Effect of footwear and overhead goal on the Landing Error Scoring System

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Abstract

A large proportion of the population undertakes sport and exercise either for recreation or competition. However, with increased participation in sport and exercise, the occurrence of sport-related injuries also increases. Anterior Cruciate Ligament (ACL) injuries are injuries to the knee and one of the most common injuries in a sporting environment that occur from noncontact mechanisms. The Landing Error Scoring System (LESS) is a common screening tool used to identify individuals who are more at risk of sustaining an ACL injury based on double-leg jump-landing (DLJL) kinematics. Despite the LESS demonstrating good-to-excellent reliability and predictive value, the LESS is sensitive to various factors (e.g., protocol alterations) and has been criticised for lacking sport specificity. Despite studies conducting the LESS both with and without footwear and using an overhead goal during jumping tasks to increase sport specificity, to date, there is no research comparing LESS outcomes based on the presence/absence of footwear or presence/absence of an overhead goal.

Chapter One summarises literature surrounding sports injuries, ACL injuries, injury aetiology, injury prevention models, and injury risk screening tools used in sports with a focus on the LESS. Footwear and cueing in sports are also addressed. Chapter Two is experimental and compares overall LESS scores, group- and individual-level injury risk categorisation, specific LESS errors, and jump heights between footwear and no footwear conditions. Chapter Three is experimental and compares these same outcome measures between overhead goal and no goal conditions. Chapter Four summarises the key findings from the two experimental chapters, and addresses the limitations, strengths, and future research directions arising from this Thesis.

In Chapter Two, 80 participants (55% male) performed a DLJL task where they landed from a 30-cm high box to 50% of their own body height and immediately jumped vertically for maximum height for LESS assessment. Participants completed three trials under two random-ordered conditions: with and without footwear. Group mean LESS scores were greater (0.3 errors, $p = 0.022$) and jump heights were lower (0.6 cm, $p = 0.029$) in the footwear than barefoot condition, but differences were *trivial* and not clinically meaningful. Although the number of high-risk participants was comparable between groups ($p = 1.000$), categorisation was inconsistent for 16.25% of individuals and the occurrence of four of the 17 specific landing errors significantly differed between conditions. Based on the study findings, footwear does not appear to meaningfully influence mean LESS scores, risk categorisation, or jump height at a group level. At an individual level, footwear can affect risk categorisation and landing strategies. Hence, use of a consistent protocol is recommended in clinical setting, and use of footwear is advised for assessing injury risk given the predictive value of the LESS barefoot is unknown.

In Chapter Three, 76 participants (51% male) performed a DLJL task where they landed from a 30-cm high box to 50% of their own body height and immediately jumped vertically for maximum height for LESS assessment. Participants completed three trials under two random-ordered conditions: with and without an overhead goal. Mean LESS scores were greater (0.3 errors, $p < 0.001$) with the overhead goal, but this *small* difference was not clinically meaningful. Similarly, although the number of high-risk participants was significantly greater with the overhead goal ($p = 0.039$), the 9.2% difference was *trivial*. Participants jumped 2.7 cm higher with the overhead goal ($p < 0.001$) without affecting the occurrence of any specific LESS errors. Based on the results found, performing the LESS with an overhead goal enhances sport specificity and elicits greater vertical jump performances with minimal change in landing errors and risk categorisation. Adding an overhead goal to LESS might enhance its suitability

for injury risk screening, although the predictive value of LESS with an overhead goal needs confirmation.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

2D – 2-dimensional

3D – 3-dimensional

ACC – Accident Compensation Corporation

ACL – Anterior Cruciate Ligament

DLJL – Double-leg jump-landing

FMS – Functional Movement Screen™

GRF - Ground reaction forces

ICC – Intra-class correlation coefficient

LESS – Landing Error Scoring System

SD – Standard deviation

TIP – Team-sport Injury Prevention Cycle

TRIPP – Translating Research into Injury Prevention Practice

Research Outputs Arising from this Thesis

Manuscripts submitted for peer review publication

Chapter 2

Boswell-Smith, C., Hanzlíková, I., & Hébert-Losier, K. (*under review*). Effect of footwear on the Landing Error Scoring System and jump height measures.

Chapter 3

Boswell-Smith, C., Hanzlíková, I., & Hébert-Losier, K. (*under review*). Effect of an overhead goal on the Landing Error Scoring System and jump height measures.

Structure of the Thesis

The main aims of this Thesis on the Landing Error Scoring System (LESS) are two-fold: (1) to examine the effect of footwear on the LESS, and (2) to examine the effect of on overhead goal on the LESS. This Thesis consists of four chapters (**Figure 1**), with Chapter Two and Chapter Three suitable for submission to peer-reviewed journals. Chapter One summarises literature surrounding sports injuries, ACL injuries, injury aetiology, injury prevention models, and injury risk screening tools used in sports with a focus on the LESS. Footwear and cueing in sports are also addressed. Chapter Two is experimental and compares overall LESS scores, group- and individual-level injury risk categorisation, specific LESS errors, and jump heights between footwear and no footwear conditions. Chapter Three is experimental and compares these same outcome measures between overhead goal and no goal conditions. Chapter Four summarises the key findings from the two experimental chapters, and addresses the limitations, strengths, and future research directions arising from this Thesis.

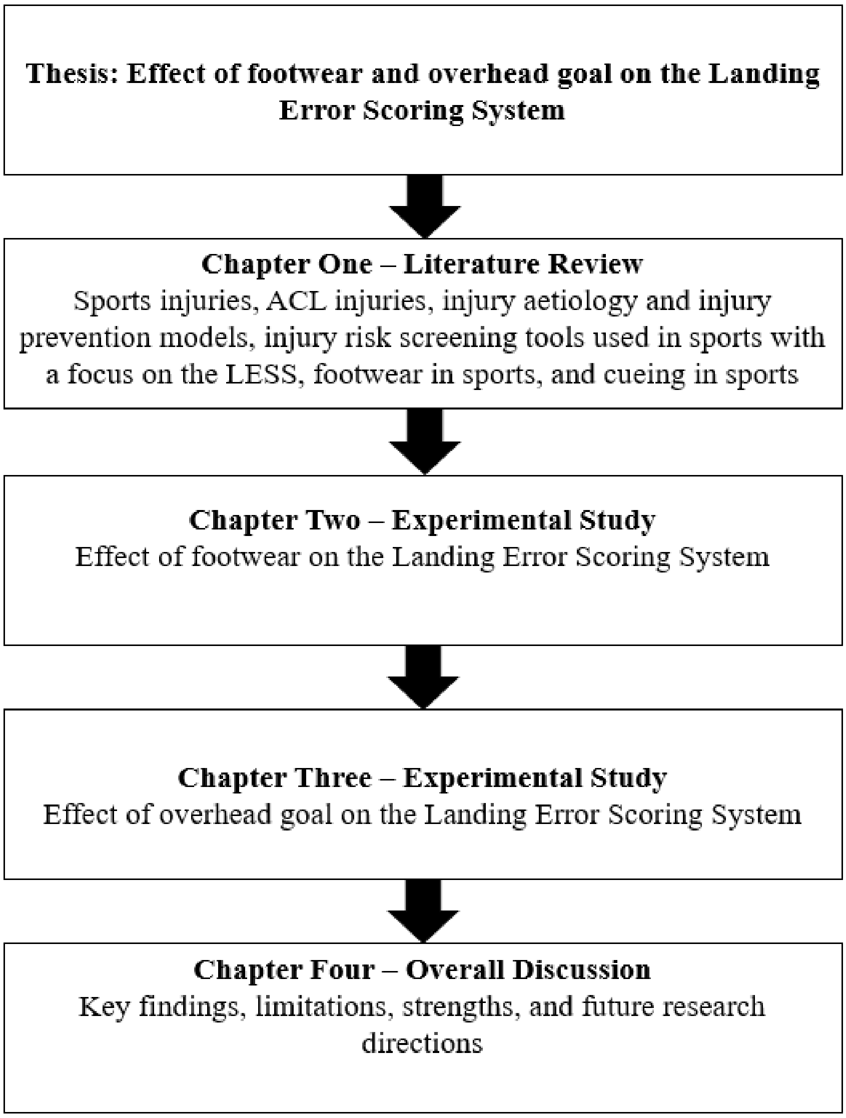

Figure 1. Structure of the Thesis.

Chapter One – Literature Review

1.1 Sport injuries

Sport and exercise are important for both physical and psychological well-being, and a large proportion of the population undertakes sport and exercise either for recreation or competition (Neely, 1998). As the population participating in sport and exercise increases, so does the occurrence of sport-related injuries. Despite injury prevention efforts, sports injury ranks among the major public health problems because of its important social and economic burden for society (Öztürk & Kılıç, 2013). Sport injuries are a considerable burden for the health and welfare system, and a noteworthy loss of societal productivity (Kisser & Bauer, 2012). Sports injuries are important public health concerns (Finch, 2012), with sport organisations constantly striving to improve their injury management and prevention strategies to make their sports safer (Leung et al., 2017). Sports injuries may be classified as hard or soft tissue injuries. Hard tissue injuries are injuries that involve skeletal structures, such as fractures. Soft tissue injuries are injuries that occur to tissues that connect, support, or surround other structures and organs of the body, not being bone (Li et al., 2014). Soft tissue injuries involve muscles, tendons, and ligaments.

1.1.1 Sport injuries in New Zealand

Between 2012 to 2016, the Accident Compensation Corporation (ACC) in New Zealand recorded 853,824 sport-related injury claims across five sports (rugby union, rugby league, netball, cricket, and football) (King et al., 2019). The total cost of these injuries to ACC was $778 million NZD. Moderate to serious soft tissue injuries were the most common injury during this period (39,144 claims, $329.1 million NZD, $8,408 per injury). Specifically, lower limb injuries accounted for the largest proportion of moderate to serious injuries (both hard and soft tissue injuries), with the knee region being the most frequently injured (19,206 claims, $172.2 million NZD, $9,051 per injury) (King et al., 2019).

1.2 Anterior Cruciate Ligament injuries

The Anterior Cruciate Ligament (ACL) is an important ligament of the knee that prevents anterior translation of the tibia on the femur. The ACL is also involved in limiting excessive internal tibial rotation, knee hyperextension, and knee valgus and varus, notably in weightbearing (Hébert-Losier & Häger, 2020). ACL injuries are one of the most common injuries in a sporting environment that occur from noncontact mechanisms, with nearly three quarters of ACL injuries being noncontact injuries (Boden et al., 2010). Combining data from multiple sports, noncontact mechanisms explained approximately 18% of injuries in game situations and 37% of injuries in practice or training situations that required medical attention and resulted in at least one day of time loss (Hootman et al., 2007). Of these injuries, more than 50% were to the lower extremity, with the annual incidence of ACL injuries increasing over the 16-year monitoring period. In a separate study involving 17,397 clinical patients with sports injuries, injuries to the knee accounted for over a third of injuries (6,434, 37%) (Majewski et al., 2006). In Australia over the last 20 years, there has been a significant annual increase in the number of total knee injuries, with the most common knee injury being to the ACL (Maniar et al., 2022). Griffin et al. (2006) reported the incidence of ACL injuries to be between 80,000 to 250,000 ruptures per year in the United States, with most of these (58 to 70%) being non-contact injuries occurring in young athletes 15 to 25 years of age (50%). More recent data from Australia support that younger individuals (age 15 to 29 years) have the highest incidence of ACL injuries, with an annual incidence in 2017 – 2018 reaching approximately 48 and 28 per 100,000 population for males and females, respectively (Maniar et al., 2022). Approximately

90% of individuals who sustain an ACL injury in the United States eventually undergo ACL reconstruction, which represents large costs to individuals and society (Paterno et al., 2017). However, it should be noted that this large proportion of individuals undergoing surgery could be due to the aggressive promotion of surgical management of ACL injuries in some countries, like the United States (Moses et al., 2012). Surgical and associated costs (e.g., rehabilitation) of ACL injuries annually in the United States is approximately $3 billion USD (Mather III et al., 2013). In New Zealand, active claims associated with receiving ACL reconstruction surgery totalled 2,380 and cost 25.7 million NZD in the 2020-2021 financial year (Analytics & Reporting ACC, 2021). These costs are much higher than most other injuries because injuries to the ACL are immediately disabling and take a significant amount of time to rehabilitate (Smith et al., 2012a; Smith et al., 2012b), which increases the overall rehabilitative cost.

1.2.1 Medium to long term consequences of Anterior Cruciate Ligament injuries

While the financial costs due to medical care are considerable, the burden of ACL injury on individual's medium to long term also warrant consideration. At least nine months post-ACL reconstructive surgery is suggested before return to play to limit occurrence of reinjury and enhance likelihood of successful return to sport (Kaplan & Witvrouw, 2019). For instance, a 51% reduction in reinjury was achieved for each month return to sport was delayed until reaching nine months post-surgery (Grindem et al., 2016). On the other hand, knee reinjury rate was 100% for those returning to sports before reaching five months post-surgery (Grindem et al., 2016). A systematic review by Ardern et al. (2014) found 81% of individuals returned to some form of sport following ACL reconstruction, but only 65% returned to their preinjury levels and 55% to competitive sport. The incidence of another ACL injury in the first 12 months after ACL reconstruction and return to sport in a young and active population has been reported to be 15 times greater compared to previously uninjured participants (Nagelli & Hewett, 2017; Paterno et al., 2017). Results from Webster et al. (2014) indicate that one in every 3.4 patients (29%) younger than 20 years at their primary ACL reconstruction surgery had a graft rupture or contralateral ACL injury within the following 5-year period.

There are also longer-term consequences of sustaining an ACL injury. A recent systematic review of prospectively collected data in individuals ≥ 20 years post-ACL reconstruction highlights that only 40% of individuals present normal radiographic osteoarthritis scores and the majority present strength deficits despite having stable and well-functioning knees (Everhart et al., 2021). Osteoarthritis is a highly burdensome condition and a major cause of disability, psychological stress, and poor quality of life (Hunter & Bierma-Zeinstra, 2019). Whilst osteoarthritis can affect numerous joints, knee osteoarthritis accounts for approximately 85% of the global burden of the disease (James et al., 2018). Knee osteoarthritis is observed in 50 to 90% of ACL injured individuals (Hébert-Losier & Häger, 2020), with the odds of developing tibiofemoral osteoarthritis being 4.2 times greater in ACL injured individuals than uninjured individuals (Poulsen et al., 2019). Whilst knee osteoarthritis can be managed conservatively or surgically (Brand et al., 2014), surgical management is a common approach with osteoarthritis being the leading cause of total knee replacement surgeries (Piscitelli et al., 2012). Knee replacement surgeries are increasing rapidly in Australia (Ackerman et al., 2019). Specifically, there has been an 105% increase in primary total knee replacement surgeries over a 10-year period (2003 – 2013) in Australia (Ackerman et al., 2017). Furthermore, total knee replacement surgeries due to osteoarthritis are estimated to increase by a further 276% by 2030 (Ackerman et al., 2019). Trends appear similar in New Zealand, with the number of total knee replacements predicted to increase by 183% by 2026 (Hooper et al., 2014). Preventing an ACL injury from occurring is the only certain way to reduce the burden associated with sustaining an ACL injury.

