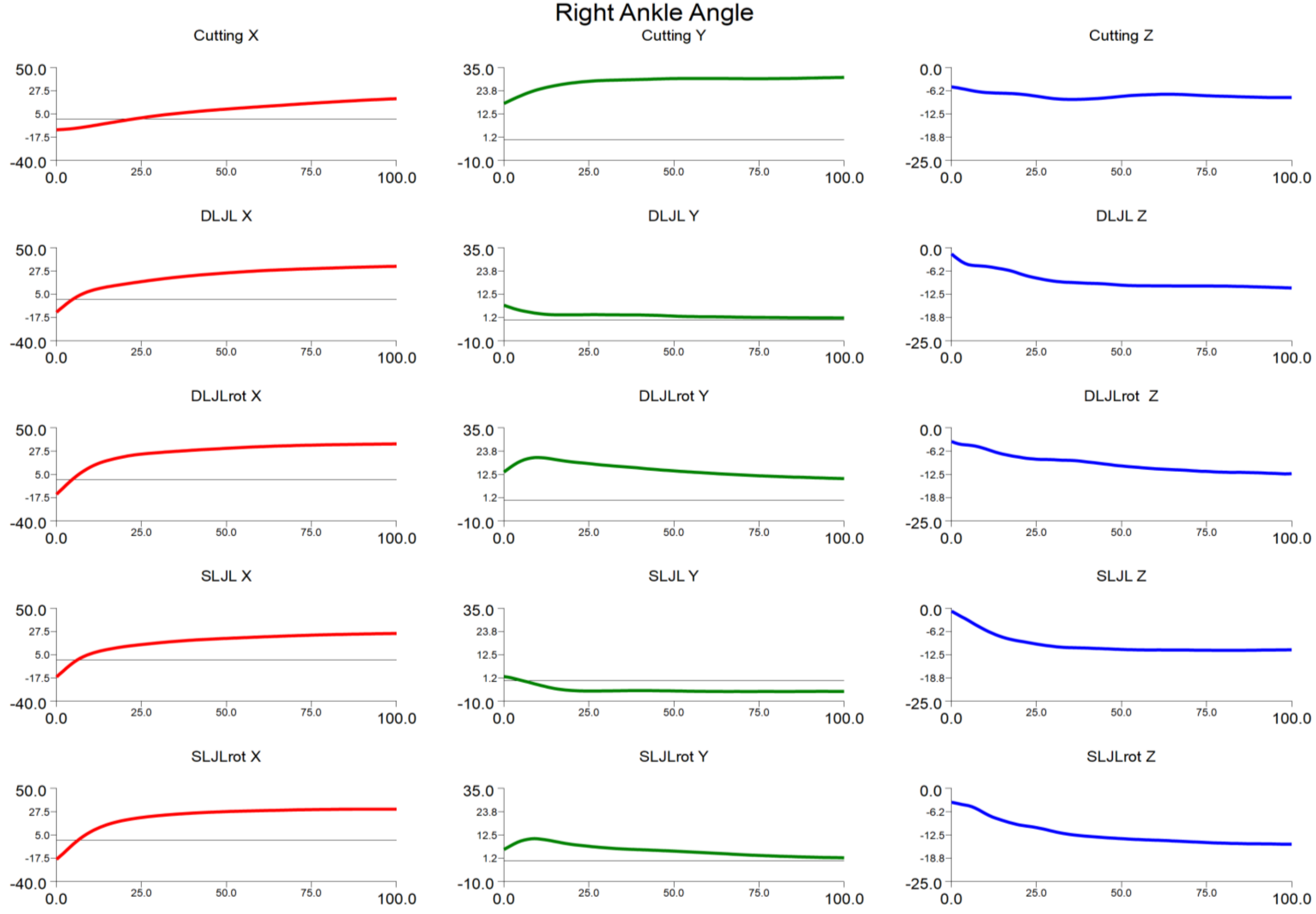
	Non-dominant-leg variables at Initial Contact									
	Mean Cutting	SD Cutting	Mean DLJL	SD DLJL	Mean DLJLrot	SD DLJLrot	Mean SLJL	SD SLJL	Mean SLJLrot	SD SLJLrot
Non-dominant-leg Ankle Angle_X	**-11.9**	6.2	**-12.0**	8.1	**-14.0**	7.1	**-16.9**	7.4	**-16.9**	6.6
Non-dominant-leg Ankle Angle_Y	**16.0**	5.7	**6.8**	4.5	**13.5**	5.7	**1.1**	4.2	**5.2**	4.7
Non-dominant-leg Ankle Angle_Z	-3.4	8.5	**1.5**	7.1	**-1.5**	7.1	**1.9**	6.5	**-1.2**	6.6
Non-dominant-leg Ankle Angular Velocity_X	-39.5	324.7	**975.3**	372.2	**959.6**	286.6	**1066.8**	315.0	**943.5**	329.7
Non-dominant-leg Ankle Angular Velocity_Y	**752.3**	449.6	**-240.5**	214.4	**432.8**	182.9	**-104.0**	194.9	**329.8**	193.3
Non-dominant-leg Ankle Angular Velocity_Z	**-114.6**	198.4	**-236.9**	149.6	**-210.8**	168.1	**-132.0**	149.8	**-163.2**	154.1
Non-dominant-leg Hip Angle_X	**35.7**	13.9	**38.7**	12.3	**29.3**	11.4	**25.3**	12.0	**19.3**	12.6
Non-dominant-leg Hip Angle_Y	**-17.1**	7.1	**-11.1**	4.8	**-14.8**	4.3	**-14.2**	5.8	**-17.9**	6.7
Non-dominant-leg Hip Angle_Z	-2.5	10.1	**-14.2**	10.5	**-10.9**	9.1	**-16.2**	10.7	**-11.1**	9.8
Non-dominant-leg Hip Angular Velocity_X	**-134.4**	148.9	**156.4**	89.3	**134.8**	100.3	-1.9	75.9	15.5	58.6
Non-dominant-leg Hip Angular Velocity_Y	14.4	157.1	-26.8	105.1	**47.9**	106.3	-30.1	106.0	31.7	82.1
Non-dominant-leg Hip Angular Velocity_Z	-35.8	194.1	12.9	110.3	-24.0	143.0	**77.6**	167.8	-9.4	111.9
Non-dominant-leg Knee Angle_X	**25.7**	4.9	**34.2**	7.9	**28.0**	7.2	**18.2**	4.3	**17.6**	5.4
Non-dominant-leg Knee Angle_Y	-6.1	5.1	-0.9	4.9	-2.5	4.1	-1.7	3.8	-2.9	4.3
Non-dominant-leg Knee Angle_Z	1.5	9.0	2.3	8.2	1.8	8.2	0.5	9.3	1.8	9.3
Non-dominant-leg Knee Angular Velocity_X	**238.4**	157.2	**716.8**	165.9	**602.0**	190.4	**501.5**	172.6	**418.7**	166.5
Non-dominant-leg Knee Angular Velocity_Y	**-100.4**	104.9	**94.4**	180.6	-1.9	121.9	42.2	120.0	9.1	111.9
Non-dominant-leg Knee Angular Velocity_Z	83.7	250.7	**200.4**	111.7	**175.9**	144.1	**146.8**	237.2	**138.9**	209.3
Non-dominant-leg Pelvis Angle_X	3.3	9.0	**11.5**	8.1	**15.5**	9.0	**11.9**	8.8	**18.5**	8.7
Non-dominant-leg Pelvis Angle_Y	**7.4**	7.6	0.1	3.7	**-3.4**	3.9	**-9.9**	8.3	**12.1**	5.4
Non-dominant-leg Pelvis Angle_Z	**-17.0**	14.3	-0.6	4.0	**6.2**	7.2	-6.9	7.7	**9.9**	9.5
Non-dominant-leg Pelvis Angular Velocity_X	**-55.5**	91.7	**-103.2**	58.6	**-41.4**	69.7	**-71.7**	41.3	**-29.3**	36.1
Non-dominant-leg Pelvis Angular Velocity_Y	9.3	62.2	**18.4**	38.0	**-56.3**	46.8	**16.5**	30.2	**-48.6**	35.3
Non-dominant-leg Pelvis Angular Velocity_Z	**-78.3**	139.6	11.6	35.7	**-72.3**	65.9	-4.1	39.9	**-79.9**	77.5
Non-dominant-leg Trunk Angle_X	**7.0**	9.4	**16.2**	7.4	**10.1**	6.6	**7.9**	6.8	2.0	6.5
Non-dominant-leg Trunk Angle_Y	-1.1	6.2	-0.7	3.0	2.2	4.4	**-5.7**	4.2	**7.5**	5.3
Non-dominant-leg Trunk Angle_Z	-3.8	12.9	0.6	2.7	**9.0**	9.4	2.6	5.5	**19.3**	16.7
Non-dominant-leg Trunk Angular Velocity_X	9.6	47.9	**36.9**	48.3	**118.5**	52.0	**27.1**	38.7	**39.7**	34.0
Non-dominant-leg Trunk Angular Velocity_Y	14.9	39.9	2.6	16.5	**-17.3**	25.9	**-13.2**	21.9	-5.8	25.8
Non-dominant-leg Trunk Angular Velocity_Z	**-82.8**	102.4	-4.4	18.6	**-76.5**	55.9	-8.1	31.1	**-65.1**	55.5
Non-dominant-leg Pelvis Linear Acceleration_Vertical	**-0.9**	0.5	0.0	0.8	0.1	0.7	-0.1	0.3	**0.5**	0.2
Non-dominant-leg Pelvis Linear Acceleration_Medio-lateral	0.7	1.0	0.1	0.2	0.2	0.3	-0.1	0.3	0.0	0.2
Non-dominant-leg Pelvis Linear Acceleration_Anterio-poster	0.4	1.1	**0.9**	0.8	**1.1**	0.6	**0.5**	0.4	**0.4**	0.3
Non-dominant-leg Foot-ground Contact_X*	4.9	6.3	**-11.4**	5.9	**-22.6**	7.0	**-18.2**	6.6	**-22.9**	6.6
Non-dominant-leg Foot-ground Contact_Y*	**-12.2**	8.4	**9.0**	5.1	2.1	4.9	**9.2**	5.4	**7.0**	4.9
Non-dominant-leg Foot-ground Contact_Z*	3.7	11.6	**-14.4**	4.5	**-26.6**	7.5	**-8.8**	5.8	**-26.8**	7.9