1.2.2 Risk factors

Injury prevention programmes can successfully reduce injury incidence, but the exact mechanism by which they reduce risk is unclear (Dischiavi et al., 2021). Several risk factors have been found to be associated with ACL injuries. Sports or exercise that involve frequent sudden decelerations, changes of direction, pivoting with the foot firmly planted, landing from jumps, or stopping suddenly increase the risk of ACL injuries (Griffin et al., 2006; Utturkar et al., 2013). Studies have also found that multidirectional, reactive phases of play (e.g., pressing, defending, and tackling) or high-speed jumping and landing events are amongst the most common inciting events (Della Villa et al., 2020). In general, movement patterns that produce knee valgus and varus or extension moments, especially when the knee is only slightly bent, appear to increase risk (Griffin et al., 2006). One of the primary mechanisms of ACL injury emphasised in the literature is a valgus collapse of the knee about the frontal plane coupled with a rotational component (Arundale et al., 2018; Della Villa et al., 2020), as shown in **Figure 2**, particularly during unilateral weightbearing tasks (Montgomery et al., 2018). Data indicate that athletes are at greater risk of ACL injury in game situations; hence, increased game-play exposure has been linked with ACL injury risk (Shultz et al., 2015). These data together suggest that screening for risk of ACL injury using dynamic sport-like tasks may be of benefit in identifying those at greater risk of injury.

Figure 2. Representation of knee valgus collapse with internal rotation of the knee.

1.3 Injury aetiology models

Understanding injury mechanisms can shed light on injury risk factors and help guide injury prevention efforts. Several injury aetiology and prevention models have been proposed over the years. Meeuwisse (1994) proposed a multifactorial model to sport injury aetiology (**Figure 3).** In this model, Meeuwisse (1994) advances that intrinsic and extrinsic factors predispose an athlete to injury and, with an inciting event, injury can occur.

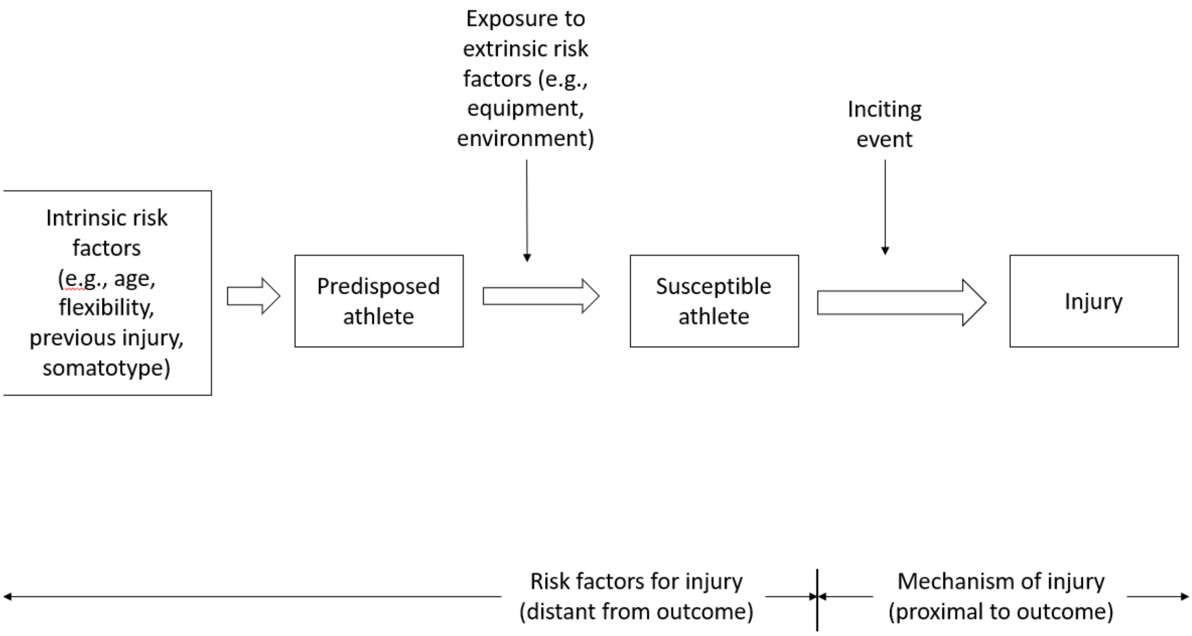

Figure 3. Multifactorial model of athletic injury aetiology according to Meeuwisse (1994).

Note: Permission has been gained.

Bahr and Krosshaug (2005) argued this multifactorial model had limitations and did not sufficiently consider injury from a biomechanical perspective. More specifically, a precise description of the inciting event is a key component to understanding the causes of any sport injury. It was argued that injury mechanism must be considered alongside internal and external risk factors. Based on the limitations raised (Bahr & Krosshaug, 2005), Meeuwisse et al. (2007) improved their original model to consider that sport injury, injury risk, and aetiology are more dynamic and recursive in nature (**Figure 4**). Meeuwisse et al. (2007) explained how the true nature of sport injury is not reflected in a linear approach that contains a start and an end point: Sports injury is cyclic in nature. There may also be recurrent changes in susceptibility to injury during sports participation and that these exposures can produce adaptation and continually change injury risk. Furthermore, risk factors may change through repeated participation in sport.

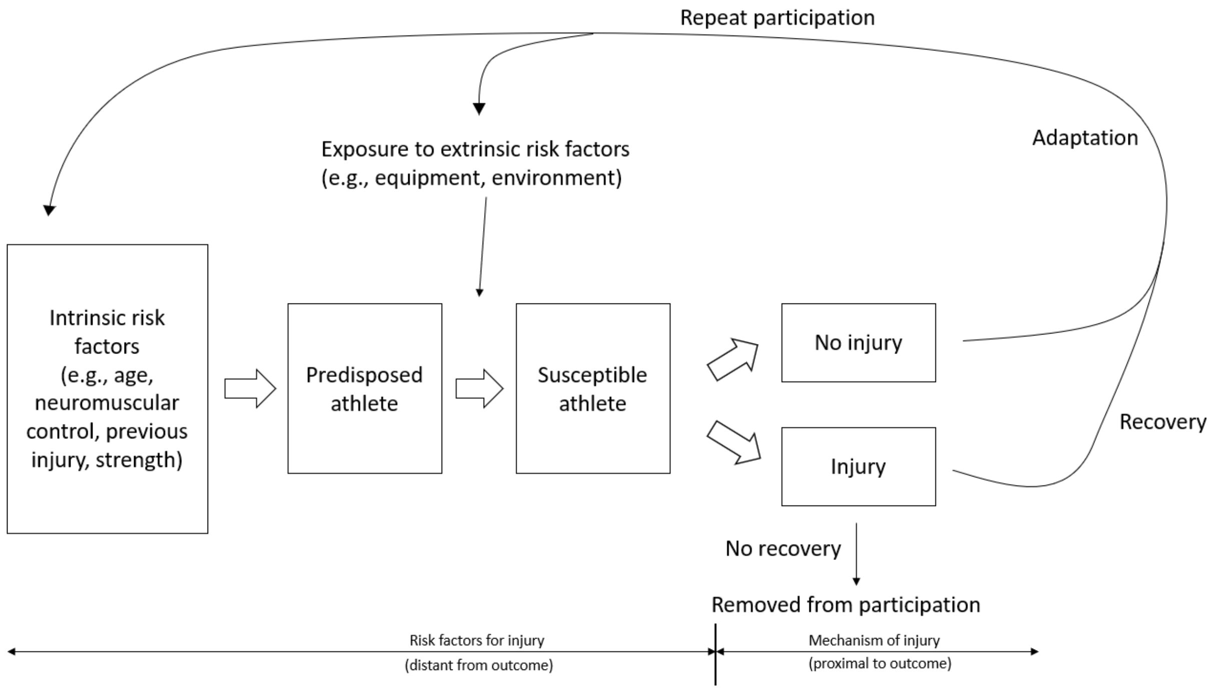

Figure 4. A dynamic, recursive of athletic injury aetiology according to Meeuwisse et al. (2007). *Note*: Permission has been gained.

1.4 Injury prevention models

Injury prevention programmes try to combat the likelihood of injuries occurring or reoccurring and decrease the risk of injury. One of the earliest injury prevention models was the "sequence of prevention model" from Van Mechelen et al. (1992). This model involved four steps to injury prevention (**Figure 5**). Firstly, the extent of the sports injury problem (or problems) must be identified and described in terms of the incidence and severity of the injury. Secondly, the factors and mechanisms that play a part in the occurrence of sports injuries must be identified. Thirdly, preventative measures that will likely reduce the future risk and severity of the injuries must be introduced. Lastly, the effect of the preventative measures must be evaluated by repeating the first step.

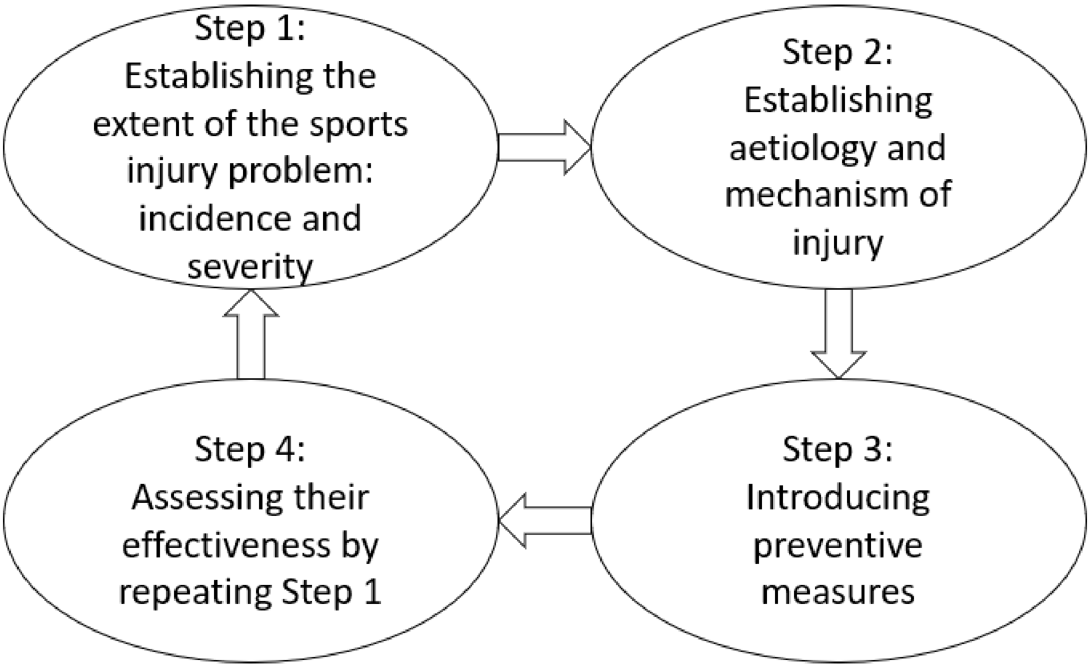

Figure 5. Sequence of prevention model according to Van Mechelen et al. (1992). *Note*: Permission has been gained.

However, the sequence of prevention model was challenged and criticised for not considering the need for research implementation (Finch, 2006). Indeed, Finch (2006) argued that the model did not consider the determinants and influences of sport safety behaviours, or that athletes and coaches will not implement preventative strategies if these are not proven effective or implementable in sports. Therefore, the six-staged Translating Research into Injury Prevention Practice (TRIPP) framework was advanced to address these limitations (**Figure 6**).

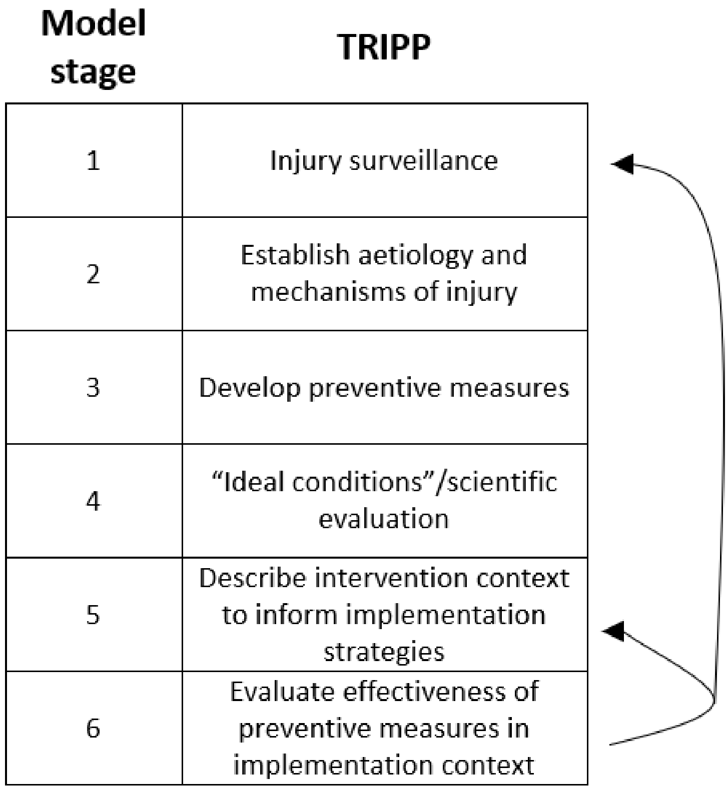

Figure 6. Translating Research into Injury Prevention Practice framework according to Finch (2006). *Note*: Permission has been gained.

More recent research has offered a slightly different approach to injury prevention models. O'Brien et al. (2019) proposed a three-phase model termed the Team-sport Injury Prevention Cycle (TIP) (**Figure 7**). Phase one evaluates the current state of play in the team. The current injury situation (e.g., the type, incidence, and severity of injuries in the team) and injury prevention situation (e.g., which injury prevention strategies are being implemented and why) are included in this stage. Phase two explores the risk factors and mechanisms underpinning the injuries identified in phase one. This phase two also involves identifying barriers and facilitators to implementing injury prevention strategies. Phase three plans both the content (what to do) and delivery (how to do it) of injury prevention strategies. The TIP also promotes ongoing re-evaluation and modification.

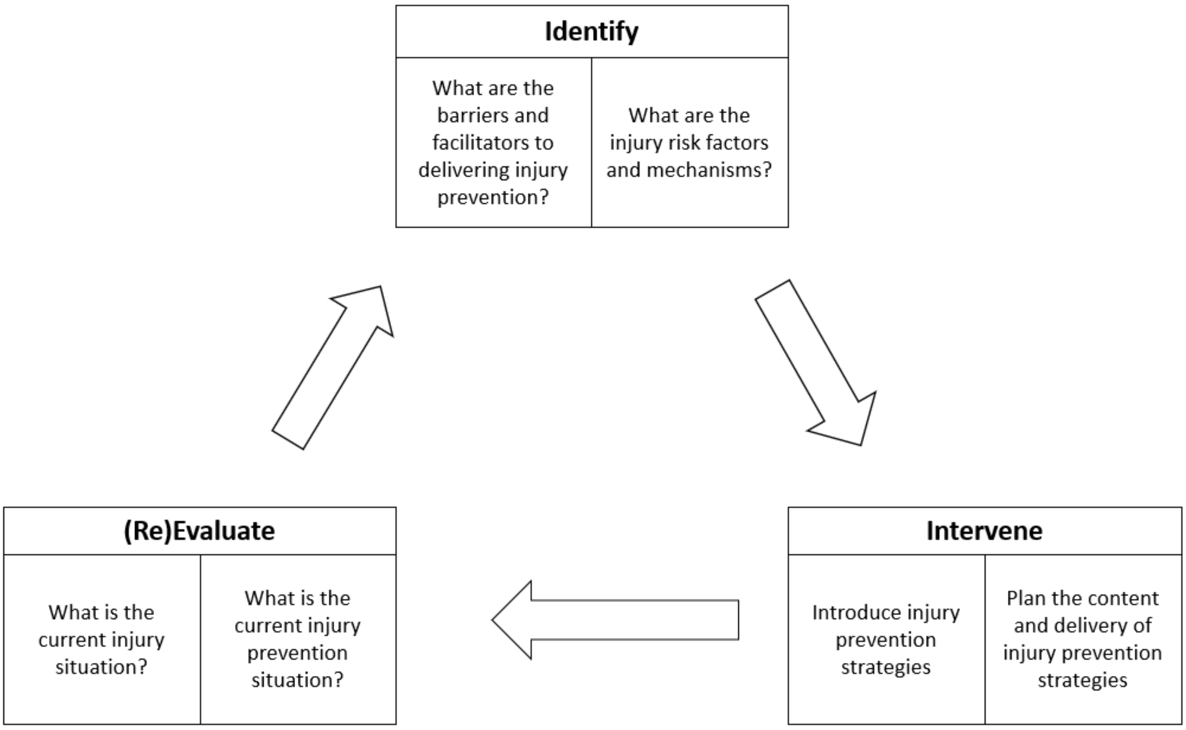

Figure 7. Team-sport Injury Prevention Cycle according to O'Brien et al. (2019). *Note*: Permission has been gained.

1.4.1 Injury prevention challenges

Injury prevention researchers typically develop generic injury prevention solutions, but the adoption of these solutions in practice is low. This lack of implementation in practice occurs because implementation contexts are both unique and dynamic in nature. As a result, singular generic solutions are often incompatible with the real-world sporting context (Tee et al., 2020).

Sports injury prevention remains complex irrespective of the underlying injury prevention model (Tee et al., 2020). One area that remains debated is whether or not injury prevention models and injury risk screening tools are useful in predicting and preventing injuries in sports. Bahr (2016) believes there is no appropriate screening test for predicting injuries in sports with sufficient accuracy because there is substantial overlap between players with a "high" and "low" risk of injury. Short et al. (2021) support this notion and propose the use of the term risk "reduction" rather than "prevention" in the context of sport injuries.

1.5 Screening tools

Screening tools are used to identify pathological conditions early (Bahr, 2016) and identify athletes that are at high risk of developing an injury (Dallinga et al., 2012). Screening tools are an inherent part of injury aetiology and injury prevention models. Once injury mechanisms are understood, relevant screening tools can be implemented. In the multifactorial model of athletic injury aetiology (**Figure 3**) and the dynamic, recursive of athletic injury aetiology model (**Figure 4**); screening tools are useful for identifying predisposed and susceptible athletes. Screening tools can be used in step three of both the sequence of prevention model (**Figure 5**) and TRIPP framework (**Figure 6**). In the TIP model (**Figure 7**), screening tools are useful in phase two to explore risk factors and replicate mechanisms of injury.

1.5.1 Functional Movement Screen

Over the years, several injury risk screening tools in sports have been developed (Chimera & Warren, 2016; Collings et al., 2021). One of the most commonly used and known injury-risk screening tool is the Functional Movement Screen^{TM} (FMS) (Whittaker et al., 2017). The FMS is a standardised, field-friendly test intended to assess movement quality. This test has been used in preparticipation screening and sports injury research and practice (Moran et al., 2016). Seven functional movement patterns (deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push up, and rotary stability) are tested with a score of 0, 1, 2 or 3 given to each movement pattern. The maximum score is 21, where higher scores reflect better movement quality and competency. Although the FMS has been identified as one of the most popular field-based injury risk screening tool (Asgari et al., 2021; Whittaker et al., 2017), the predictive validity of the FMS is under question (Asgari et al., 2021). The current literature demonstrates a general lack of consistency between FMS scores and injury risk, calling into question its utility for this purpose (Monaco & Schoenfeld, 2019). Noteworthy is the FMS only involves slow, controlled movements that are not representative of the more dynamic nature of sports. The FMS may therefore not be the most ideal screening tool for use in sport.

1.5.2 Landing Error Scoring System

The Landing Error Scoring System (LESS) screening tool is another functional movement tool used to identify athletes at higher risk of injuries, specifically those at greater risk of noncontact ACL (Padua et al., 2015) and musculoskeletal (Everard et al., 2018) injuries. Participants are required to complete a double-leg jump-landing (DLJL) task that involves jumping with both feet at the same time horizontally from a 30-cm box to 50% of their body height and jumping vertically upwards as high as possible immediately upon landing with both feet at the same time (Padua et al., 2009). One camera is placed to record sagittal plane motion from the right side of participants and another camera to record frontal plane motion from the front of participants. The tool is used to identify athletes who present high injury-risk biomechanical patterns during the described DLJL task described above (Padua et al., 2009). An overall LESS score is derived based on clinicians scoring 17 items related to the DLJL kinematics, with overall scores ranging from 0 to 17 errors. Fewer landing errors and lower overall LESS scores suggest fewer movement patterns linked with noncontact ACL injuries during the DLJL. Items 1 to 15 are scored as 0 (error absent) or 1 (error present), whereas items 16 and 17 are scored on a scale of 0 (soft/excellent landing), 1 (average landing), or 2 (stiff/poor landing). Some items cannot be present at the same time, e.g., Items 7 [stance width at initial contact (wide)] and 8 [stance width at initial contact (narrow)]. Therefore, the maximum possible score is 17 errors (**Table 1**). Across the literature, the overall LESS score demonstrates good-to-excellent reliability and moderate-to-excellent validity for assessing key knee-injury risk factors and overall landing biomechanics (Hanzlíková & Hébert-Losier, 2020a). In terms of injury risk screening, the odds of sustaining a noncontact ACL injury has been reported to be 10.7 times greater (Padua et al., 2015) and of sustaining a musculoskeletal injury to be 16.1 times greater (Everard et al., 2018) in individuals who scored five errors or more upon LESS assessment compared to individuals who scored less than five errors.

Table 1. Scoring template for the Landing Error Scoring System.

No.	Item	Definition of error*
1	Knee flexion at initial contact	Knee flexion < 30°
2	Hip flexion at initial contact	Thigh is in line with the trunk (hips not flexed)
3	Trunk flexion at initial contact	Trunk is vertical or extended at the hips (i.e., not flexed)
4	Ankle plantar flexion at initial contact	Heel-to-toe or flat foot landing at initial contact
5	Knee valgus at initial contact	Centre of the patella is medial to the midfoot at initial contact
6	Lateral trunk flexion at initial contact	Midline of the trunk is flexed to the left or the right side of the body at initial contact
7	Stance width (wide)	Feet are positioned greater than shoulder width apart at initial contact
8	Stance width (narrow)	Feet are positioned less than shoulder width apart at initial contact
9	Foot position (toe-in)	Foot is externally rotated more than 30° between initial contact and maximum knee flexion
10	Foot position (toe-out)	Foot is internally rotated more than 30° between initial contact and maximum knee flexion
11	Symmetric foot contact at initial contact	One foot lands before the other foot or one foot lands heel to toe and the other foot lands toe to heel
12	Knee flexion displacement	Knee flexes less than 45° between initial contact and maximum knee flexion
13	Hip flexion at maximal knee flexion	Thigh does not flex more on the trunk between initial contact and maximum knee flexion
14	Trunk flexion at maximal knee flexion	Trunk does not flex more between initial contact and maximum knee flexion
15	Knee valgus displacement	At the point of maximum medial knee position, the centre of the patella is medial to the midfoot
16	Joint displacement*	Soft (0), Average (1), Stiff (2)
17	Overall impression*	Excellent (0), Average (1), Poor (2)

*Error present or absent = 1 or 0, respectively, except for items 16 and 17. Template adapted from Padua et al. (2009).

Given that the LESS has demonstrated predictive value and is a clinically-friendly field-based intervention, the LESS is often used to examine risk of ACL injury (Hanzlíková & Hébert-Losier, 2020a; Padua et al., 2015; Padua et al., 2009; Smith et al., 2012a). It is easy to implement and more dynamic than other field-based injury risk screening tools, such as the FMS. The LESS is therefore more reflective of ACL injury mechanism than the FMS as the DLJL task incorporates landing and deceleration, which are common ACL injury mechanisms. Tasks that encapsulate movements that more closely resemble the mechanism of an ACL injury need to be included in preventative programmes for optimal risk reduction (Dischiavi et al., 2021), and by association, risk screening.

However, the overall LESS is sensitive to various factors. A recent meta-analysis examined the influence of gender, previous injury, and intervention programmes on LESS scores (Hanzlíková et al., 2021a). Overall, females scored 0.6 more errors than males; individuals with previous ACL injuries scored 1.2 more errors than uninjured individuals; and LESS scores improved by 1.2 errors following neuromuscular training programmes lasting at least six weeks. Research has also identified that jump landing distance (Hanzlíková & Hébert-Losier, 2021) and final LESS score computational method (Hanzlíková et al., 2020) can affect scores and individual-level risk categorisation. Altogether, these studies highlight that several factors and procedural methods need to be considered when administering and interpreting LESS outcomes.

Although the LESS is traditionally performed wearing shoes, it has also been conducted barefoot (O'Malley et al., 2017). However, research is yet to examine the influence of footwear, or lack thereof, on LESS outcomes. In addition, despite the DLJL task used in the LESS being more dynamic than the FMS, the DLJL has also been criticised for lacking sport specificity (Kristianslund & Krosshaug, 2013). Several jump tests used in athlete assessment add an overhead goal as an external cue to enhance performance and increase sport specificity of jumping tasks (Ford et al., 2005; Wulf et al., 2007). How an overhead goal affects LESS outcomes remains unexamined and could be a way to enhance the sport specify of the LESS assessment. These two aspects of footwear and cueing in sport are further examined within this Thesis (Chapter 2 and Chapter 3) and are briefly addressed here.

1.6 Footwear in sports

Footwear plays an important role when it comes to participating in sport and exercise. Shoes have changed over the years. Footwear has changed from being very minimal to being highly supportive and cushioned, then returning to being very minimal and back to highly cushioned (Krabak et al., 2017). An important role of shoes in sports is to reduce high-impact forces by absorbing shock, achieved by the cushioning properties of the soles (Gross & Bunch, 1989). However, many researchers believe that a return to a more primitive or naturalistic condition is paramount for optimal health (LaPorta et al., 2013), with barefoot and minimal footwear potentially reducing high-impact loads through the adoption of better neuromuscular mitigating strategies (Altman & Davis, 2012; Lieberman et al., 2010; Squadrone & Gallozzi, 2009).

Specifically for jumping tasks as it relates to the LESS, biomechanical differences have been found when performing a DLJL with compared to without footwear. Indeed, initial contact from a 30-cm DLJL task similar to the LESS has been associated with a more plantar-flexed ankle and greater foot-ground angle when performed barefoot compared to with shoes (Koyama & Yamauchi, 2018), as well as involving a smaller knee range of motion (Yeow et al., 2011). Together, these studies indicate that LESS scoring might differ between barefoot and footwear conditions, although this topic has not explicitly been examined to date.

Previous research has been undertaken around footwear and biomechanics, but mainly the influence of footwear on running mechanics (LaPorta et al., 2013). Jacobs et al. (2021) examined the effect of different surfaces during a DLJL task on LESS outcomes and found no significant differences in mean LESS scores when performed on court, grass, and laboratory-tile surfaces. Hence, it remains unclear how footwear might influence LESS outcomes.

1.7 Cueing in sports

Cueing is the use of verbal instructions to direct the attentional focus of individuals to a particular feature of a movement (Wulf et al., 2007). An external cue or focus is typically one that directs the attention of individuals away from their body movements towards the external environment or the effects of their movement on that environment (Bredin et al., 2013). Instructing an individual to jump as high as possible versus jumping upwards to reach an overhead goal are examples corresponding to internal and external cues often used when assessing countermovement jump (Wulf et al., 2007) or drop jump (Ford et al., 2005) performances. Use of an external goal has generally been shown to improve performance across physical fitness tests. Specifically, adopting an external focus compared to an internal or no attentional focus leads to superior performances in seven physical tests (modified Canadian Aerobic Fitness Test, grip strength, push-ups, sit and reach, partial curl-ups, vertical jump, and back extension, all $p < 0.05$) (Bredin et al., 2013).

Several studies have examined the effect of externally- and internally-oriented goals on vertical jump height performance (Ford et al., 2005; Król et al., 2016; Oliver et al., 2019; Wulf et al., 2007), which overall indicate increased performance when using an externally-oriented goal. Indeed, Oliver et al. (2019) found that participants reached the greatest vertical drop jump heights with an external height cue (getting as close to the ceiling as possible) compared to an internal control (jump as high as possible), contact (spending as little amount of time on the floor as possible), and quiet (as quiet as possible when landing) without increasing impact peak and changing landing biomechanics in a way that suggests increased injury risk. Ford et al. (2005) also found increased jump height during a DLJL task in presence of an overhead goal compared to no goal (p = 0.002). From a biomechanical perspective, this enhanced performance during the DLJL task was concurrent with increased knee extension moments at take-off and tended to be associated with shorter ground contact times and increased knee and ankle ranges of motion (Ford et al., 2005). In addition to enhancing jump performance, the use of an overhead goal during a DLJL can enhance sport specificity and the relevance of the DLJL task in screening for risk of injury in sport. Whilst studies have examined the effect of using an overhead goal on jump performance and landing mechanics of the DLJL task (Ford et al., 2005); it remains unclear whether use of an overhead goal affects LESS outcomes.

1.8 Research statement

The first experiment (Chapter 2) aimed to compare overall LESS scores, risk categorisation, and specific LESS errors between footwear and barefoot conditions. It was hypothesised that wearing footwear while performing the DLJL task compared to barefoot would involve higher overall LESS scores, lead to a greater number of individuals classified at high risk of injuries and influence specific LESS errors. Given how footwear can influence jump performance (Harry et al., 2015; LaPorta et al., 2013), jump height from flight times was also compared between conditions. Chapter 2 is presented in a format suitable for submission to a peer-reviewed journal.

The second experiment (Chapter 3) aimed to compare the overall LESS scores, risk categorisation, and specific LESS errors between overhead goal and no goal conditions. It was hypothesised that adding an overhead goal to the DLJL task would involve higher overall LESS scores, lead to a greater number of individuals classified at high risk of injuries, and influence specific LESS errors compared to performing the DLJL task without an overhead goal. Also, higher jump heights were anticipated when using an overhead goal during LESS assessment based on prior research (Ford et al., 2005; Wulf et al., 2010; Wulf et al., 2007). Chapter 3 is presented in a format suitable for submission to a peer-reviewed journal.

Overall, the results from these studies are anticipated to inform clinical practice and use of the LESS in the context of screening for risk of ACL injuries in sport. The results from these two experiments could inform LESS use and standardisation of the LESS protocols.