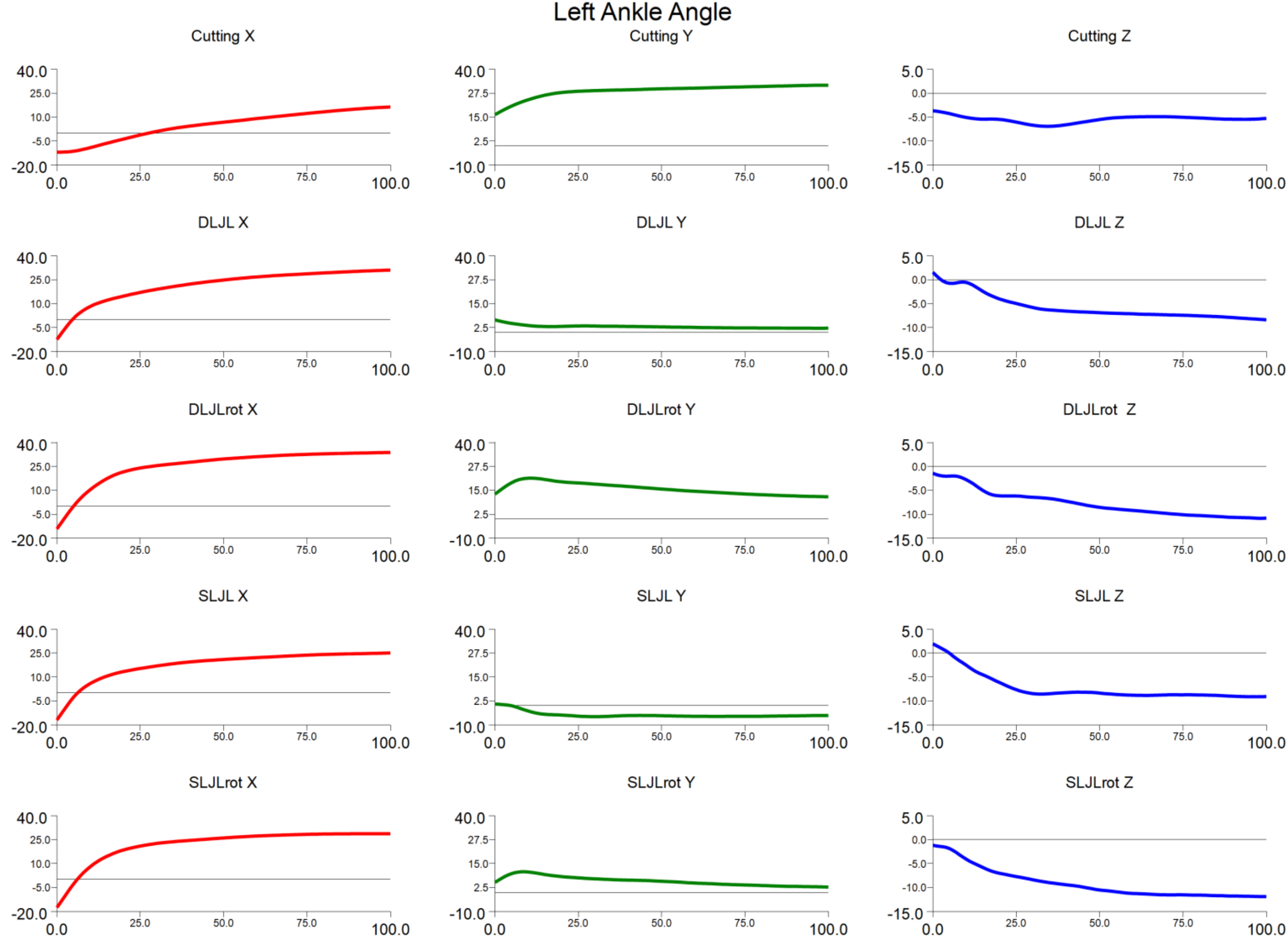
Note , that the directionality and interpretation of joint movements are presented in Table 13

Abbreviations: DLJL, double-leg jump-landing; DLJLrot, rotated double-leg jump-landing; SLJL, single-leg jump-landing; SLJLrot, rotated single-leg jump-landing; SD, standard deviation

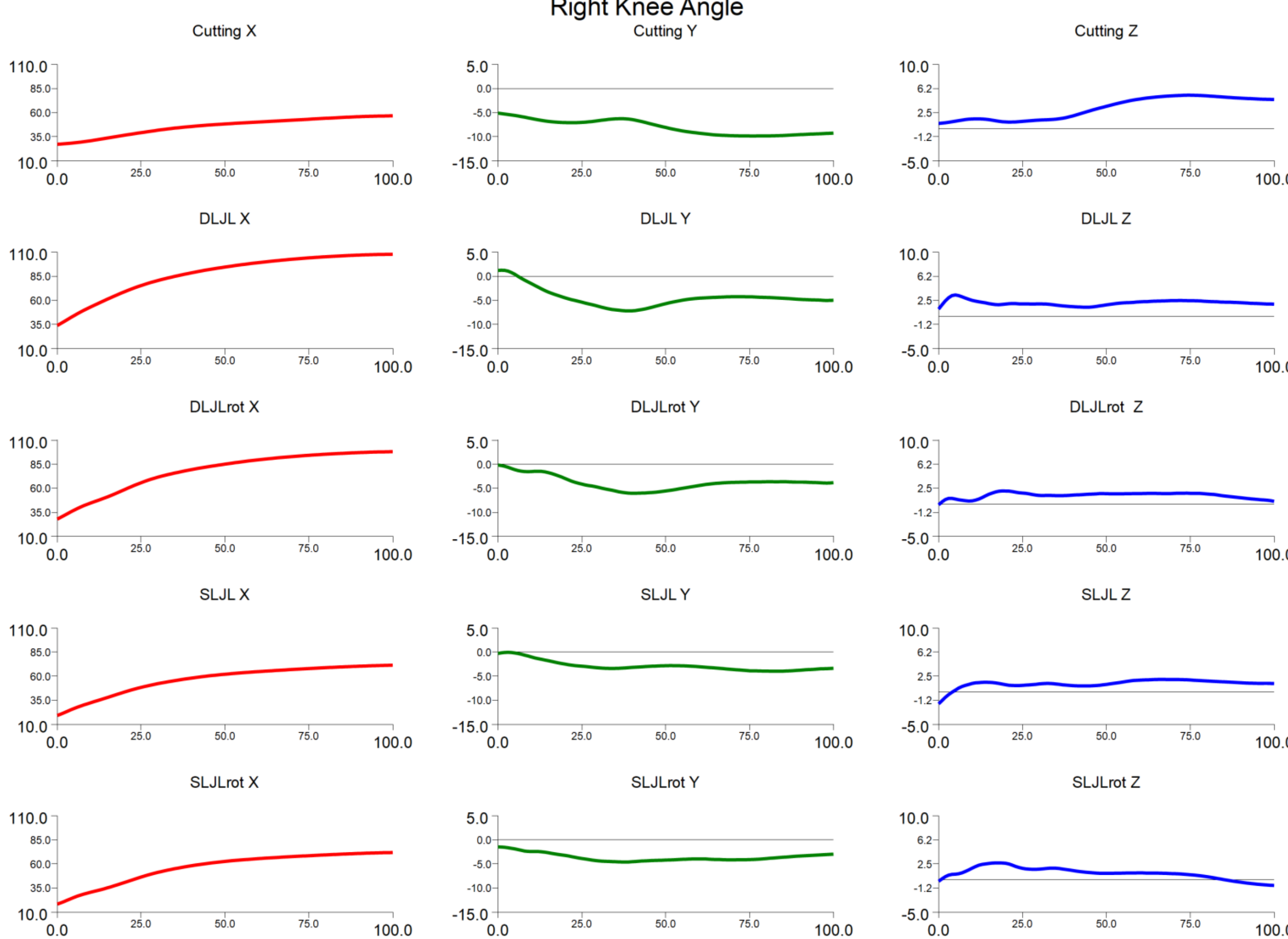
** Foot-ground angle one frame before initial contact*

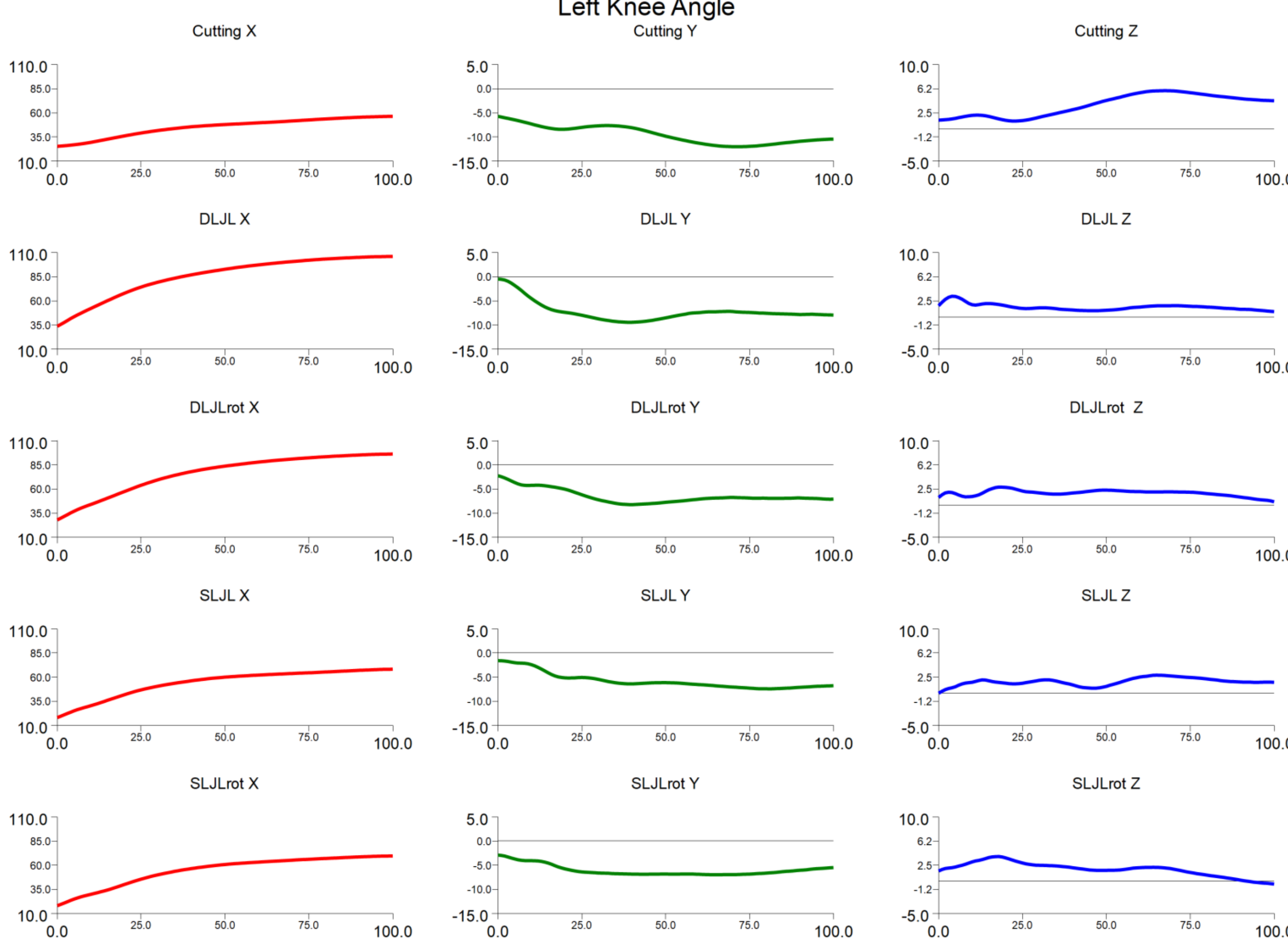
Appendix F2. *Mean waveform diagrams of ankle, knee, and hip angles (°) between initial contact and maximal knee flexion for all tasks.*