Chapter Two – Experimental Study

Effect of footwear on the Landing Error Scoring System and jump height measures.

2.1 Abstract

Objectives: Compare overall Landing Error Scoring System (LESS) scores, risk categorisation, specific LESS errors, and double-leg jump-landing jump heights between footwear and barefoot conditions. **Design:** Randomised cross-over. **Setting:** Laboratory. **Participants:** 80 (55% male). **Main outcome measures:** Participants landed three times from a 30-cm box to 50% of their body height and jumped vertically for maximal height in two conditions assigned randomly: footwear and barefoot. Group-level mean LESS scores, group-level and individual-level risk categorisation (five-error threshold), specific landing errors, and jump heights between conditions were compared. **Results:** Group-level mean LESS scores were greater (0.3 errors, $p = 0.022$) and jump heights were lower (0.6 cm, $p = 0.029$) in footwear than barefoot, but differences were *trivial* and not clinically meaningful. Although the number of high-risk participants was comparable between conditions ($p = 1.000$), categorisation was inconsistent for 16.25% of individuals and four of the 17 specific landing errors differed. **Discussion:** At a group level, footwear did not meaningfully influence mean LESS scores, risk categorisation, or jump heights. At an individual level, footwear affected risk categorisation and landing strategies. Hence, use of a consistent LESS protocol is recommended in clinical setting, and use of footwear is advised for assessing injury risk given the predictive value of the LESS barefoot is unknown.

Keywords: Anterior Cruciate Ligament; injury risk; jump-landing biomechanics; movement screen

2.2 Introduction

Anterior Cruciate Ligament (ACL) injury is one of the most common injuries in sport and has a devastating influence on individuals' activity levels and quality of life (Yu & Garrett, 2007). ACL injuries can occur without physical contact, and thus, are considered preventable (Waldén et al., 2012). The most common high-risk situation for noncontact ACL injuries appears to be deceleration, which occurs when the athlete cuts, changes direction, or lands from a jump (Griffin et al., 2006). The Landing Error Scoring System (LESS) is a screening tool used to identify athletes presenting high injury-risk biomechanical patterns during a double-leg jump-landing (DLJL) task (Padua et al., 2009), and to detect individuals at greater risk of noncontact ACL injuries (Padua et al., 2015). Clinicians score 17 items based on the DLJL task kinematics to derive an overall LESS score, with overall scores ranging from 0 to 17 errors. Lower scores reflect fewer landing errors and thus fewer movement patterns linked with noncontact ACL injuries. Items 1 to 15 are scored as 0 (error absent) or 1 (error present), whereas items 16 and 17 are scored on a scale of 0 (soft/excellent landing), 1 (average landing), or 2 (stiff/poor landing). The maximum score is 17 because some items cannot be present at the same time, e.g., Items 9 [foot position (toe in)] and 10 [foot position (toe out)]. Scores of five or more errors indicate poor jump-landing technique and have been linked to higher risk of ACL injury (Hanzlíková & Hébert-Losier, 2020a; Padua et al., 2015; Padua et al., 2009). Specifically, the risk ratio for sustaining a noncontact or indirect contact ACL injury was 10.7 in individuals scoring five errors or more compared to less than five errors (Padua et al., 2015). Across the literature, the overall LESS score demonstrates good-to-excellent reliability, and moderate-to-excellent validity versus 3-dimensional (3D) motion capture data for the LESS items reflecting key knee-injury risk factors (Hanzlíková & Hébert-Losier, 2020a).

The overall LESS is, however, sensitive to various factors. A recent meta-analysis examined the influence of gender, previous injury, and intervention programmes on LESS scores (Hanzlíková et al., 2021a). Overall, females scored 0.6 more errors than males; individuals with previous ACL injuries scored 1.2 more errors than uninjured individuals; and LESS scores improved by 1.2 errors following neuromuscular training programmes lasting at least six weeks. Research has also identified that jump landing distance (Hanzlíková & Hébert-Losier, 2021) and final LESS score computational method (Hanzlíková et al., 2020) can affect scores and individual-level risk categorisation. Altogether, these studies highlight that several factors and procedural methods need to be considered when administering and interpreting LESS outcomes.

Footwear plays a central role in sport and is typically designed to enhance performance and protect the body from acute and chronic injuries (Lake, 2000). In the context of injury, an important function of footwear is to reduce high-impact forces via shock absorption and moderation of ground reaction forces (GRF) due to the cushioning properties of soles (Gross & Bunch, 1989). Nonetheless, impacts remain high in cushioned shoes due to humans typically landing harder when wearing shoes to increase stability (Robbins & Waked, 1997). McNair and Prapavessis (1999) examined the vertical GRF in 234 individuals landing from a 30-cm drop in a standardised sport shoe, finding mean and standard deviation (SD) vertical GRF reaching 4.5 ± 1.7 times bodyweight. Shultz et al. (2012) reported greater GRF in footwear than barefoot when performing both drop landing (1.92 vs 1.75 bodyweight, $p = 0.005$) and drop jump (1.67 vs 1.61 bodyweight, $p = 0.053$) tasks from a 45-cm high box. These findings are comparable to Koyama and Yamauchi (2018) who also found greater GRF during a DLJL task from a 30-cm height in footwear compared to barefoot (20.6 vs 18.6 N/kg, $p < 0.05$). In contrast, two other studies reported no significant differences in GRF between barefoot and footwear conditions when performing double-leg landings from a 30-cm (Yeow et al., 2011), 45.72-cm (LaPorta et al., 2013), and 60-cm (Yeow et al., 2011) height.

The differing study outcomes with regards to the effect of footwear on GRF during various landing tasks might result from differences in multi-joint strategies used to moderate impact forces, as well as differences between double-leg landings with compared to without subsequent movements (Shultz et al., 2012). Indeed, initial contact from a 30-cm DLJL task similar to the LESS has been associated with a more plantar-flexed ankle and greater foot-ground angle when performed barefoot compared to with shoes (Koyama & Yamauchi, 2018), as well as with a smaller knee range of motion (Yeow et al., 2011). Together, these studies indicate that LESS scoring might differ between barefoot and footwear conditions, although this topic has not explicitly been examined to date. Although the LESS is traditionally performed wearing shoes, it has also been conducted barefoot (O'Malley et al., 2017). Therefore, the aim was to compare overall LESS scores, risk categorisation, and specific LESS errors between footwear and barefoot conditions. It was hypothesised that wearing footwear while performing the DLJL task compared to barefoot would involve higher overall LESS scores, lead to a greater number of individuals classified at high risk of injuries, and influence specific LESS errors. Given how footwear can influence jump performance (Harry et al., 2015; LaPorta et al., 2013), jump height from flight times was also compared between conditions.

2.3 Materials and methods

2.3.1 Experimental approach

A randomised cross-over experimental design was used to explore the influence of footwear on LESS scores, LESS risk categorisation, specific LESS errors, and jump heights. Sample size calculations were performed *a priori* using G*Power 3.1.9.7. A standard two-tailed hypothesis, 90% power ($\beta = 0.10$), 5% significance level ($\alpha = 0.05$), one-error LESS difference in paired means defining a clinically-meaningful change (Hanzlíková et al., 2021a; Padua et al., 2009), and an 2.47 standard deviation of the difference in paired means based on previous work implementing similar testing procedures and comparing between two experimental conditions (Hanzlíková & Hébert-Losier, 2021) were applied. Based on these assumptions, 67 participants were required and would be sufficient to detect a *small* effect size difference (Cohen $d = 0.40$) between conditions. A sample size of 76 to 80 participants was targeted to account for a 15 to 20% drop-out rate.

2.3.2 Participants

Eighty participants (44 males and 36 females, **Table 1**) were recruited from a convenience sample of healthy university students and who volunteered to participate in this investigation. All participants were free of injury, illness, or conditions that may have affected their movements or landing mechanics. Participants with a lower extremity, back, or pelvis injury in the last three months were excluded. Testing was performed in individuals' own athletic footwear, as is typical in research and clinical settings when examining the LESS (Bell et al., 2014; Hanzlíková et al., 2020; Mauntel et al., 2017). Participants were not tested when their footwear scored 70% or above on the Minimalist Index (Esculier et al., 2015) (described under 2.3.3 Procedures) as deemed to represent minimal shoes (Fuller et al., 2017) that could potentially mimic the barefoot condition (Squadrone et al., 2015). All participants signed an informed consent document that explained the potential risks of participation (e.g., chance of injury due to physical activity participation). The University of Waikato Human Research Ethics Committee (HREC(Health)#2017-41) approved the research project prior to data collection, which adhered to the Declaration of Helsinki.

Table 2. Demographic characteristics of participants and characteristics of footwear properties. Values are means ± standard deviations or counts.

Characteristics	Males (*n* = 44)	Females (*n* = 36)	Both (*n* = 80)
Participants			
Age (y)	20.1 ± 2.0	19.9 ± 2.6	20.0 ± 2.3
Height (cm)	180.5 ± 7.0	168.4 ± 6.6	175 ± 9.1
Mass (kg)	84.1 ± 19.3	68.8 ± 10.2	77.1 ± 17.6
BMI (kg/m^2)	25.9 ± 6.8	24.2 ± 3.2	25.1 ± 5.5
IPAQ (high:mod:low)	34:8:1[a]	22:11:1[b]	56:19:2[c]
Footwear			
Mass (g)	329.8 ± 70.2	305.2 ± 66.1	318.8 ± 69.5
Stack height (mm)	25.5 ± 8.0	24.6 ± 6.5	25.1 ± 7.4
Forefoot height (mm)	14.7 ± 4.4	15.4 ± 4.7	15.0 ± 4.5
Heel-to-toe drop (mm)	10.8 ± 5.8	9.2 ± 4.5	10.1 ± 5.3
Minimalist Index (%)	30.9 ± 18.1	31.1 ± 16.1	30.9 ± 17.2
Asker-C heel hardness (a.u.)	35.4 ± 7.7	38.4 ± 6.2	36.8 ± 7.2

Notes. [a]Missing data from 1 participant. [b]Missing data from 2 participants. [c]Missing data from 3 participants. a.u., arbitrary units; BMI, body mass index; IPAQ, International Physical Activity Questionnaire; mod, moderate.

2.3.3 Procedures

Following informed consent, baseline characteristics of participants were collected, which included measuring body height using a stadiometer (seca model 0123, Medical Measuring Systems and Scales, Mount Pleasant, South Carolina) and mass on an electronic scale (seca model ESE813, Medical Measuring Systems and Scales, Mount Pleasant, South Carolina).

Participants also completed the self-administered short-form International Physical Activity Questionnaire and were accordingly categorised as having high, moderate, or low physical activity levels (Craig et al., 2003). Participants were pre-informed of the aims of the study and asked to bring their own athletic footwear for testing. Footwear characteristics were measured for all participants (**Table 2**) and included measuring the Minimalist Index (Esculier et al., 2015) alongside more traditional footwear characteristics. In summary, the Minimal Index measures five shoe features to quantify the level of minimalism of footwear, where 100% represents the highest degree of minimalism. The five characteristics are footwear mass, longitudinal and torsional flexibility, heel height, heel-to-toe drop, and the presence/absence of technologies. Minimal Index scores of participants' own shoes ranged from 4 to 64%. The midsole material hardness of footwear was assessed in the centre of the heel region using an Asker-C durometer (Supertech Precision Supply Co., LTD, Osaka, Japan) with an accuracy of 1 unit (Ramsey et al., 2018). The average of three consecutive durometer measurements was recorded and used to quantify heel hardness.

For experimentation, the original LESS testing and scoring procedures were applied (Padua et al., 2009), except in the barefoot condition when no shoes were worn. Participants jumped horizontally from a 30-cm box to 50% of their body height and jumped vertically as high as possible upon landing. The horizontal landing distance was indicated on the floor using tape. A DLJL trial was disregarded when participants did not land at 50% of their body height or did not perform the task in one fluid motion. Feedback on performance was not given to participants to avoid influencing outcomes (Hanzlíková & Hébert-Losier, 2020b) unless the task was performed inappropriately. Before the formal tests begun, participants were allowed up to three familiarisation trials in both the footwear and barefoot conditions. For data collection, each participant performed three trials in each condition with 30 seconds rest between trials and 15 minutes rest between conditions to limit fatigue. The order of conditions was randomised.

Two cameras with a focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm) captured the DLJL trials at 120 frames per second (Sony RX10 II, Sony Corporation, Tokyo, Japan). One camera was positioned in front of participants to capture frontal plane movement and the other was positioned to the right of participants to capture sagittal plane movement. Each camera was placed 3.5 metres away from the landing area and mounted on tripods with a lens-to-ground distance of 1.3 metres. The videos were analysed using the Kinovea software (version 0.9.4, www.kinovea.org). The time from take-off from the ground to the final landing was extracted from the sagittal plane videos to compute jump height from flight time based on the following equation (Linthorne, 2001; Moir, 2008):

$$h = \frac{1}{8} \cdot g \cdot t^2 \cdot 100$$

where h is the jump height (cm), g is gravitational acceleration constant (9.81 m/s^2), and t is the flight time (s).

2.3.4 Data processing

A single rater (CBS) conducted all analyses after receiving training from an expert rater (IH) who had completed over 400 LESS evaluations. Inter-rater and intra-rater reliability of the overall LESS score was examined for a subset of 10 participants. The inter-rater reliability of the overall score was excellent based on intra-class correlation coefficient (ICC) and 95% confidence interval [lower, upper] values for both footwear ($ICC_{(2,1)}$ = 0.957 [0.815, 0.990]) and barefoot ($ICC_{(2,1)}$ = 0.957 [0.847, 0.989]) conditions. Intra-rater reliability was also excellent for both footwear ($ICC_{(3,1)}$ = 0.974 [0.903, 0.993]) and barefoot ($ICC_{(3,1)}$ = 0.970 [0.815, 0.993]) conditions.

2.3.5 Statistical analysis

The effect of footwear on group mean LESS scores, injury risk categorisation (high risk, LESS ≥ five errors; low risk, LESS < five errors), individual-level risk categorisation, and jump height was examined. The average of participants' three trials was used in analysing the overall LESS score and jump height of participants. Differences in group mean LESS scores and jump heights between footwear and barefoot conditions were assessed using mean differences, two tailed paired *t*-tests, and Cohen's *d* effect sizes for paired samples using an average variance with 95% confidence intervals. Cohen's *d* effect sizes were considered *small*, *medium*, and *large* when reaching 0.20, 0.50, and 0.80, respectively, and *trivial* when less than 0.20 (Cohen, 2013).

Differences in the number of participants categorised at high and low risk of injury based on the five-error LESS threshold between footwear and barefoot conditions were assessed using McNemar's tests and odds ratio with 95% confidence intervals. The odds ratio reflects the number of participants exclusively at high risk in the footwear condition versus those exclusively at high risk in the barefoot condition. Hence, an odds ratio > 1.0 reflects a higher proportion of at-risk individuals in the footwear condition. Finally, differences in the occurrence of specific LESS errors between conditions were also examined using McNemar's tests. For each participant, an error was considered present when present in two of the three trials for Items 1-15. For Items 16 and 17, an error was considered present when the 'average' rating was present in two of three trials or when the 'poor/stiff' rating was present in one of three trials (Hanzlíková & Hébert-Losier, 2021; Padua et al., 2009). The significance level was set at $p \leq 0.05$ for all analyses, which were conducted using Microsoft Excel for Microsoft 365 MSO (version 2109, Microsoft Corp, Redmond, WA, USA) and RStudio® version 1.1.463 with R version 4.0.5 (R Core Team, 2021).