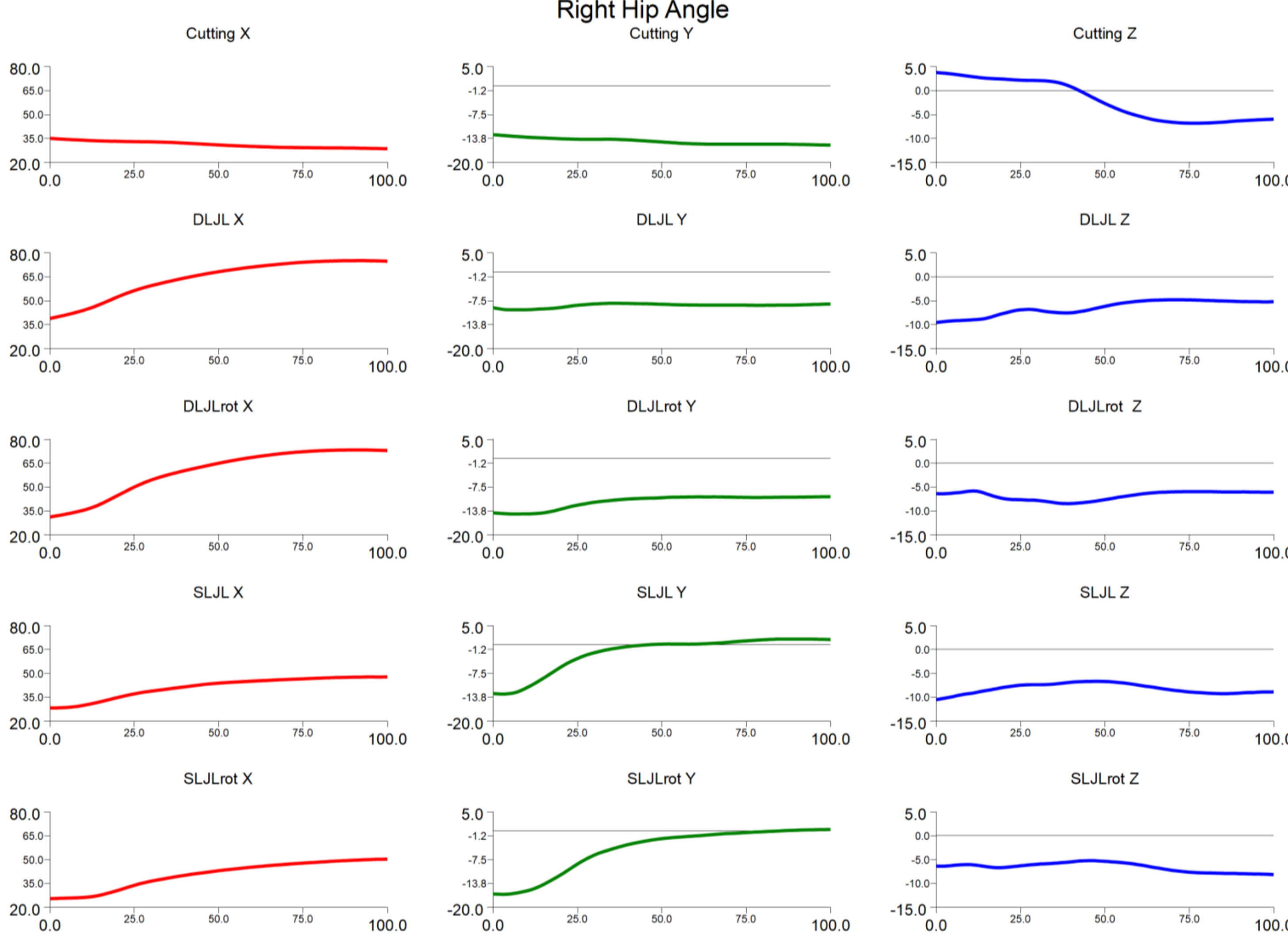




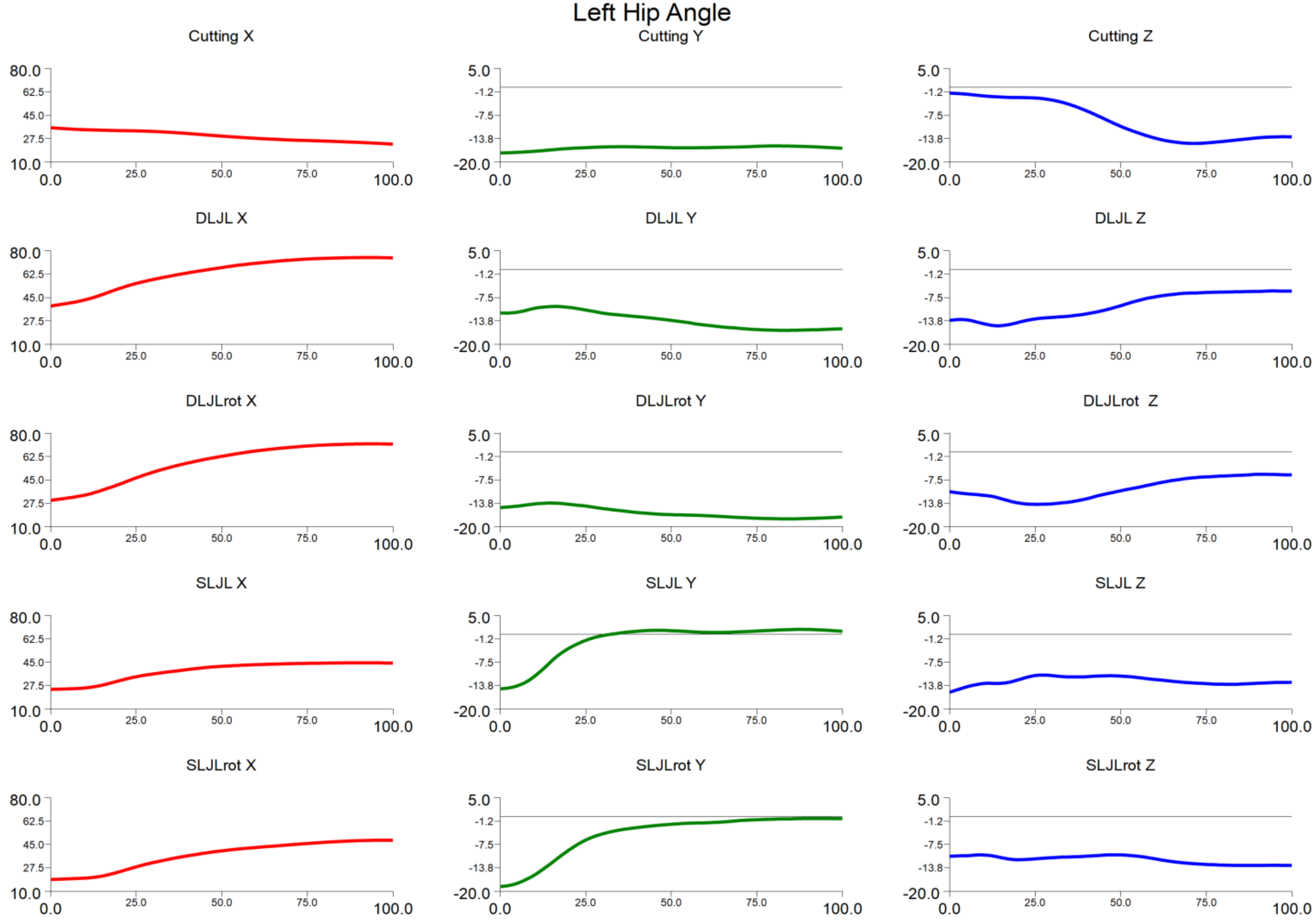
Left Ankle Angle
Cutting X
Cutting Y
Cutting Z
DLJL X
DLJL Y
DLJL Z
DLJLrot X
DLJLrot Y
DLJLrot Z
SLJL X
SLJL Y
SLJL Z
SLJLrot X
SLJLrot Y
SLJLrot Z
40.0
25.0
10.0
-5.0
-20.0
27.5
15.0
2.5
-10.0
5.0
0.0
-15.0
0.0
25.0
50.0
75.0
100.0


Right Knee Angle
Cutting X
Cutting Y
Cutting Z
DLJL X
DLJL Y
DLJL Z
DLJLrot X
DLJLrot Y
DLJLrot Z
SLJL X
SLJL Y
SLJL Z
SLJLrot X
SLJLrot Y
SLJLrot Z


Left Knee Angle
Cutting X
Cutting Y
Cutting Z
DLJL X
DLJL Y
DLJL Z
DLJLrot X
DLJLrot Y
DLJLrot Z
SLJL X
SLJL Y
SLJL Z
SLJLrot X
SLJLrot Y
SLJLrot Z
110.0
85.0
60.0
35.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
10.0
6.2
2.5
-1.2
-5.0
0.0
25.0
50.0
75.0
100.0



Right Hip Angle
Cutting X
Cutting Y
Cutting Z
DLJL X
DLJL Y
DLJL Z
DLJLrot X
DLJLrot Y
DLJLrot Z
SLJL X
SLJL Y
SLJL Z
SLJLrot X
SLJLrot Y
SLJLrot Z



Abbreviations: DLJL, double-leg jump-landing; $DLJL_{rot}$, rotated double-leg jump-landing; SLJL, single-leg jump-landing; $SLJL_{rot}$, rotated single-leg jump-landing; X, sagittal plane; Y, coronal plane; Z, transverse plane. Positive values indicate flexion (dorsiflexion), adduction (varus), internal rotation.

Appendix G. Preliminary template for a modified Landing Error Scoring System.

Appendix G1. *Mean ± standard deviation of angle values (°) of Landing Error Scoring System items for double-leg jump-landing (DLJL) and rotated single-leg jump-landing ($SLJL_{rot}$) tasks based on motion capture data from 42 participants. Method of data collection presented in Chapter 8.*

Items	**Dominant leg**		**Non-dominant leg**	
	DLJL	**$SLJL_{rot}$**	**DLJL**	**SLJLrot**
Knee flexion: IC	33.7 ± 8.3	18.3 ± 5.6	34.2 ± 7.9	17.6 ± 5.4
Hip flexion: IC	38.9 ± 13.1	25.2 ± 9.9	38.7 ± 12.3	19.3 ± 12.6
Trunk flexion: IC	16.4 ± 7.5	4.5 ± 5.6	16.2 ± 7.4	2.0 ± 6.5
Ankle plantar flexion: IC	-13.1 ± 7.9	-18.8 ± 7.5	-12.0 ± 8.1	-16.9 ± 6.6
Medial knee position: IC	1.4 ± 4.6	-1.6 ± 3.8	-0.9 ± 4.9	-2.9 ± 4.3
Lateral trunk flexion: IC	-0.7 ± 2.9	7.3 ± 4.7	-0.7 ± 3.0	7.5 ± 5.3
Foot position: external rotation	-12.4 ± 6.6	-16.9 ± 5.7	-9.8 ± 6.7	-14.1 ± 6.3
Foot position: internal rotation	-0.8 ± 6.1	-3.1 ± 6.4	2.6 ± 7.0	0.0 ± 6.7
Knee flexion displacement	74.4 ± 14.9	53.6 ± 7.8	72.0 ± 14.2	51.6 ± 6.2
Hip flexion displacement	38.3 ± 12.4	27.5 ± 9.1	38.0 ± 12.7	31.3 ± 10.3
Trunk flexion displacement	22.8 ± 11.4	28.7 ± 10.9	22.7 ± 11.6	28.9 ± 12.4
Medial knee displacement[a]	-9.4 ± 7.8	-8.0 ± 6.5	-13.3 ± 9.1	-11.2 ± 7.4
Lateral trunk flexion displacement	3.3 ± 1.2	8.6 ± 3.8	3.3 ± 1.4	8.8 ± 4.2

IC, initial contact
[a] According to the Landing Error Scoring System definition, medial knee displacement represent the maximal knee valgus.

Positive values represent flexion, knee varus, lateral trunk flexion towards the stance leg, and internal rotation; negative values represent plantar flexion, knee valgus, and lateral flexion away from the stance leg.

Appendix G2. *Preliminary operational definition of modified Landing Error Scoring System items with rationale for the suggested thresholds.*

Items	**Operational definition of original LESS errors**[a]	**Suggested operational definition of modified LESS errors**	**Rational**
Knee flexion: IC	The knee is flexed less than 30° at IC	The knee is flexed less than 15° at IC	VA of ACL injuries reported knee flexion at IC between 5° to 30°[1-4]. Based on our data, knee flexion at IC is almost 50% lower for $SLJL_{rot}$ compared to DLJL, therefore 50% of the original threshold was used.
Hip flexion: IC	The thigh is in line with the trunk at IC	The thigh is in line with the trunk at IC	According to our data, hip flexion at IC is lower for $SLJL_{rot}$ compared to DLJL. The threshold for error is already set at 0° of hip flexion. A hip extension threshold would be functionally irrelevant.
Trunk flexion: IC	The trunk is vertical or extended on the hips at IC	The trunk is vertical or extended on the hips at IC	VA of ACL injuries reported trunk flexion at IC of 4°[5]. Upright and extended positions of the trunk have been associated with ACL loading[6]. Based on our data, trunk flexion at IC is lower during $SLJL_{rot}$ compared to DLJL. However, the threshold for error is already set at 0° of trunk flexion.
Ankle plantar flexion: IC	The foot lands heel to toe or with flat foot at IC	The foot lands with less than 5° of plantar flexion	VA of ACL injuries reported plantar flexion less than 10°[3,7]. Based on our data, plantar flexion at IC is greater during $SLJL_{rot}$ compared to DLJL (~5°). Therefore, the threshold was conservatively set to 5° of plantar flexion.
Medial knee position: IC	The centre of the patella is medial to the midfoot at IC	The line connecting the hip and centre of the patella is medial to the ankle joint centre at IC	Due to the nature of the single-leg jump-landing, the line connecting hip and patella is needed to estimate knee valgus. The ankle joint centre may be a more accurate term than the midfoot.
Lateral trunk flexion: IC	The midline of the trunk is flexed to the left or the right side of the body at IC	The trunk lateral flexion is more than 10°	VA of ACL injuries reported lateral trunk flexion at IC of 11°[8]. Based on our data, lateral trunk flexion at IC is greater during $SLJL_{rot}$ compared to DLJL (~8°). Therefore, the threshold was rounded up to 10° of lateral trunk flexion.
Stance width: wide	The feet are positioned greater than shoulder width apart (acromion processes) at initial contact.	Item removed	Not applicable for $SLJL_{rot}$.

Stance width: narrow	The feet are positioned less than shoulder width apart (acromion processes) at initial contact.	Item removed	Not applicable for $SLJL_{rot}$.
Foot position: external rotation	The foot is externally rotated more than 30° between IC and MKF	The foot is externally rotated more than 35° between IC and MKF	According to our data, foot external rotation is greater during $SLJL_{rot}$ compared to DLJL (~5°), therefore the threshold was changed to 35° of foot external rotation.
Foot position: internal rotation	The foot is internally rotated more than 30° between IC and MKF	The foot is internally rotated more than 30° between IC and MKF	Our data showed similar foot internal rotation between $SLJL_{rot}$ and DLJL, therefore we kept the original threshold for an error.
Symmetric initial foot contact: IC	One foot lands before the other foot or one foot lands heel to toe and the other foot lands toe to heel.	Item removed	Not applicable for $SLJL_{rot}$.
Knee flexion displacement	The knee flexes less than 45° between IC and MKF	The knee flexes less than 30° between IC and MKF	According to our data, the knee flexion displacement is 70% lower during $SLJL_{rot}$ compared to DLJL, therefore 70% of the original threshold was used.
Hip flexion displacement	The thigh does not flex more on the trunk between IC and MKF	The thigh does not flex more on the trunk between IC and MKF	Based on our data, hip flexion displacement is lower during $SLJL_{rot}$ compared to DLJL. However, the threshold for error is already set at 0° of hip flexion displacement.
Trunk flexion displacement	The trunk does not flex more between IC and MKF	The trunk does not flex more than 5° between IC and MKF	According to our data, trunk flexion displacement is greater during $SLJL_{rot}$ compared to DLJL (~5°). Therefore, the threshold was changed to 5° of trunk flexon displacement.
Medial knee displacement	At the point of maximum medial knee position, the centre of the patella is medial to the midfoot	At the point of maximum medial knee position, the centre of the patella is medial to the ankle joint centre	The ankle joint centre may be a more accurate term than the midfoot.
Joint displacement	Soft: the participant demonstrates a large amount of trunk, hip, and knee displacement. Average: the participant has some, but not a large amount of, trunk, hip, and knee displacement. Stiff: the participant goes through very	Item removed	This item is subjective in nature. The purely subjective rating or ranking of human movement to define performance[9] or injury risk[10] has been criticised and has been shown to be inaccurate. Furthermore, this item is an obstacle for automated qualification of the LESS[11].

	little, if any, trunk, hip, and knee displacement		
Overall impression	Excellent: the participant displays a soft landing with no frontal-plane or transverse-plane motion. Average: all other landings. Poor: the participant displays large frontal-plane or transverse-plane motion, or the participant displays a stiff landing with some frontal-plane or transverse-plane motion.	Item removed	See the rational above.
Lateral trunk flexion displacement		The trunk lateral flexion increases between IC and MKF	We suggest adding this item to the modified LESS given the important role of trunk displacement in ACL injuries[8,12].

ACL, Anterior Cruciate Ligament; DLJL, double-leg jump-landing; IC, initial contact; LESS, Landing Error Scoring System; MKF, maximal knee flexion; $SLJL_{rot}$, rotated single-leg jump-landing; VA, video analysis

[a] Adapted from Padua et al. 2015.

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2. Koga, H., et al., *Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball.* American journal of sports medicine, 2010. **38**(11): p. 2218-2225.
3. Montgomery, C., et al., *Mechanisms of ACL injury in professional rugby union: a systematic video analysis of 36 cases.* British journal of sports medicine, 2016. **52**(15): p. 994-1001.
4. Olsen, O.-E., et al., *Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis.* American journal of sports medicine, 2004. **32**(4): p. 1002-1012.
5. Sheehan, F.T., W.H. Sipprell III, and B.P. Boden, *Dynamic sagittal plane trunk control during anterior cruciate ligament injury.* American journal of sports medicine, 2012. **40**(5): p. 1068-1074.
6. Hashemi, J., et al., *Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury.* Journal of biomechanics, 2011. **44**(4): p. 577-585.
7. Boden, B.P., et al., *Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics.* American journal of sports medicine, 2009. **37**(2): p. 252-259.
8. Hewett, T.E., J.S. Torg, and B.P. Boden, *Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism.* British journal of sports medicine, 2009. **43**(6): p. 417-422.
9. Cochrum, R.G., et al., *Visual classification of running economy by distance running coaches.* European Journal of Sport Science, 2020: p. 1-8.

10. Mørtvedt, A.I., et al., *I spy with my little eye… a knee about to go 'pop'? Can coaches and sports medicine professionals predict who is at greater risk of ACL rupture?* British journal of sports medicine, 2020. **54**(3): p. 154-158.
11. Dar, G., A. Yehiel, and M. Cale' Benzoor, *Concurrent criterion validity of a novel portable motion analysis system for assessing the Landing Error Scoring System (LESS) test.* Sports biomechanics, 2019. **4**: p. 426-436.
12. Zazulak, B.T., et al., *Deficits in neuromuscular control of the trunk predict knee injury risk: prospective biomechanical-epidemiologic study.* American journal of sports medicine, 2007. **35**(7): p. 1123-1130.

Appendix G3. *Scoring sheet template of the proposed modified Landing Error Scoring System.*

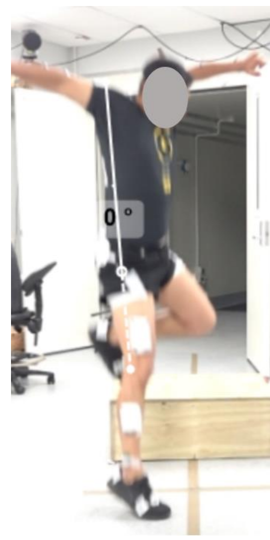
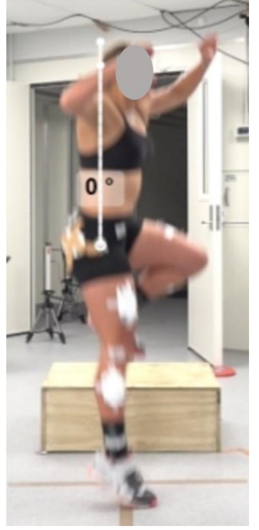
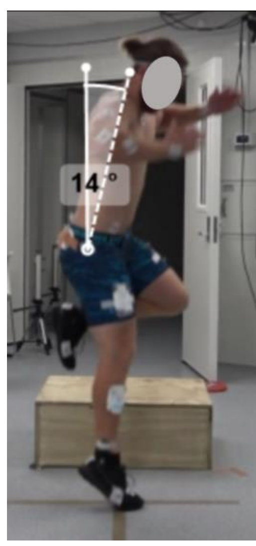
Items	Suggested operational definition of modified LESS errors	Camera view	Scoring
1 Knee flexion: IC	The knee is flexed less than 15° at IC	Side	Yes = 1; No = 0
2 Hip flexion: IC	The thigh is in line with the trunk at IC	Side	Yes = 1; No = 0
3 Trunk flexion: IC	The trunk is vertical or extended on the hips at IC	Side	Yes = 1; No = 0
4 Ankle plantar flexion: IC	The foot lands with less than 5° of plantar flexion	Side	Yes = 1; No = 0
5 Medial knee position: IC	The line connecting the hip and the centre of patella is medial to the ankle joint centre at IC	Front	Yes = 1; No = 0
6 Lateral trunk flexion: IC	The trunk lateral flexion is more than 10°	Front	Yes = 1; No = 0
7 Foot position: external rotation	The foot is externally rotated more than 35° between IC and MKF	Front	Yes = 1; No = 0
8 Foot position: internal rotation	The foot is internally rotated more than 30° between IC and MKF	Front	Yes = 1; No = 0
9 Knee flexion displacement	The knee flexes less than 30° between IC and MKF	Side	Yes = 1; No = 0
10 Hip flexion displacement	The thigh does not flex more on the trunk between IC and MKF	Side	Yes = 1; No = 0
11 Trunk flexion displacement	The trunk does not flex more than 5° between IC and MKF	Side	Yes = 1; No = 0