2.4 Results

The group mean LESS scores in the footwear condition (range: 2.7 to 10.0 errors) was significantly greater (0.3 errors, $p = 0.022$) than in the barefoot condition (range: 2.3 to 10.0 errors), as shown in **Table 3**. However, the magnitude of the difference was *trivial* (Cohen d = 0.18 [0.03, 0.33]). The number of individuals classified at high risk was similar between conditions (62 participants footwear vs 61 participants barefoot, $p = 1.000$), with seven participants categorised at high risk exclusively for the footwear condition and six participants exclusively for the barefoot condition (**Figure 8**). At an individual level, the risk categorisation was conflicting for 13 participants (16.25%, **Figure 8**). Jump height in the footwear condition (range: 8.5 to 56.4 cm) was significantly lower (-0.6 cm, $p = 0.029$) than in the barefoot condition (range: 11.4 to 55.1 cm), but the magnitude of the difference was *trivial* (**Table 3**).

Table 3. Comparison of Landing Error Scoring System mean scores and group-level risk categorisation between footwear and barefoot conditions. Data are means ± standard deviations and differences with 95% confidence intervals [lower, upper].

Outcome	Footwear	Barefoot	Difference	*p*-value
LESS score (errors)	6.2 ± 1.5	5.9 ± 1.6	0.3 [0.05 to 0.52]	**0.022***[a]
High risk (%)	77.5%	76.3%	1.17 [0.39 to 3.47]	1.000 [b]
Jump height (cm)	32.1 ± 9.2	32.8 ± 8.9	-0.6 [-0.1, -1.2]	**0.029***[a]

Note. *Significant difference between conditions ($p \leq 0.05$). [a] Difference in means with paired *t*-test. [b] Odds ratio significance with McNemar's test.

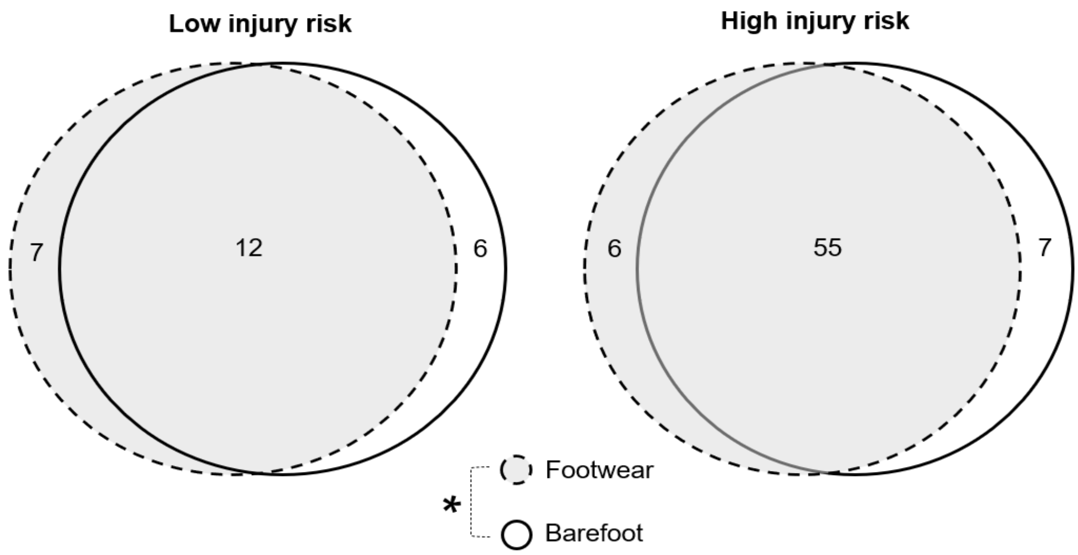

Figure 8. Venn diagrams representing participants at low risk (less than five errors) and high risk (five errors or more) of injury for both footwear and barefoot conditions. *Note:* The number in the circle represents the sum of participants categorised at low or high risk for each condition. The overlapping area represents the number of participants at low or high risk in both conditions. *Significant difference in the proportion of individuals at high and low risk based on McNemar's tests ($p \leq 0.05$).

The occurrence of specific LESS errors significantly differed between conditions for four of the 17 items. Specifically, there were more errors for Item 4 (ankle plantar flexion at initial contact) and Item 5 (knee valgus at initial contact) in footwear, and more errors for Item 8 (stance width-narrow) and Item 10 (foot position-toe out) barefoot (**Table 4**).

Table 4. Landing Error Scoring System specific errors for 80 participants.

No.	Items	Number of errors		*p*-value[a]
		Footwear	Barefoot	
1	Knee flexion at initial contact	57	50	0.118
2	Hip flexion at initial contact	0	0	1.000
3	Trunk flexion at initial contact	1	0	1.000
4	Ankle plantar flexion at initial contact	14	4	**0.006***
5	Knee valgus at initial contact	69	59	**0.012***
6	Lateral trunk flexion at initial contact	6	8	0.688
7	Stance width (wide) at initial contact	12	11	1.000
8	Stance width (narrow) at initial contact	25	32	**0.039***
9	Foot position (toe-in)	0	1	1.000
10	Foot position (toe-out)	12	26	**0.003***
11	Symmetric foot contact at initial contact	53	52	1.000
12	Knee flexion at maximal knee flexion	5	5	1.000
13	Hip flexion at maximal knee flexion	1	1	1.000
14	Trunk flexion at maximal knee flexion	3	2	1.000
15	Knee valgus displacement	60	56	0.289
16	Joint displacement	55	58	0.581
17	Overall impression	76	70	0.109

Note. *Significant difference between conditions ($p \leq 0.05$). [a]McNemar's test *p*-values for differences between conditions.

2.5 Discussion

The effect of footwear on LESS scores was examined. In agreement with the hypothesis, footwear led to significantly higher LESS scores than barefoot; however, the difference was *trivial* and not clinically meaningful as the difference was less than one error (Padua et al., 2009). Footwear led to significantly lower jump heights than barefoot, but the difference was also *trivial*. A greater number of participants categorised at high risk was anticipated when wearing footwear; however, the number of high-risk participants was comparable between conditions. Despite the similarities in LESS scores and high-risk categorisation, differences in specific errors were noted, with footwear associated with greater odds of knee valgus and heel-to-toe or flat foot landing at initial contact, and lesser odds of landing with a narrow stance width and toe-out foot position. Overall, performing the LESS with compared to without shoes led to comparable mean LESS scores, group-level risk categorisation, and jump heights, but influenced specific LESS errors and individual-level risk categorisation (i.e., 16.25% of individuals inconsistently categorised between conditions).

This study was conducted given the knowledge that footwear can affect landing mechanics (Koyama & Yamauchi, 2018; Shultz et al., 2012; Yeow et al., 2011) and that the LESS has been used both with (Padua et al., 2009) and without (O'Malley et al., 2017) footwear. Mean LESS scores in the footwear condition in this study was comparable to means reported elsewhere for similar cohorts of young active individuals (Hanzlíková et al., 2020; Hanzlíková & Hébert-Losier, 2021). The findings of this study also reflect previous ones where altering the jump landing distance of the LESS did not meaningfully affect group-level LESS scores and risk categorisation, but significantly influenced the odds of individual LESS errors and individual-level risk categorisation (Hanzlíková & Hébert-Losier, 2021). The comparable outcomes imply that studies can implement the LESS either with shoes or barefoot when the main outcome is the group mean LESS score or group-level risk categorisation. Implementing the LESS barefoot can be easier to standardise across participants as guarantees no effect of footwear or footwear type on landing mechanics. Nonetheless, it would be inappropriate to compare specific LESS errors between studies or infer similar risk at an individual level. For instance, O'Malley et al. (2017) performed the LESS barefoot. Their results would likely be comparable if performed with shoes in terms of the group mean LESS score and proportion of high-risk individuals, but the individual-level risk categorisation might differ. Furthermore, the predictive value of the LESS performed barefoot for noncontact ACL injury has not been researched. Hence, when using the LESS in a clinical setting, the LESS parameters should be kept constant for a given individual on separate occasions and the use of footwear is recommended given it’s demonstrated predictive value in youth (Padua et al., 2015).

In biomechanics research, relying solely on null hypothesis significance testing without use of appropriate effect sizes or consideration of the magnitude of the difference is discouraged (Harrison et al., 2020; Wasserstein & Lazar, 2016). A previous review revealed statistically significant higher LESS scores in females compared to males, although the difference did not reach the established one-error threshold for clinical meaningfulness (Hanzlíková et al., 2021a). In fact, the inter-session standard error of measurement for the LESS is 0.81 error (Scarneo et al., 2017), which exceeds the observed difference of 0.3 errors between footwear and barefoot conditions. Hence, although reaching statistical significance, the effect of footwear on overall mean LESS scores was not clinically meaningful. Despite this, 16.25% of individuals changed risk categorisation between footwear and barefoot conditions, again supporting use of a consistent footwear or barefoot LESS protocol for a given individual when assessing risk or movement strategies over time.

The odds of errors significantly differed between footwear and barefoot conditions for four LESS items: knee valgus, ankle plantar flexion, narrow stance width, and toe-out foot position at initial contact (Items 4, 5, 8, and 10). Hanzlíková and Hébert-Losier (2021) also found that these specific LESS errors differed between self-selected and 50% body height landing conditions, alongside knee valgus displacement (Item 15). These findings combined suggest these specific LESS errors are more sensitive to change and alterations in protocol than the other errors. Whilst LESS scores can differentiate between poor, moderate, good, and excellent landing kinematics and kinetics collected in laboratory environments (Padua et al., 2009), it is based on 2-dimensional (2D) video recordings and is not as sensitive to kinematic changes as 3D motion capture. Onate et al. (2010) found poor-to-excellent agreement between 2D clinical ratings and 3D motion capture ratings across the individual LESS items, indicating that item-dependent validity. Using 3D motion capture can accurately determine multi-planar kinematics, including rotations across joints (Schurr et al., 2017), whereas clinicians evaluate only frontal and sagittal plane 2D videos from the LESS. Noncontact ACL injuries are multi-factorial in origin and involve multiple joints and planes of motion (Hewett et al., 2006), which 2D motion is not able to accurately capture due to its inherent limitations linked with perspective errors and inability to assess kinematics in planes not perpendicular to the camera (Herrington et al., 2017). The current study findings revealed no difference in the joint displacement and overall impression items (Items 16 and 17) between footwear and barefoot conditions, which somewhat contradicts previous 3D motion capture with force plate research reporting greater overall joint stiffness in footwear during drop jump and drop landing tasks (Shultz et al., 2012). These between-study disparities highlight the advantages of research-grade technology that are not often accessible to clinicians.

The differences in likelihood of specific LESS errors between footwear and barefoot conditions indicate differences in multi-joint strategies used to moderate impact forces during landing tasks, as shown elsewhere (Shultz et al., 2012). Barefoot, participants were more likely to land with greater ankle plantar flexion at initial contact and the front part of their foot. These observations are comparable to findings of a more plantar-flexed ankle and greater foot-ground angle at initial contact from a 30-cm DLJL task similar to the LESS when performed barefoot compared to with shoes (Koyama & Yamauchi, 2018). Landing in greater ankle plantar flexion during DLJL likely shifts loading between joints, with greater ankle but lesser knee joint loading. Indeed, participants with an ACL reconstruction landed from a 60-cm drop with greater ankle plantar flexion and absorbed a greater amount of force at the ankle at initial contact compared to non-injured controls, presumably to protect their injured knee (Decker et al., 2002). Furthermore, research also indicates that single-leg landing with greater ankle plantar flexion from a drop jump increases total energy dissipation and reduces peak vertical loading rates (Lee et al., 2018). Since landing in greater plantar flexion may reduce the risk of knee and hip injuries, DLJL barefoot may be considered as a training tool in the early stages of ACL injury rehabilitation to reduce knee loads and peak vertical loading rates. In addition, the current data indicate that maximal jump performance is not compromised barefoot, which is often of concern to coaches, clinicians, and athletes.

Although knee valgus at initial contact was one of the most frequent errors in both footwear and barefoot conditions (Item 5), this error was more prevalent in footwear. Previous research has identified knee valgus as a risk factor for ACL injury (Hewett et al., 2005; McLean et al., 2005). Hewett et al. (2005) tracked 205 female adolescent athletes over 13 months: nine sustained ACL injuries. These nine athletes all exhibited increased knee valgus when performing drop vertical jumps pre-injury. Therefore, this metric alone in the context of the

LESS might suggest an increased ACL injury risk when wearing footwear compared to barefoot. However, knee valgus alone does not cause ACL injury (Yu & Garrett, 2007). ACL injuries are moreover linked with multi-planar mechanisms (Quatman et al., 2010), often with a hyperextended or slightly flexed knee undergoing a valgus motion with either internal or external rotation (Shimokochi & Shultz, 2008). Despite overt methodological limitations (Russo et al., 2021), more recent research continues to challenge that knee valgus during drop jumps is a valid predictor of ACL injury, with no association between 2D frontal plane knee and hip motion during a vertical drop jump and noncontact ACL injuries (Nilstad et al., 2021).

In our study, a threshold of five or more errors was used to categorise participants at high risk of injury based on previous research (Padua et al., 2015). However, the predictive value of the LESS is debatable given research also indicating a lack of association between LESS scores and noncontact ACL injury (Smith et al., 2012a). Furthermore, a series of studies suggest that the vertical drop jump and DLJL tasks are poor predictors of future ACL injury (Krosshaug et al., 2016; Mørtvedt et al., 2020; Petushek et al., 2021). Out of five biomechanical variables examined across these studies (knee valgus angle at initial contact, peak knee abduction moment, peak knee flexion angle, peak vertical ground reaction force, and medial knee displacement), only medial knee displacement during the drop vertical jump was linked to ACL injuries prospectively, but sensitivity (0.6) and specificity (0.6) were poor (Krosshaug et al., 2016). In recent investigations, the ability to control knees in the frontal plane during landing from a DLJL was unable to distinguish between athletes who sustained an ACL injury to those who remained uninjured (Petushek et al., 2021). Despite these findings, DLJL tasks can still be useful as part of neuromuscular training programmes for reducing ACL injury incidence (Hewett et al., 1999; Myer et al., 2007). The LESS can also be useful for monitoring the effectiveness of programmes and changes in biomechanical patterns (Garbenytė-Apolinskienė et al., 2018). Performing the DLJL in footwear and barefoot likely involves different multi-joint strategies, loads, and muscle recruitment and activation patterns, which might ultimately lead to different adaptations. As such, performing DLJL tasks in both footwear and barefoot within neuromuscular training programmes could provide different stimulus to individuals.