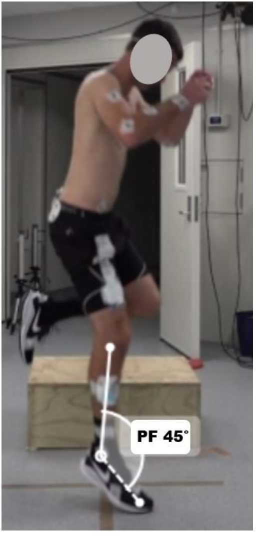
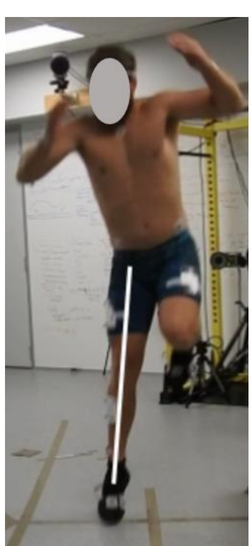
12 Medial knee displacement	At the point of maximum medial knee position, the centre of the patella is medial to the ankle joint centre	Front	Yes = 1; No = 0
13 Lateral trunk flexion displacement	The trunk lateral flexion increases between IC and MKF	Front	Yes = 1; No = 0
MAXIMAL SCORE			**12 errors**[a]

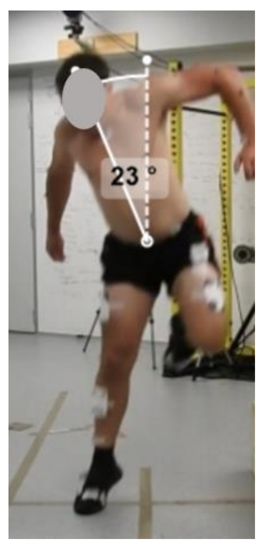
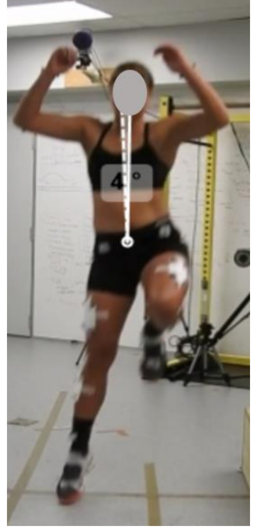
IC, initial contact; LESS, Landing Error Scoring System; MKF, maximal knee flexion
[a] It is not probable to score error 7 and 8 at the same time. Therefore, the maximal score is 12 errors.

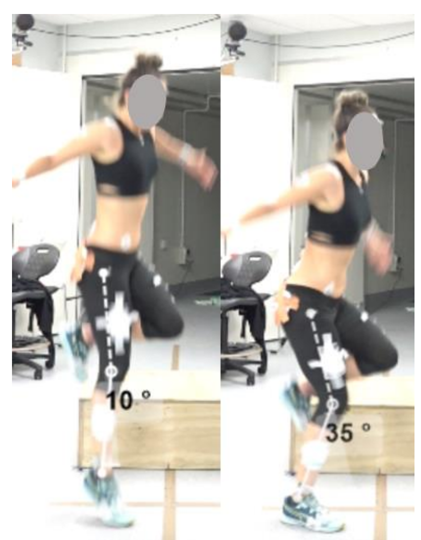
Appendix G4. *Alternative scoring sheet template of the proposed modified Landing Error Scoring System with pictorial representation of errors.*

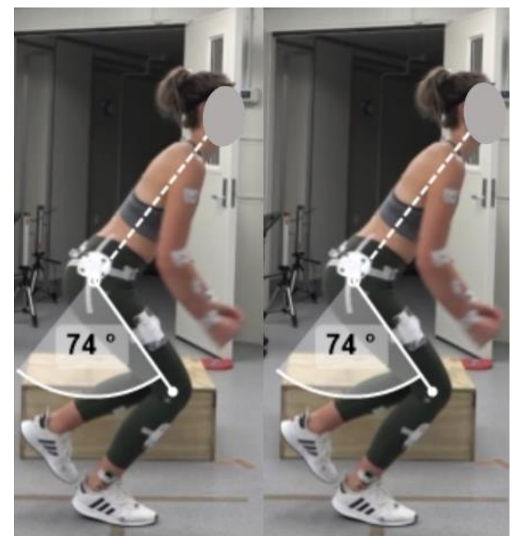
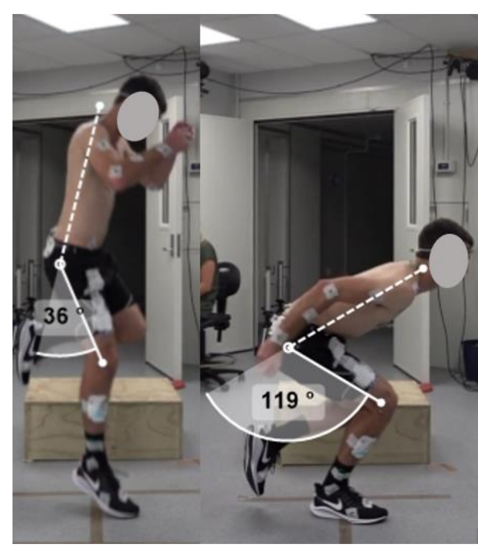
Items	Suggested operational definition of modified LESS errors	Error present (1)	Error absent (0)
1 Knee flexion: IC	The knee is flexed less than 15° at IC	10 °	25 °

2 Hip flexion: IC	The thigh is in line with the trunk at IC	 	
3 Trunk flexion: IC	The trunk is vertical or extended on the hips at IC	 	

4 Ankle plantar flexion: IC	The foot lands with less than 5° of plantar flexion	 	
5 Medial knee position: IC	The line connecting the hip and the centre of patella is medial to the ankle joint centre at IC		

6 Lateral trunk flexion: IC	The trunk lateral flexion is more than 10°		
7 Foot position: external rotation	The foot is externally rotated more than 35° between IC and MKF		

8 Foot position: internal rotation	The foot is internally rotated more than 30° between IC and MKF		
9 Knee flexion displacement	The knee flexes less than 30° between IC and MKF		

10 Hip flexion displacement	The thigh does not flex more on the trunk between IC and MKF		

11 Trunk flexion displacement	The trunk does not flex more than 5° between IC and MKF	 	
12 Medial knee displacement	At the point of maximum medial knee position, the centre of the patella is medial to the ankle joint centre		

<table>
<tr>
<td>13 Lateral trunk flexion displacement</td>
<td>The trunk lateral flexion increases between IC and MKF</td>
<td>
</td>
<td>
</td>
</tr>
</table>

IC, initial contact; LESS, Landing Error Scoring System; MKF, maximal knee flexion

Appendix H. Ethical approvals.

Appendix H1. *Ethical approval for Chapter 5 to 7.*

The University of Waikato
Private Bag 3105
Gate 1, Knighton Road
Hamilton, New Zealand

Human Research Ethics Committee
Julie Barbour
Telephone: +64 7 837 9336
Email:humanethics@waikato.ac.nz

17 November 2017

Dr Kim Hébert-Losier
Faculty of Health, Sport and Human Performance

Dear Kim,

UoW HREC(Health)#2017-41: An automated injury risk screening platform

Thank you for submitting your amended application HREC(Health)#2017-41 for ethical approval.

We are now pleased to provide formal approval for your project including the recruitment of approximately 200 participants (including children and young people) to complete a movement task while being monitored in a variety of ways.

Please contact the committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

Julie Barbour PhD
Chairperson
University of Waikato Human Research Ethics Committee

Appendix H2. *Ethical approval for Chapter 8 to 12.*

The University of Waikato
Private Bag 3105
Gate 1, Knighton Road
Hamilton, New Zealand

Human Research Ethics Committee
Julie Barbour
Telephone: +64 7 837 9336
Email:humanethics@waikato.ac.nz

31 May 2018

Ivana Hanzliková
By email: xhanzlikova@gmail.com

Dear Ivana

UoW HREC(Health)#2018-27: Landing Error Scoring System Modification

Thank you for submitting your amended application HREC(Health)#2018-27 for ethical approval.

We are now pleased to provide formal approval for your study of the Landing Error Scoring System (LESS) with participants engaging in a series of low risk tasks at the University of Waikato Adams Centre:

1. Baseline questionnaires (demographic, training, iPAQ, MSR)
2. Hypermobility testing (Beighton scale, Weight-bearing Lunge test)
3. Filmed biomechanical assessments (three repetitions each of: double leg drop vertical jump, single leg drop vertical jump, double leg rotated drop vertical jump, single leg rotated drop vertical jump, side-step cutting) with sensors attached. The jump test will be repeated on three occasions.

Please contact the committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

Julie Barbour PhD
Chairperson
University of Waikato Human Research Ethics Committee

Appendix I. Forms and questionnaires used within the PhD thesis.

Appendix I1. *Participant data collection sheet.*

Participant Data Collection Sheet

Project Title
Landing Error Scoring System Modification

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

NAME	
DATE OF BIRTH (dd /mm/yyyy)	
SEX (please tick)	☐ *MALE* ☐ *FEMALE*
HEIGHT (cm)	
WEIGHT (kg)	
Handedness (hand used to throw a ball)	☐ *RIGHT* ☐ *LEFT*
Footedness (foot used to kick a ball)	☐ *RIGHT* ☐ *LEFT*
ETHNICITY (optional)	
E-MAIL (for report)	
What sport do you play?	
What position do you play?	
What level do you play?	☐ *school* ☐ *club* ☐ *national club* ☐ *recreational* ☐ *other* ________
How many times a week do you play? *(games + trainings)*	
How many hours a week do you play? *(games + trainings)*	
How many years have you been playing?	
Have you suffered any injuries in the past?	☐ *YES* ☐ *NO*
What and when were these injuries? *(e.g., right ACL tear 2015)*	
What shoes are you wearing for testing? *(e.g., running, indoor soccer shoes…)*	

Appendix I2. *Perceived Recovery Status Scale. Adapted from Laurent et al. (2011).*

10	**Very well recovered / Highly energetic**
9	
8	**Well recovered / Somewhat energetic**
7	
6	**Moderately recovered**
5	**Adequately recovered**
4	**Somewhat recovered**
3	
2	**Not well recovered /Somewhat tired**
1	
0	**Very poorly recovered / Extremely tired**

Appendix I3. *International Physical Activity Questionnaire (Craig et al., 2003).*

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE (August 2002)

SHORT LAST 7 DAYS SELF-ADMINISTERED FORMAT

FOR USE WITH YOUNG AND MIDDLE-AGED ADULTS (15-69 years)

The International Physical Activity Questionnaires (IPAQ) comprises a set of 4 questionnaires. Long (5 activity domains asked independently) and short (4 generic items) versions for use by either telephone or self-administered methods are available. The purpose of the questionnaires is to provide common instruments that can be used to obtain internationally comparable data on health–related physical activity.

Background on IPAQ

The development of an international measure for physical activity commenced in Geneva in 1998 and was followed by extensive reliability and validity testing undertaken across 12 countries (14 sites) during 2000. The final results suggest that these measures have acceptable measurement properties for use in many settings and in different languages, and are suitable for national population-based prevalence studies of participation in physical activity.

Using IPAQ

Use of the IPAQ instruments for monitoring and research purposes is encouraged. It is recommended that no changes be made to the order or wording of the questions as this will affect the psychometric properties of the instruments.

Translation from English and Cultural Adaptation

Translation from English is supported to facilitate worldwide use of IPAQ. Information on the availability of IPAQ in different languages can be obtained at www.ipaq.ki.se. If a new translation is undertaken we highly recommend using the prescribed back translation methods available on the IPAQ website. If possible please consider making your translated version of IPAQ available to others by contributing it to the IPAQ website. Further details on translation and cultural adaptation can be downloaded from the website.

Further Developments of IPAQ

International collaboration on IPAQ is on-going and an ***International Physical Activity Prevalence Study*** is in progress. For further information see the IPAQ website.

More Information

More detailed information on the IPAQ process and the research methods used in the development of IPAQ instruments is available at www.ipaq.ki.se and Booth, M.L. (2000). *Assessment of Physical Activity: An International Perspective*. Research Quarterly for Exercise and Sport, 71 (2): s114-20. Other scientific publications and presentations on the use of IPAQ are summarized on the website.

SHORT LAST 7 DAYS SELF-ADMINISTERED version of the IPAQ. Revised August 2002.

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think *only* about those physical activities that you did for at least 10 minutes at a time.

1. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, aerobics, or fast bicycling?

   _____ **days per week**

   ☐ No vigorous physical activities → ***Skip to question 3***

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

   _____ **hours per day**

   _____ **minutes per day**

   ☐ Don't know/Not sure

Think about all the **moderate** activities that you did in the **last 7 days**. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

   _____ **days per week**

   ☐ No moderate physical activities → ***Skip to question 5***

4. How much time did you usually spend doing **moderate** physical activities on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

Think about the time you spent **walking** in the **last 7 days**. This includes at work and at home, walking to travel from place to place, and any other walking that you have done solely for recreation, sport, exercise, or leisure.

5. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time?

_____ **days per week**

☐ No walking ➡ ***Skip to question 7***

6. How much time did you usually spend **walking** on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

The last question is about the time you spent **sitting** on weekdays during the **last 7 days**. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.

7. During the **last 7 days**, how much time did you spend **sitting** on a **week day**?

_____ **hours per day**

_____ **minutes per day**

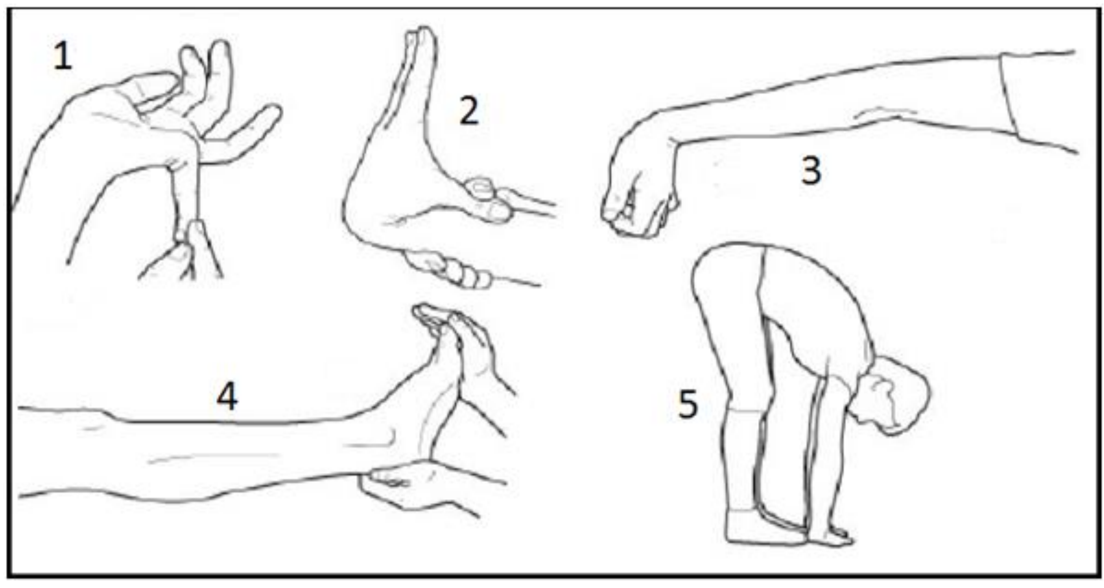
☐ Don't know/Not sure

This is the end of the questionnaire, thank you for participating.

SHORT LAST 7 DAYS SELF-ADMINISTERED version of the IPAQ. Revised August 2002.