2.6 Conclusions

Overall LESS scores were significantly greater and jump heights were significantly lower in footwear than barefoot, but differences were *trivial* and not clinically meaningful. At the group level, the proportion of high-risk participants was comparable between conditions when based on a five-error threshold; however, differences in specific landing errors and inconsistency in risk categorisation at an individual level were noted. In clinical settings or for screening purposes, performing the LESS with shoes is still recommended given that the predictive value of the LESS barefoot has not yet been established. If the DLJL is used in neuromuscular training programmes, performing the task both with and without shoes can offer variety in landing strategies and potentially different stimulus and neuromuscular adaptations to individuals.

2.7 Acknowledgments

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Chapter Three – Experimental Study

Effect of an overhead goal on the Landing Error Scoring System and jump height measures.

3.1 Abstract

Objectives: Compare overall Landing Error Scoring System (LESS) scores, risk categorisation, specific LESS errors, and double-leg jump-landing jump heights between overhead goal and no goal conditions. **Design:** Randomised cross-over. **Setting:** Laboratory. **Participants:** 76 (51% male). **Main outcome measures:** Participants landed from a 30-cm box to 50% of their body height and immediately jumped vertically for maximum height. Participants completed three trials under two random-ordered conditions: with and without overhead goal. Group-level mean LESS scores, risk categorisation (five-error threshold), specific landing errors, and jump heights between conditions were compared. **Results:** Mean LESS scores were greater (0.3 errors, $p < 0.0001$) with the overhead goal, but this *small* difference was not clinically meaningful. Similarly, although the number of participants categorised at high risk of injury was greater with the overhead goal ($p = 0.039$), the 9.2% difference was *trivial.* Participants jumped 2.7 cm higher with the overhead goal ($p < 0.0001$) without affecting the occurrence of any specific LESS errors. **Discussion:** Performing the LESS with an overhead goal enhances sport specificity and elicits greater vertical jump performances with minimal change in landing errors and risk categorisation. Adding an overhead goal to the LESS might enhance its suitability for injury risk screening, although the predictive value of the LESS with an overhead goal needs confirmation.

***Keywords**:* Anterior Cruciate Ligament; injury risk; jump-landing biomechanics; movement screen

3.2 Introduction

Goal setting is a widely used and accepted strategy in physical activity to increase motivation or to achieve a performance target (Swann et al., 2021). Cueing is the use of verbal instructions to direct the attentional focus of individuals to a particular feature of a movement (Wulf et al., 2007). An internal cue or focus is one that directs the attention of individuals towards their own body movements (Wulf et al., 1998). An external cue or focus is one that directs the attention of individuals away from their body movements towards the external environment or the effects of their movement on that environment (Bredin et al., 2013). Instructing individuals to jump as high as possible versus upwards to reach an overhead goal are examples corresponding to an internal and external cue often used when assessing countermovement jump (Wulf et al., 2007) or drop jump (Ford et al., 2005) performances. Use of an external goal has generally been shown to improve performance across physical fitness tests. Specifically, adopting an external focus compared to an internal or no attentional focus leads to superior performances in seven physical tests (modified Canadian Aerobic Fitness Test, grip strength, push-ups, sit and reach, partial curl-ups, vertical jump, and back extension, all $p < 0.05$) (Bredin et al., 2013). Several studies have examined the effect of externally- and internally-oriented goals on vertical jump height performance (Ford et al., 2005; Król et al., 2016; Oliver et al., 2019; Wulf et al., 2007). The results from these studies overall indicate increased jump performances when using an externally-oriented goal. Specifically, Oliver et al. (2019) found that participants reached a greater vertical drop jump height with an external height cue ("focus on getting as close to the ceiling as possible") compared to an internal ("jump as high as possible"), contact ("focus on spending as little amount of time on the floor as possible"), and quiet ("focus on being as quiet as possible when landing") cue. This increased jump height was achieved without increasing impact peak and changing landing biomechanics in a way that suggests increased injury risk. Ford et al. (2005) also found an increased jump height during a double-leg jump-landing (DLJL) task with an overhead goal compared to no goal (*p* = 0.002). From a biomechanical perspective, this enhanced DLJL jump height performance was concurrent with an increased knee extension moment at take-off and tended to be associated with shorter ground contact times and increased knee and ankle ranges of motion (Ford et al., 2005).

Across sports, lower extremity injuries account for more than 50% of all injuries (Hootman et al., 2007), with the knee being the most commonly injured region (Murphy et al., 2003). Anterior Cruciate Ligament (ACL) knee injuries in particular are associated with high costs and burden (Rekik et al., 2018; Webster et al., 2021), and can considerably affect individuals' activity levels and quality of life (Filbay et al., 2015). Noncontact ACL injuries are considered preventable (Waldén et al., 2012), with research indicating a reduced incidence of ACL injuries when individuals undertake neuromuscular training programmes (Webster & Hewett, 2018). The most common situations for noncontact ACL injuries in sports are decelerations due to cutting, changing direction, or landing from jumps (Belcher et al., 2022; Griffin et al., 2006). The Landing Error Scoring System (LESS) screening tool detects individuals at greater risk of noncontact ACL (Padua et al., 2015) and musculoskeletal injuries (Everard et al., 2018), and identifies athletes who present high injury-risk biomechanical patterns during a DLJL task (Padua et al., 2009). An overall LESS score is derived from clinicians scoring 17 items related to DLJL kinematics, with overall scores ranging from 0 to 17 errors. Fewer landing errors and lower overall LESS scores suggest fewer movement patterns linked with noncontact ACL injuries during the DLJL. Items 1 to 15 are scored as 0 (error absent) or 1 (error present), whereas Items 16 and 17 are scored on a scale of 0 (soft/excellent landing), 1 (average landing), or 2 (stiff/poor landing). Some items cannot be present at the same time, e.g., Items 7 [stance width at initial contact (wide)] and 8 [stance width at initial contact (narrow)]. Therefore, the maximum possible LESS score is 17 errors. The odds of sustaining a noncontact ACL injury was 10.7 times greater (Padua et al., 2015) and of sustaining a musculoskeletal injury was 16.1 times greater (Everard et al., 2018) in individuals who scored five errors or more upon LESS assessment compared to individuals who scored less than five errors. Across the literature, the overall LESS score demonstrates good-to-excellent reliability and moderate-to-excellent validity for assessing key knee-injury risk factors and overall landing biomechanics (Hanzlíková & Hébert-Losier, 2020a).

There are some limitations to the LESS. Overall LESS scores are sensitive to various factors. Hanzlíková et al. (2021a) conducted a meta-analysis examining the influence of previous injury, intervention programmes, and gender on LESS scores. Overall, LESS scores are 1.2 errors lower when individuals follow a neuromuscular training programme lasting at least six weeks; 1.2 errors lower in uninjured individuals than individuals with prior ACL injuries; and 0.6 errors lower in males than females. In addition, research has identified final LESS score computational method (Hanzlíková et al., 2020) and jump landing distance (Hanzlíková & Hébert-Losier, 2021) can affect individual-level risk categorisation and LESS scores. To appropriately interpret LESS scores, clinicians and researchers should consider that several factors and procedural methods can affect outcomes.

Whilst studies have examined the effect of using an overhead goal on jump performances and landing mechanics of the DLJL task (Ford et al., 2005); whether use of an overhead goal affects LESS outcomes is unclear. The DLJL task used in the LESS has been criticised in terms of lack of sport specificity (Kristianslund & Krosshaug, 2013). In addition to enhancing jump performance, the use of an overhead goal during DLJL can enhance sport specificity and the relevance of the DLJL task in screening for risk of injury in sport. Therefore, the aim was to compare overall LESS scores, injury risk categorisation based on a five-error threshold, occurrence of specific LESS errors, and DLJL jump heights between goal and no goal conditions. It was hypothesised that adding an overhead goal to the DLJL task would involve higher overall LESS scores, lead to a greater number of individuals classified at high risk of injuries, and influence specific LESS errors compared to performing the DLJL task without an overhead goal. Higher jump heights when using an overhead goal compared to no goal during LESS assessment based on prior research (Ford et al., 2005; Wulf et al., 2010; Wulf et al., 2007).

3.3 Materials and methods

3.3.1 Experimental approach

A randomised cross-over experimental study design was implemented to examine the effect of using an overhead goal on LESS scores, risk categorisation, specific LESS errors, and DLJL jump heights. A priori sample size calculations were performed using G*Power 3.1.9.7 applying a standard two-tailed hypothesis, 5% significance level ($\alpha = 0.05$), 90% power ($\beta = 0.10$), one-error LESS difference in paired means defining a clinically-meaningful change (Hanzlíková et al., 2021a; Padua et al., 2009), and 2.47 standard deviation of the difference in paired means based on previous work implementing similar testing procedures (Hanzlíková & Hébert-Losier, 2021). Based on these assumptions, 67 participants were required and would be sufficient to detect a *small* effect size difference (Cohen $d = 0.40$) between conditions. A sample size of 76 to 80 participants was targeted to account for a 15 to 20% drop-out rate.

3.3.2 Participants

Seventy-six participants (39 males and 37 females, **Table 5**) were recruited and volunteered to participate in this investigation. Participants were invited to participate from a convenience sample of healthy university students. Individuals had to be free from illness, injury, or conditions that may affect landing mechanics and movements. Participants were excluded if presenting with a recent (less than three months) lower extremity, back, or pelvis injury. Participants signed informed consent documents that explained potential risks of participation (e.g., injury or delayed onset muscle soreness due to physical activity) prior to study participation. Participants were informed of the study aims. The research protocol was approved by the University of Waikato Human Research Ethics Committee (HREC(Health)#2017-41) before data collection.

Table 5. Demographic characteristics of participants. Values are means ± standard deviations or counts.

Characteristics	Males (*n* = 39)	Females (*n* = 37)	Both (*n* = 76)
Age (y)	20.7 ± 6.4	19.7 ± 2.5	20.2 ± 4.9
Height (cm)	182.1 ± 5.9	168.4 ± 7.0	175.0 ± 9.4
Mass (kg)	83.2 ± 13.5	68.2 ± 11.1	75.7 ± 14.4
BMI (kg/m^2)	24.5 ± 3.0	23.9 ± 2.8	24.2 ± 2.9
IPAQ (high:mod:low)	33:5:0[a]	26:8:1[a]	60:13:1[b]

Notes. [a]Missing data from 1 participant. [b]Missing data from 2 participants. BMI, body mass index; IPAQ, International Physical Activity Questionnaire; mod, moderate.

3.3.3 Procedures

Participants' baseline characteristics were collected following informed consent, which included measuring body mass using an electronic floor scale (seca model ESE813, Medical Measuring Systems and Scales, Mount Pleasant, South Carolina) and height using a stadiometer (seca model 0123, Medical Measuring Systems and Scales, Mount Pleasant, South Carolina). Participants were categorised as having high, moderate, or low physical activity levels based on their responses to the self-administered short-form International Physical

Activity Questionnaire (Craig et al., 2003). All participants but one were either moderately or highly physically active.

For experimentation, participants completed three DLJL trials in the two experimental conditions (goal and no goal) allocated in a block randomised order. Specifically, each participant performed three trials in each condition with 30 seconds rest between trials and 15 minutes rest between conditions to limit fatigue. Half of the participants performed the goal condition first, with the other half beginning with the no goal condition. Three familiarisation trials were permitted before formal LESS assessment in both the goal and no goal condition, with participants wearing their own athletic footwear during testing.

As per the original LESS testing protocol (Padua et al., 2009), participants were required to jump horizontally from a 30-cm box to 50% of their body height and jump vertically as high as possible upon landing. A strip of tape on the floor indicated the individualised landing distance. In the goal condition, participants were instructed to jump upwards as high as possible upon landing reaching for a ball, which was taped to the ceiling. In the no goal condition, participants were instructed to jump upwards as high as possible upon landing, while the ball was hidden from view. The bottom of the ball was 2.7 m from the floor and placed immediately above the landing area. A DLJL trial was disregarded when participants did not perform the task in one fluid motion or did not reach the prescribed horizontal landing distance. Unless the task was performed inadequately and disregarded, no feedback on performance was provided to avoid influencing outcomes (Hanzlíková & Hébert-Losier, 2020b).

The DLJL trials were recorded at 120 frames per second using two high-speed video cameras (Sony RX10 II, Sony Corporation, Tokyo, Japan) with a focal length of 8.8 to 73.3 mm (35-

mm equivalent focal length of 24-200 mm). One camera was placed to the right-side of participants to record sagittal plane motion and the other camera was placed in front of participants to record frontal plane motion. Each camera was positioned 3.5 m away from the landing area and mounted on tripods with a 1.3 m lens-to-ground distance. The Kinovea software (version 0.9.4, www.kinovea.org) was used to analyse videos. Jump height was computed from the flight time of the maximal vertical jump extracted from the sagittal plane videos using the following equation (Linthorne, 2001; Moir, 2008):

$$h = \frac{1}{8} \cdot g \cdot t^2 \cdot 100$$

where h is the jump height (cm), g is gravitational acceleration constant (9.81 m/s^2), and t is the flight time (s).

3.3.4 Data processing

A single expert rater (CBS) who had scored over 500 LESS videos completed all analyses. Videos from a subset of 10 participants were used to examine intra-rater and inter-rater reliability of the overall LESS scores. Based on intra-class correlation coefficient (ICC) and 95% confidence interval [lower, upper] values, intra-rater reliability was excellent for both goal ($ICC_{(3,1)}$ = 0.978 [0.912, 0.995]) and no goal ($ICC_{(3,1)}$ = 0.976 [0.909, 0.994]) conditions. Inter-rater reliability was also excellent for both goal ($ICC_{(2,1)}$ = 0.979 [0.917, 0.995]) and no goal ($ICC_{(2,1)}$ = 0.982 [0.935, 0.996]) conditions.

3.3.5 Statistical analysis

The effect of an overhead goal on group mean LESS scores, injury risk categorisation (high risk, LESS ≥ five errors; low risk, LESS < five errors), individual-level risk categorisation, and jump heights was examined. The average of participants three trials was computed and used as the overall LESS score and jump height measure for each participant. Group mean LESS score and jump height differences between goal and no goal conditions were examined using mean differences, two tailed paired *t*-tests, and Cohen's *d* effect sizes for paired samples using an average variance with 95% confidence intervals [lower, upper]. Cohen's *d* effect sizes were considered *small*, *medium*, and *large* when reaching thresholds of 0.20, 0.50, and 0.80, respectively, and *trivial* when less than 0.20 (Cohen, 2013).

Differences in the number of participants categorised at high and low risk of injury between the two experimental conditions based on a five-error LESS threshold (Padua et al., 2015) were assessed using McNemar's tests and odds ratio with 95% confidence intervals. The odds ratio reflects the number of participants exclusively at high risk in the goal condition versus those exclusively at high risk in the no goal condition. Therefore, an odds ratio > 1.0 reflects a higher proportion of individuals at high risk in the goal condition. McNemar's tests were also used to examine differences in the occurrence of specific LESS errors between the two experimental conditions. For each participant, an error was considered present when present in two of the three trials for Items 1-15. For Items 16 and 17, an error was considered present when the 'average' rating was present in two of three trials or when the 'poor/stiff' rating was present in one of three trials (Hanzlíková & Hébert-Losier, 2021; Padua et al., 2009). Changes in frequency were considered *small*, *medium*, and *large* when reaching thresholds of 10%, 30%, and 50%, respectively, and *trivial* when less than 10% (Hopkins et al., 2009). Significance was set at $p \leq 0.05$ for all analyses, which were conducted using Microsoft Excel for Microsoft 365 MSO (version 2109, Microsoft Corp, Redmond, WA, USA) and RStudio® version 1.1.463 with R version 4.0.5 (R Core Team, 2021).