Appendix I4. *Beighton hypermobility scale (Beighton et al., 1973).*

	Left	Right
1. Passive dorsiflexion and hyperextension of the fifth MCP joint beyond 90°	1	1
2. Passive apposition of the thumb to the flexor aspect of the forearm	1	1
3. Passive hyperextension of the elbow beyond 10°	1	1
4. Passive hyperextension of the knee beyond 10°	1	1
5. Active forward flexion of the trunk with the knees fully extended so that the palms of the hands rest flat on the floor	1	
Score	/ 9	



Appendix I5. *Movement-Specific Reinvestment Scale (Masters et al., 2005).*

THE MOVEMENT SPECIFIC REINVESTMENT SCALE

© Masters, Eves & Maxwell (2005)

Name: ___________________________ **Date:** _____ **Age:** _____ **Hand: L / R**

DIRECTIONS: Below are a number of statements about your movements. The possible answers go from 'strongly agree' to 'strongly disagree'. There are no right or wrong answers so circle the answer that best describes how you feel for each question.

1 I rarely forget the times when my movements have failed me, however slight the failure.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

2 I'm always trying to figure out why my actions failed.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

3 I reflect about my movement a lot.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

4 I am always trying to think about my movements when I carry them out.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

5 I'm self conscious about the way I look when I am moving.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

6 I sometimes have the feeling that I'm watching myself move.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

7 I'm aware of the way my mind and body works when I am carrying out a movement.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

8 I'm concerned about my style of moving.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

9 If I see my reflection in a shop window, I will examine my movements.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

10 I am concerned about what people think about me when I am moving.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

Appendix J. Co-authorship forms for Chapter 3 to 12.

Appendix J1. *Co-authorship form for Chapter 3.*

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 3: Is the Landing Error Scoring System reliable and valid? A systematic review

Hanzlíková, I., & Hébert-Losier, K. (2020). Is the Landing Error Scoring System reliable and valid? A systematic review. Sports Health, 12(2), 181-188.

Nature of contribution by PhD candidate	Development of research question and protocol, literature search, study selection, risk of bias assessment, data extraction, summarising the evidence, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Risk of bias assessment, supervision of all stages, and critical revision of the manuscript.

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020

Appendix J2. *Co-authorship form for Chapter 4.*

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 4: Factors influencing the Landing Error Scoring System: Systematic review with meta-analysis

Hanzlíková, I., Athens, J., & Hébert-Losier, K. (2020). Factors influencing the Landing Error Scoring System: Systematic review with meta-analysis. Journal of Sport Science and Medicine. Advance online publication. https://doi.org/10.1016/j.jsams.2020.08.013

Nature of contribution by PhD candidate	Development of research question and protocol, literature search, study selection, risk of bias assessment, data extraction, analysing the evidence, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Risk of bias assessment, supervision of all stages, and critical revision of the manuscript.
Dr. Josie Athens	Statistical analyses support and critical revision of the manuscript.

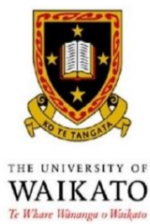
Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020
Dr. Josie Athens	[signature]	12. 11. 2020

Appendix J3. *Co-authorship form for Chapter 5.*



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Chapter 5: Clinical implications of Landing Error Scoring System calculation methods

Hanzlíková, I., Athens, J., & Hébert-Losier, K. (2020). Clinical implications of Landing Error Scoring System calculation methods. Physical Therapy in Sport, 44, 61-66.

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision of all stages and critical revision of the manuscript.
Dr. Josie Athens	Statistical analyses support and critical revision of the manuscript.

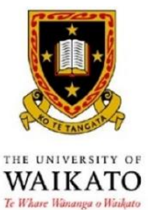
Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020
Dr. Josie Athens	[signature]	12. 11. 2020

Appendix J4. *Co-authorship form for Chapter 6.*



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Chapter 6: Clinical implication of landing distance on Landing Error Scoring System scores

Hanzlíková, I., & Hébert-Losier, K. (in press). Clinical implications of landing distance on Landing Error Scoring System scores. Journal of Athletic Training.

Nature of contribution by PhD candidate	Data collection, data analysis, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Development of research question and protocol, supervision of all stages, and critical revision of the manuscript.

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	Kim Hébert-Losier	12. 11. 2020

Appendix J5. *Co-authorship form for Chapter 7.*

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 7: Landing Error Scoring System scores change with knowledge of scoring criteria and prior performance

Hanzlíková, I., & Hébert-Losier, K. (2020). Landing Error Scoring System scores change with knowledge of scoring criteria and prior performance. Physical Therapy in Sport 46, 155-161.

Nature of contribution by PhD candidate	Data collection, data analysis, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Development of research question and protocol, supervision of all stages, and critical revision of the manuscript.

Certification by Co-Authors

The undersigned hereby certify that:

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Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020

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Appendix J6. *Co-authorship form for Chapter 8.*

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Chapter 8: Which jump-landing task best represents lower extremity and trunk kinematics of unaticipated cutting manoeuvere?

Hanzlíková, I., Richards, J., Athens, J., & Hébert-Losier, K. (under review). Which jump-landing task best represents lower extremity and trunk kinematics of unanticipated cutting manoeuvre? Gait and Posture.

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision of all stages and critical revision of the manuscript.
Prof. Jim Richards	Supervision of all stages and critical revision of the manuscript.
Dr. Josie Athens	Statistical analyses support and critical revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020
Prof. Jim Richards	[signature]	12.11.2020
Dr. Josie Athens	[signature]	12. 11. 2020

Appendix J7. *Co-authorship form for Chapter 9.*

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Chapter 9: Do asymptomatic generalised hypermobility and knee hyperextension influence jump-landing biomechanics?

Hanzlíková, I., & Hébert-Losier, K. (2020). Do asymptomatic generalised hypermobility and knee hyperextension influence jump landing biomechanics? European Journal of Physiotherapy. Advance online publication. https://doi.org/10.1080/21679169.2020.1769721

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision of all stages and critical revision of the manuscript.

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020

Appendix J8. *Co-authorship form for Chapter 10.*

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 10: The influence of asymptomatic hypermobility on unanticipated cutting kinematics

Hanzlíková, I., Richards, J., Athens, J., & Hébert-Losier, K. (under review). The influence of asymptomatic hypermobility on unanticipated cutting kinematics. Sports Health.

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision of all stages and critical revision of the manuscript.
Prof. Jim Richards	Supervision of all stages and critical revision of the manuscript.
Dr. Josie Athens	Statistical analyses support and critical revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020
Prof. Jim Richards	[signature]	12.11.2020
Dr. Josie Athens	[signature]	12. 11. 2020

Appendix J9. *Co-authorship form for Chapter 11.*

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Chapter 11: Propensity for conscious control of movement is unrelated to asymptomatic hypermobility or injury risk scores

Hanzlíková, I., Masters, R. S. W., & Hébert-Losier, K. (in press). Propensity for conscious control of movement is unrelated to asymptomatic hypermobility or injury-risk scores. Journal of Sport and Exercise Science.

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision of all stages and critical revision of the manuscript.
Prof. Rich Masters	Interpretation of results and critical revision of the manuscript.

Certification by Co-Authors

The undersigned hereby certify that:

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Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020
Prof. Rich Masters	[signature]	12.11.2020

Appendix J10. *Co-authorship form for Chapter 12.*

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Chapter 12: The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics

Hanzlíková, I., Richards, J., & Hébert-Losier, K. (under review). The influence of ankle dorsiflexion range of motion on unanticipated cutting kinematics. Journal of Athletic Training.

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of results, manuscript preparation, and journal submission.
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision of all stages and critical revision of the manuscript.
Prof. Jim Richards	Supervision of all stages and critical revision of the manuscript.

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The undersigned hereby certify that:

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Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	12. 11. 2020
Prof. Jim Richards	[signature]	12.11.2020

Appendix K. Author's research publications not related to the PhD thesis.

Smékal, D., **Hanzlíková, I.**, Žiak, D., & Opavský, J. (2014). Remodelace štěpu a vhojení štěpu do kostěného tunelu po artroskopické náhradě předního zkříženého vazu [Intra-articular healing and graft-to-bone incorporation after arthroscopic Anterior Cruciate Ligament reconstruction]. *Rehabilitace a Fyzikální Lékařství, 21*(3), 114-123.

Hanzlíková, I., Richards, J., Tomsa, M., Chohan, A., May, K., Smékal, D., & Selfe, J. (2016). The effect of proprioceptive knee bracing on knee stability during three different sport related movement tasks in healthy subjects and the implications to the management of Anterior Cruciate Ligament (ACL) injuries. *Gait and Posture, 48*, 165-170.

Bednáříková, H., Smékal, D., Krejčiříková, P., & **Hanzlíková, I.** (2018). Effect of locally applied vibration on pain reduction in patients with chronic low back pain: A pilot study. *Acta Gymnica, 48*(2), 77-82.

Hanzlíková, I., Richards, J., Hébert-Losier, K., & Smékal, D. (2019). The effect of proprioceptive knee bracing on knee stability after Anterior Cruciate Ligament reconstruction. *Gait and Posture, 67*, 242-247.