3.4 Results

The group mean LESS scores in the goal condition (range: 2.7 to 10.0 errors) was significantly greater (0.3 errors, $p < 0.001$) than in the no goal condition (range: 2.7 to 10.0 errors), as shown in **Table 6**. The magnitude of the difference was *small* (Cohen $d = 0.24$ [0.10, 0.37]). The number of individuals classified at high risk based on a five-error threshold differed between conditions (65 participants goal vs 58 participants no goal, $p = 0.039$), with eight participants categorised at high risk exclusively for the goal condition and only one for the no goal condition (**Figure 9**). However, the 9.2% difference between condition was *trivial*. At an individual level, the risk categorisation was conflicting for nine participants (11.8%, *small* difference, **Figure 9**). Jump height in the goal condition (range: 16.5 to 49.7 cm) was significantly higher (2.7 cm, $p < 0.001$) than in the goal condition (range: 7.7 to 47.4 cm), as shown in **Table 6**. The magnitude of the difference was *small* (Cohen $d = 0.34$ [0.24, 0.44]). The occurrence of errors was similar between conditions for the 17 LESS items, as shown in **Table 7**.

Table 6. Comparison of Landing Error Scoring System mean scores and group-level risk categorisation between overhead goal and no goal conditions. Data are means ± standard deviations and differences with 95% confidence intervals [lower, upper].

Outcome	Goal	No goal	Difference	*p*-value
LESS score (errors)	6.2 ± 1.4	5.9 ± 1.5	0.3 [0.2 to 0.5]	**<0.001***[a]
High risk (%)	85.5%	76.3%	8.00 [1.00 to 63.97]	**0.039***[b]
Jump height (cm)	33.3 ± 7.9	31.7 ± 8.0	2.7 [2.1 to 3.4]	**<0.001***[a]

Note. *Significant difference between conditions ($p \leq 0.05$). [a] Difference in means and *p*-value from paired *t*-test. [b] Odds ratio and *p*-value from McNemar's test.

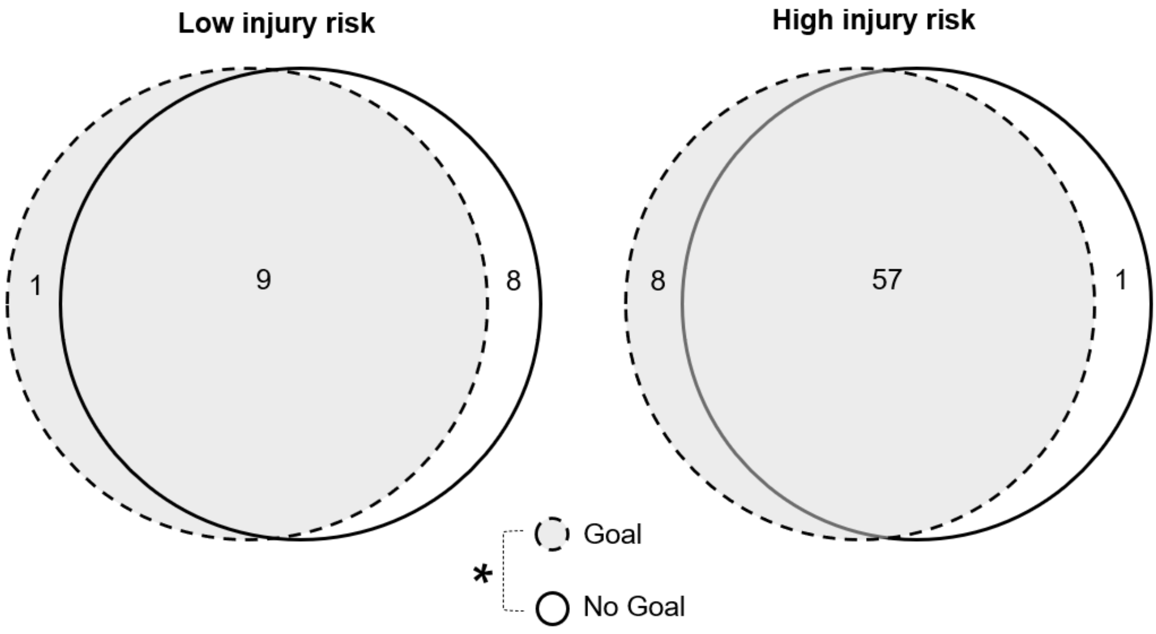

Figure 9. Venn diagrams representing participants at low risk (less than five errors) and high risk (five errors or more) of injury for both goal (hashed grey circles) and no goal (white circles) conditions. *Note*: The number in the circle represents the sum of participants categorised at low or high risk for each condition. The overlapping area represents the number of participants at low or high risk in both conditions. *Significant difference in the proportion of individuals at high and low risk based on McNemar's tests ($p \leqslant 0.05$).

Table 7. Occurrence of specific Landing Error Scoring System errors for the 76 participants under the overhead goal and no goal conditions.

No.	Items	Number of errors		*p*-value[a]
		Goal	No goal	
1	Knee flexion at initial contact	38	32	0.238
2	Hip flexion at initial contact	0	0	1.000
3	Trunk flexion at initial contact	0	0	1.000
4	Ankle plantar flexion at initial contact	9	10	1.000
5	Knee valgus at initial contact	68	69	1.000
6	Lateral trunk flexion at initial contact	1	0	1.000
7	Stance width (wide) at initial contact	11	12	1.000
8	Stance width (narrow) at initial contact	20	18	0.688
9	Foot position (toe-in)	0	0	1.000
10	Foot position (toe-out)	18	11	0.923
11	Symmetric foot contact at initial contact	50	42	0.215
12	Knee flexion at maximal knee flexion	11	7	0.219
13	Hip flexion at maximal knee flexion	0	0	1.000
14	Trunk flexion at maximal knee flexion	2	4	0.625
15	Knee valgus displacement	69	67	0.688
16	Joint displacement	62	57	0.180
17	Overall impression	76	75	1.000

Note. [a]McNemar's test *p*-values for differences between conditions.

3.5 Discussion

The effect of an overhead goal on LESS scores, risk categorisation, and jump heights was examined in this study. Congruent with the hypothesis, mean LESS scores were significantly greater in the overhead goal condition compared to the no goal condition. Despite the magnitude of the difference between conditions being *small* based on effect size statistics, it is debatable whether the 0.3 error difference in means between conditions is clinically meaningful as less than the one error threshold defining a clinically-meaningful change (Padua et al., 2009). A greater number of participants were categorised at high risk of injury with an overhead goal, also in line with the hypothesis. However, the 9.2% difference in the number of participants classified at high risk between condition was *trivial*. Furthermore, there were no differences in the occurrence of specific landing errors between conditions making it difficult to determine how landing mechanics were influenced. Lastly, jump heights were significantly improved with an overhead goal, as hypothesised and in agreement with previous literature (Ford et al., 2005; Oliver et al., 2019). The 2.7 cm improvement in DLJL jump height is considered clinically meaningful as above the 2 cm typical error associated with this measure (Gallardo-Fuentes et al., 2016; Markwick et al., 2015). Overall, these results indicate that using an external focus compared to an internal focus when performing the DLJL task improved jump height without meaningfully changing landing mechanics as assessed using the LESS. However, a more detailed biomechanical assessment would be needed to explain the significantly greater odds of being categorised at high risk of injury based on the identified five-error threshold (Padua et al., 2015) and conflicting categorisation between conditions in 11.8% of individuals.

This study was conducted with the knowledge that performing a drop jump with an overhead goal could influence landing mechanics and jump performance (Almonroeder et al., 2018; Ford et al., 2005; Oliver et al., 2019) with no specific investigation on the effect of an overhead goal on LESS scores as used in screening for injury risk. Furthermore, the DLJL task used in the LESS without an overhead goal has been criticised for lack of sport specificity (Kristianslund & Krosshaug, 2013). Adding an overhead goal has been used to enhance sport specificity elsewhere (Almonroeder et al., 2018; Fílter et al., 2021), which can increase relevance in the context of injury risk screening in sport. When using three-dimensional (3D) motion capture and force plate measuring devices, significant differences in DLJL biomechanics between goal and no goal conditions have been observed and suggest increased loading of the ACL under the goal condition (Almonroeder et al., 2018). That said, the difference in peak knee flexion (~5°) and adduction (~1°) angles between conditions captured using 3D methods would be difficult to discern reliability using 2-dimensional (2D) methods and the LESS scoring template. Hence, although differences in the biomechanics of the DLJL task have been identified under laboratory settings (Almonroeder et al., 2018; Ford et al., 2005; Oliver et al., 2019), differences are more challenging to observe using clinical methods. This challenge is reflected in the inability of the LESS to detect changes in the occurrence of specific LESS errors between the goal and no goal conditions despite conflicting risk categorisations between conditions at an individual level, changes in jump height performances, and significantly greater odds of being categorised at high risk when using an overhead goal.

The mean LESS scores for the no goal condition (5.9 ± 1.5 errors) in the cohort examined in this study, which followed the original LESS protocol (Padua et al., 2009), is in line with mean values from similar cohorts of young healthy participants (Hanzlíková et al., 2020; Hanzlíková & Hébert-Losier, 2021), although at the higher end of mean LESS score values reported across the literature for non-injured individuals (Hanzlíková et al., 2021a). These higher mean LESS scores resulted in a considerably large proportion of the participants examined being categorised at high risk (>75%) based on the five-error threshold. Greater differences between the two conditions might have surfaced in a cohort of participants with lower baseline LESS scores under the no goal condition. In addition, it is debatable whether the five-error threshold is an appropriate cut-off to define injury risk. Although results from some investigations support the predictive value of this threshold (Everard et al., 2018; Padua et al., 2015), others have failed to support the predictive value of the LESS and the five-error threshold (de la Motte et al., 2019; Smith et al., 2012a). Furthermore, it is important to highlight that the predictive value of the LESS while using an overhead goal has not been examined, which would help to confirm whether enhancing the sport-specific nature of the DLJL using an overhead goal would also enhance its usefulness in screening for risk of injury in sports.

Jump height of participants was 2.7 cm higher with the overhead goal compared to no goal, in line with the average increase in performance reported elsewhere (2.4 to 3.2 cm) comparing similar experimental conditions (Mok et al., 2015; Oliver et al., 2019). The observed 2.7 cm improvement in jump height is considered clinically meaningful as above the between-day typical error of 2 cm associated with this measure (Gallardo-Fuentes et al., 2016; Markwick et al., 2015). There are several mechanisms proposed to contribute to jump height increases when using an external focus. The constrained-action hypothesis is a commonly cited mechanism that suggests an external focus promotes greater movement control automaticity, whereas an internal focus constrains this automaticity and hinders motor performance (Vance et al., 2004; Vidal et al., 2018; Wulf et al., 2001). External focus may in fact promote the self-organisation of motor tasks (Wulf et al., 2001) and enhance movement efficiency (Vance et al., 2004; Wulf et al., 2010). On the other hand, the overhead goal may simply have incentivised participants to jump higher as setting goals can enhance motivation, focus, and performance (Swann et al., 2021). From a biomechanical perspective, higher jump heights likely involved changes in kinetic measures, which were not measured here. Jump impulse, lower extremity joint moments, and peak vertical ground reaction forces were reported as significantly greater during a DLJL with an external focus compared to an internal one (Mok et al., 2015; Wulf and Dufek, 2009; Ford et al., 2005). It is possible that all these factors contributed to various extents to the improved jump performance that was observed with the overhead goal.

Other means of enhancing sport specificity of DLJL tasks include alternative divided attention scenarios, such as asking individuals to perform a counting task alongside the motor performance task. It is possible that the combination of quick powerful movements (e.g., cutting, DLJL, and changing direction) and cognitive loads increases the odds of sustaining an injury (Grooms & Onate, 2016). When adding cognitive demands via counting to the DLJL task, Dai et al. (2018) found increased ground reaction forces and decreased knee flexion angles while dual tasking, indicative of increased ACL loading. Hence, adding an overhead goal alongside cognitive demands might speculatively elicit further LESS score and DLJL biomechanical differences compared to no goal than using an overheard goal in isolation. However, research has shown that the isolated effects of overhead goals and cognitive demands on DLJL biomechanics are similar to each other and do not further influence DLJL when combined (Almonroeder et al., 2018). Therefore, it is unlikely that increasing the cognitive load during LESS assessment using a counting task would affect landing mechanics more than using an overhead goal, the latter being conceptually more sport specific than counting. Overall, despite adding an overhead goal, there is still a concern that the DLJL task is not challenging enough or sufficiently sport specific for injury risk screening (Almonroeder et al., 2018; Hanzlíková et al., 2021b), with single-leg rotated tasks potentially a more suitable alternative (Hanzlíková et al., 2021b).

There are limitations to the current study, notably that a set overhead goal height was implemented across participants as the ball was affixed to a relatively low-hanging ceiling. As such, the overhead goal likely challenged individuals to different extents. Nonetheless, the stimulus was sufficient to elicit differences in jump height performances and provided a more sport-specific environment. As noted, greater differences in LESS scores, risk categorisation, and individual LESS errors might have surfaced between the two conditions examined in a cohort of participants with lower baseline LESS scores under the no goal condition. Furthermore, the predictive value of the implemented five-error threshold to categorise injury risk is debated in the scientific literature (de la Motte et al., 2019; Everard et al., 2018; Padua et al., 2015; Smith et al., 2012a).

3.6 Conclusions

Overall, performing the LESS with compared to without an overhead goal resulted in significant differences in mean LESS scores, group-level risk categorisation, individual-level risk categorisation, and jump heights, but not in the occurrence of specific LESS errors. Only changes in jump height and individual-level risk categorisation may be considered as clinically meaningful. Using an overhead goal during LESS testing is deemed to enhance sport specificity and elicit greater jump performances, and hence might be more suitable and relevant for injury risk screening in sport. However, prospective studies are needed to confirm the predictive value of the LESS performed with an overhead goal in terms of ACL and musculoskeletal injury, with more challenging tasks than the DLJL potentially of greater relevance to the sporting environment.

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Chapter Four – Overall Discussion

4.1 Summary

In the first experiment (Chapter 2), the aims were to examine the effect of footwear on overall Landing Error Scoring System (LESS) scores, risk categorisation, specific LESS errors, and double-leg jump-landing (DLJL) jump heights. In agreement with the hypothesis, footwear led to significantly higher LESS scores than barefoot; however, the difference was *trivial* and not clinically meaningful as less than one error (Padua et al., 2009). Footwear led to significantly lower jump heights than barefoot, but the difference was also *trivial*. A greater number of participants categorised at high risk of injury based on reaching five errors or more when wearing footwear was anticipated; however, the number of high-risk participants was comparable between conditions. Despite the similarities in LESS scores and high-risk categorisation, differences in specific LESS errors were noted, with footwear associated with greater odds of knee valgus (Item 5) and heel-to-toe or flat foot landing at initial contact (Item 4), and lesser odds of landing with a narrow stance width (Item 8) and toe-out foot position (Item 10) compared to barefoot. Overall, performing the LESS with compared to without shoes led to comparable mean LESS scores, group-level risk categorisation, and jump heights, but influenced specific LESS errors and individual-level risk categorisation (i.e., 16.25% of individuals inconsistently categorised between conditions). In clinical settings or for screening purposes, performing the LESS with shoes is still recommended over barefoot given that the predictive value of the LESS barefoot has not yet been established. If the DLJL is used in neuromuscular training programmes, performing the task both with and without shoes can offer variety in landing strategies, stimuli, and neuromuscular adaptations to individuals; and hence, can be recommended as a training or exercise to include in injury prevention programmes.

During the second experiment (Chapter 3), the effect of an overhead goal on overall LESS scores, risk categorisation, specific LESS errors, and DLJL jump heights was examined. Congruent with the hypothesis, mean LESS scores were significantly greater with an overhead goal compared to no goal. Despite the magnitude of the difference between conditions being *small* based on effect size statistics, it is debatable whether the difference of 0.3 errors between conditions is clinically meaningful as less than one error (Padua et al., 2009). A greater number of participants were categorised at high risk of injury based on reaching fiver errors or more during LESS assessment with an overhead goal, also in line with the hypothesis. However, there were no differences in the occurrence of specific landing errors between conditions making it difficult to determine how landing mechanics were influenced. Lastly, jump heights were significantly improved with an overhead goal, as hypothesised and in agreement with previous literature (Ford et al., 2005; Oliver et al., 2019). The 2.7 cm improvement in DLJL jump height is considered clinically meaningful as above the 2 cm typical error associated with this measure (Gallardo-Fuentes et al., 2016; Markwick et al., 2015). Overall, these results indicate that using an external focus compared to an internal focus when performing the DLJL task improves jump height without meaningfully changing landing mechanics as assessed using the LESS. Nonetheless, a more detailed biomechanical assessment would be needed to explain the greater odds of being categorised at high risk of injury based on the implemented five-error threshold (Padua et al., 2015). Given that using an overhead goal during LESS testing elicited greater jump performances and is deemed to enhance sport specificity, using an overhead goal might be more suitable and relevant for injury risk screening in sport. However, prospective studies are needed to confirm the predictive value of the LESS performed with an overhead goal in terms of ACL and musculoskeletal injury, with more challenging tasks than the DLJL potentially of greater relevance to the sporting environment.

4.2 Limitations

The first limitation of the two experimental chapters is that gender differences were not examined. Previous research has shown that females are more at risk of ACL injury than males (Hanzlíková et al., 2021a; Hewett et al., 2006; Sutton & Bullock, 2013). There were no *a priori* plans to compare female and male participants. Instead, to account for potential differences between genders, equal numbers of male and female participants were sought for inclusion in both studies. In a future study, differences between males and females could be explored.

A second limitation of the experimental chapters is the use of the five-error threshold for defining injury risk. A threshold of five or more errors was used to categorise participants at high risk of injury based on previous research (Padua et al., 2015); however, the five-error threshold has been challenged (de la Motte et al., 2019; Smith et al., 2012a). Although results from some investigations support the predictive value of this five-error threshold (Everard et al., 2018; Padua et al., 2015), others have failed to support its predictive value (de la Motte et al., 2019; Smith et al., 2012a). It is debatable whether the five-error threshold is an appropriate cut-off to define injury risk in the cohort here examined. The appropriateness of the threshold may be affected due numerous other factors, including age, gender, and previous ACL injuries.

As previously addressed, a series of studies suggest that the vertical drop jump and DLJL tasks are poor predictors of future ACL injury (Krosshaug et al., 2016; Mørtvedt et al., 2020; Petushek et al., 2021) as well as not challenging enough or sufficiently sport specific for injury risk screening (Almonroeder et al., 2018; Hanzlíková et al., 2021b). Together, these arguments challenge the use of the LESS in screening for ACL injury risk. Despite these limitations, DLJL tasks can still be useful as part of neuromuscular training programmes for reducing ACL injury incidence (Hewett et al., 1999; Myer et al., 2007) and has shown good ability to assess movement patterns linked to ACL injury.

4.3 Strengths

A clear strength of the experimental chapters is the achieved sample size. Both studies were sufficiently powered to 90% ($\beta = 0.10$) for detecting a *small* effect size difference between conditions based on standard two-tailed hypothesis using a 5% significance level ($\alpha = 0.05$). Therefore, the results from the experimental chapters would likely be similar if conducted again under similar conditions.

Another strength is that both inter-rater and intra-rater reliability of LESS scoring was examined for both experimental chapters. Specifically, inter-rater and intra-rater reliability of the overall LESS score was examined for a subset of 10 participants. Both the inter-rater and intra-rater reliability of the overall score was excellent based on intra-class correlation coefficient values. Hence, the findings from the two experimental chapters would presumably be similar if another investigator had scored the LESS videos.

Despite the limitations of the LESS, it remains a clinically-friendly tool that can be used on the field. The LESS is easy to set up and implement in a large cohort of participants with minimal time, space, and resource requirements. These characteristics of the LESS make it appealing for use in clinical setting and is more accessible than other methods used to assess movement, such as three-dimensional motion capture that is costly, requires expert users, and is typically confined to laboratory environments.

4.4 Future directions

Previous studies have looked at both footwear (Padua et al., 2009) and barefoot conditions (O'Malley et al., 2017) when performing the LESS, but Chapter 2 is the first experimental study to directly compare LESS outcomes between conditions. Chapter 3 is also the first experimental study to perform the LESS using an overhead goal. Further prospective studies are needed to confirm the predictive value of the LESS performed barefoot or when using an overhead goal in terms of ACL and musculoskeletal injury. Despite the overhead goal enhancing the sport specificity to the LESS, it remains debatable whether the DLJL task is challenging enough to reflect the sporting environment. Therefore, future research should seek to implement more challenging tasks than the DLJL in injury risk screening efforts, such as cutting, changes in direction, or single-leg rotated jumps. As highlighted in the limitations section, future studies could seek to explore whether gender mediates the LESS responses to footwear and overhead goal conditions.

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Appendix A – Ethics approval

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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

24 June 2021

Dr Kim Hébert-Losier
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Kia ora Kim,

HREC(Health)#2017-41: An automated injury risk screening platform

Thank you for your email requesting approval for amendments to your project HREC(Health)2017#41 *An automated injury risk screening platform*. I am pleased to approve a 12 month extension to the ethical approval timeframe, the addition of Dr Shannon O'Donnell and Caleb Boswell-Smith to the research team, and an amendment to the baseline questionnaire. I appreciated the information confirming Caleb Boswell-Smith's ethical preparation as a Masters student. If Caleb's involvement contributes to a thesis it would be important to include in the published thesis the process of ethical approval related to his aspect of the overall study.

Kind regards,

____

Emeritus Professor Roger Moltzen MNZM
Chairperson
University of Waikato Human Research Ethics Committee

Appendix B – Information sheet

Participant Information Sheet (Conditions)

Title – An automated injury risk screening platform: Conditions

Aim – Testing conditions, time, population, and interventions can influence the results from common clinical testing procedures. Our goal is to explore the influence of testing conditions, maturation, time, and best-practice interventions on current clinical methods used to screen for risk of injuries.

Overview – Should you agree to participate, you will be asked to sign an informed consent document and complete a baseline questionnaire. You will be familiarised with the testing equipment and procedures, and be given sufficient time to warm-up and practice the injury screening test.

For testing, you will be asked to jump from a box, and immediately jump upwards for maximal height. You will be asked to perform this task three "successful" times while we record your movements using the following technology. The jump test only takes a few seconds to complete and you will be given 2 minutes of rest between jumps. You will be asked to perform the same protocol under various conditions.

Technology	Picture
2D video cameras	
Force plate	

What are the potential risks – The risks associated with participating in this study are no greater than those involved in performing physical activities. Although the injury risks are considered minimal, we cannot guarantee your safety. If harm does occur during or as a result of study participation, you will be personally responsible for covering the costs of any injuries.

Children (under 14 years) and young people (14 to 17 years) – Consent for a child or young person (< 16 years) must be provided by the child or young person (wherever practical) and the child's or young person's proxy (parent or legal guardian). A person aged 16 to 17 years can consent to participate as an adult. The research will adhere to the Health Research Council's guidelines relating to research involving children and UNICEF's principles guiding ethical research involving children.

What will happen to the information collected – The information collected will be used by the research team to write research reports, give scientific presentations, and help in educating students at the University of Waikato and the wider community. The information could be used in postgraduate student projects and thesis dissertations. Only the research team, their research associates, and students under their supervision will have direct access to the notes, documents, and recordings. At the end of the project, any personal information will be destroyed immediately except that, as required by the University's research policy, any raw data on which the results of the project depend will be retained in secure storage for five years, after which they will be destroyed. All data will be treated with the strictest confidentiality. No participants will be named in the publications and every effort will be made to disguise their identity. No videos or images will be published or presented in a way that allows your identification (i.e., your face will be concealed to protect your identity) unless you provide written informed consent to having them used without alterations. All data used in teaching will be de-identified (i.e., will not contain your personal information) to protect your identity and confidentiality.

Declaration to participants – If you take part in the study, you have the right to:

- Ask any further questions about the study that occurs to you during your participation;
- Be given access to a summary of findings from the study when it is concluded;
- Have a support person (family, whanau, and/or friend) present during your participation;
- Refuse to answer any particular question, and to withdraw from the study at any time.

Who is responsible – If you have any questions about the project, please feel free to contact:

Dr Kim Hébert-Losier **(Primary Investigator)**
The University of Waikato, Adams Centre for High Performance
52 Miro Street, Mount Maunganui 3116
kim.hebert-losier@waikato.ac.nz

Caleb Boswell-Smith
Master Student
calebbs1999@gmail.com

Human Research Ethics Committee – This research project has been approved by the Human Research Ethics Committee (Health) of the University of Waikato under *HREC(Health)#2017-41*.

Any questions about the ethical conduct of this research may be addressed to the Secretary of the Committee, email humanethics@waikato.ac.nz, postal address, University of Waikato, Te Whare Wananga o Waikato, Private Bag 3105, Hamilton 3240.

Appendix C – Consent form

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Title – An automated injury risk screening platform: Conditions

I have read the Participant Information Sheet for this study and have had the details of the study explained to me. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I also understand that:

- I am free to withdraw from the study at any time or to decline to answer any particular questions.
- I can withdraw any information I have provided up until data analysis has commenced on my data.
- Any data or answers will remain confidential in regards to my identity through a coding system.
- The data might be published, so every effort will be made to ensure confidentiality and anonymity. However, anonymity cannot be guaranteed.

I agree to provide information to the researchers under the conditions of confidentiality set out on the Participant Information Sheet.

Consent to Participate

I agree to participate in this study under the conditions set out in the Participant Information Sheet.

	Participant:	Research team member:
Signature:	______________________	______________________
Name:	______________________	______________________
Date:	______________________	______________________

Additional Consent (Optional)

I agree to my images and videos being used in their original (unaltered) form for publication, scientific presentation, and/or education purposes.

	Participant:	Research team member:
Signature:	______________________	______________________
Name:	______________________	______________________
Date:	______________________	______________________

Any questions about the ethical conduct of this research may be addressed to the Secretary of the Committee, email humanethics@waikato.ac.nz, postal address, University of Waikato, Te Whare Wananga o Waikato, Private Bag 3105, Hamilton 3240.

Appendix D – Participant data collection sheet

Participant Data Collection Sheet

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Project Title – *An automated injury risk screening platform*

GENERAL	
Name	
Date of birth (day / month / year)	
Age (years)	
Gender (please tick)	☐ *Male* ☐ *Female* ☐ *Other*
Ethnicity (please tick all that apply)	☐ *NZ European* ☐ *Māori* ☐ *Pacific Island* ☐ *Asian* ☐ *Other* ________________________
Are you in good general health?	☐ *Yes* ☐ *No*
Do you have a current or recent injury (last 3 months)? *If YES, please provide detail (date, side, diagnosis)*	☐ *Yes* ☐ *No*
Have you suffered any important injuries in the past? *If YES, please provide detail (date, side, diagnosis) (e.g., right ACL tear 2015)*	☐ *Yes* ☐ *No*

What foot do you use to kick a ball?	☐ *Right*	☐ *Left*
What hand do you use to write?	☐ *Right*	☐ *Left*
E-mail (for report)		
FOOTWEAR		
What shoes are you wearing for testing? 1. *Type (Running shoes)* 2. *Make (Brooks)* 3. *Model (Glycerine 13)* 4. *Size (US 7.5)*	*1.* ______________ *2.* ______________ *3.* ______________ *4.* ______________	
SPORT		
What sport do you play?		
What level do you play?	☐ *School* ☐ *National*	☐ *Club* ☐ *Other* __________
How many times a week do you play / train?		
How many hours a week do you play / train?		
How many years have you been playing / training?		
PHYSICAL ACTIVITY QUESTIONNAIRE		
Have you completed the physical activity questions? *If NO, please complete all pages of this document.*	☐ *Yes*	☐ *No*

We are trying to find out about your level of **PHYSICAL ACTIVITY**. Remember:

- ✓ There are no right and wrong answers — this is not a test.
- ✓ Please answer all the questions as honestly and accurately as you can — this is very important.
- ✓ Answer all 2 questions.

QUESTION 1. During the past **12 months** (year), how much do you move and exert yourself physically during leisure/play time? If your activity varies greatly during the year (for example, between summer and winter) try to estimate overall. Tick **one** answer only.

☐ Hardly no physical activity (reading, watching TV, using the computer)

☐ Mostly sitting, sometimes walk, easy tasks/play

☐ Light physical activity for about 2 – 4 hours a week, like fishing, talking, dancing

- ☐ Moderate exercise 1 – 2 hours a week, like jogging, swimming, gymnastics
- ☐ Moderate exercise at least 3 hours a week, like jogging, swimming, gymnastics
- ☐ Hard or very hard exercise regularly and several times a week, during which the physical exercise is great, like jogging, rugby, football

QUESTION 2. During the past **7 days,** please tell us how much time you have spent in each category of activity.

- ✓ **Vigorous** physical activites require hard physical effort and make you breath much harder than normal
- ✓ **Moderate** activities take moderate physical effort or make you breathe somewhat harder than normal
- ✓ **Walking** includes at work, at school, and at home, walking from place to place, and any other walking that you have done for recreation, sport, exercise, or leisure/fun
- ✓ **Sitting** includes time spent sitting at work, at schoolm and at home, while doing some course work and leisure/play time. This may include time spend sitting at a desk, visiting friends, reading, or sitting or lying down to watch TV.

Activity	**How much time do you usually spend doing this activity?**	
	Days per week?	**Time per day?**
Vigorous	days per week	minutes per day
Moderate	days per week	minutes per day
Walking	days per week	minutes per day
Sitting	days per week	**hours** per day

FOR RESEARCH USE ONLY			
ID number	***(RESEARCH USE)***		
Consent form	***(RESEARCH USE)***	☐ *Yes*	☐ *No*
Date today (day / month / year)	***(RESEARCH USE)***		
Height (cm)	***(RESEARCH USE)***		
Mass (kg)	***(RESEARCH USE)***		
Questionnaire complete	***(RESEARCH USE)***	☐ *Yes*	☐ *No*