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Landing Error Scoring System: The Effect of Head Position and Dual Tasking

A Thesis

submitted in fulfilment

of the requirements for the degree

of

Master of Health, Sport and Human Performance

at

The University of Waikato

by

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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2025

Abstract

Sport has many mental and physical health benefits. However, with overall participation in sport increasing, sport-related issues and injuries are also increasing. Anterior cruciate ligament (ACL) injuries are common knee injuries in athletes and the general population, often occurring through non-contact mechanisms. The Landing Error Scoring System (LESS) is a screening task used to identify athletes at higher risk of non-contact ACL and musculoskeletal injuries, where higher scores indicate poorer landing mechanics and greater risk of injury. Although the LESS is reliable, its predictive value is debated and it has been criticised for lacking validity in a sporting context. Previous studies have adapted LESS protocols in attempts to increase sport specificity, with changing head position or completing a dual task potentially suitable for this purpose as linked with ACL injury situations in sports. This thesis contains two experimental chapters.

In the first experiment, 35 participants (22 males, 13 females) performed the LESS in two conditions allocated in a random order. In the control condition, participants jumped horizontally with both legs from a 30-cm high box to half their body height, landed with both feet, and jumped vertically as high as possible in one motion. In the head turned condition, participants performed the same double-leg jump landing movement while maintaining eye contact with an 'X' marked on a wall to their right, in line with the landing area. Participants performed three trials in each condition. Group mean LESS scores were significantly greater ($P = 0.027$) in the head turned (mean errors = 6.8 ± 1.5) than the control (mean errors = 6.4 ± 1.4) condition, with the mean difference of 0.4 errors being of *small* magnitude (Cohen's $d = 0.27$ [0.51, 0.03]). No significant difference was found in the odds of being categorised at risk between conditions ($P = 0.625$, *odds ratio* = 3.00 [0.312, 28.8]) based on a 5-error threshold. On an individual level, 28 participants were at risk in both conditions, although 13 had a meaningful increase in LESS score of one or more in the head turned condition. Average jump heights were significantly lower in the head turned condition, with the mean difference of 2.1 cm being of *small* magnitude (Cohen's $d = 0.20$ [0.07, 0.34]). Overall, performing the LESS with a head turned position appeared to increase the complexity and sport specificity of the task. Future research is required to

determine the ability of the LESS to predict ACL injuries with a head turned condition as this aspect was not assessed.

In the second experiment, an element of cognitive challenge was incorporated to the LESS in attempt to recreate the complex athlete-environment relationship of sports. In experiment two, 41 participants (20 males, 19 females, 2 others) performed the LESS in two conditions allocated in a random order. The control condition was the same as in the first experiment. In the tone counting condition, participants completed the same double-leg jump landing movement while mentally counting a random series of high-pitched and low-pitched tones, known as a tone counting task. Group mean LESS scores were not significantly different between tone counting (mean errors = 6.0 ± 1.3) and control (mean errors = 6.2 ± 1.5) conditions. Average jump heights were significantly lower in the tone counting than the control condition, with the mean difference of -4.2 cm being of *small* magnitude (Cohen's $d = 0.48$ [0.30, 0.66]). No significant difference was found in the odds of being categorised at risk between conditions ($P = 1.000$, *odds ratio* = 1.00 [0.20, 4.95]) based on a 5-error threshold. Overall, performing the LESS with a secondary tone counting task significantly decreased jump heights with a *small* effect size, corroborating an increased cognitive load during testing that impaired jump performance. However, LESS scores were not meaningfully influenced.

Overall, introducing a head turned position to the LESS task increased LESS errors significantly, and introducing a tone counting task or head turned position decreased jump heights. Although future research is required to determine the ability of the LESS to predict ACL injuries with these dual tasking conditions, this Thesis demonstrates that the complexity and sport specificity of the LESS task can be increased by introducing dual tasking requirements.

Acknowledgments

Firstly, I would like to acknowledge all of the participants that voluntarily gave up their time to be a part of this study.

To Kim Hebert-Losier, my supervisor, thank you for your encouragement, support, insight, and patience, without you this work would not have been possible. You inspire myself and others with your knowledge and passion, and I am grateful for the opportunity to write this thesis with you as my supervisor.

To other university staff that helped during the planning and data collection process, Anna Butcher, Steve Finlayson, and Rich Masters, thank you for your ideas, time and enthusiasm when helping on this Thesis.

To my fellow postgraduate students, thank you for providing perspective and support throughout this journey, I have many good memories of our times spent together.

Finally, thank you to my friends and family, for your consistent support and belief in me throughout this process.

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List of Abbreviations

3D – Three dimensional

2D – Two dimensional

ACC – Accident Compensation Corporation

ACL – Anterior cruciate ligament

BMI – Body mass index

DLJL – Double leg jump landing

EMG – Electromyography

F – Female

IMU – Inertial measurement unit

IPAQ – International Physical Activity Questionnaire

LESS – Landing Error Scoring System

M – Male

MOD – Moderate

O – Other

OR – Odds ratio

Structure of Thesis

This Thesis on the Landing Error Scoring System (LESS) has two main aims. First, it aims to examine the effect of a turned head position on the LESS; and second, to examine the effect of increased cognitive load via tone counting on the LESS. The structure of this Thesis is outlined in **Figure 1**. Four chapters are included, with chapters two and three being experimental chapters, and chapters one and four being introductory and concluding chapters, respectively. Chapter One reviews current literature on sporting injuries, anterior cruciate ligament injuries, injury risk screening tools and prevention models, head turned position in sports, and cognitive load in sports. Chapter Two is an experimental Chapter and examines differences between a control LESS and a head turned LESS, focusing on overall LESS scores, individual LESS errors, group-level risk categorisation, and jump heights. Chapter Three is also experimental and examines the differences between a control LESS and a simultaneous tone counting LESS task, addressing the same metrics as Chapter Two. Chapter Four concludes the Thesis, discussing practical implications, strengths, limitations, and directions of future research.

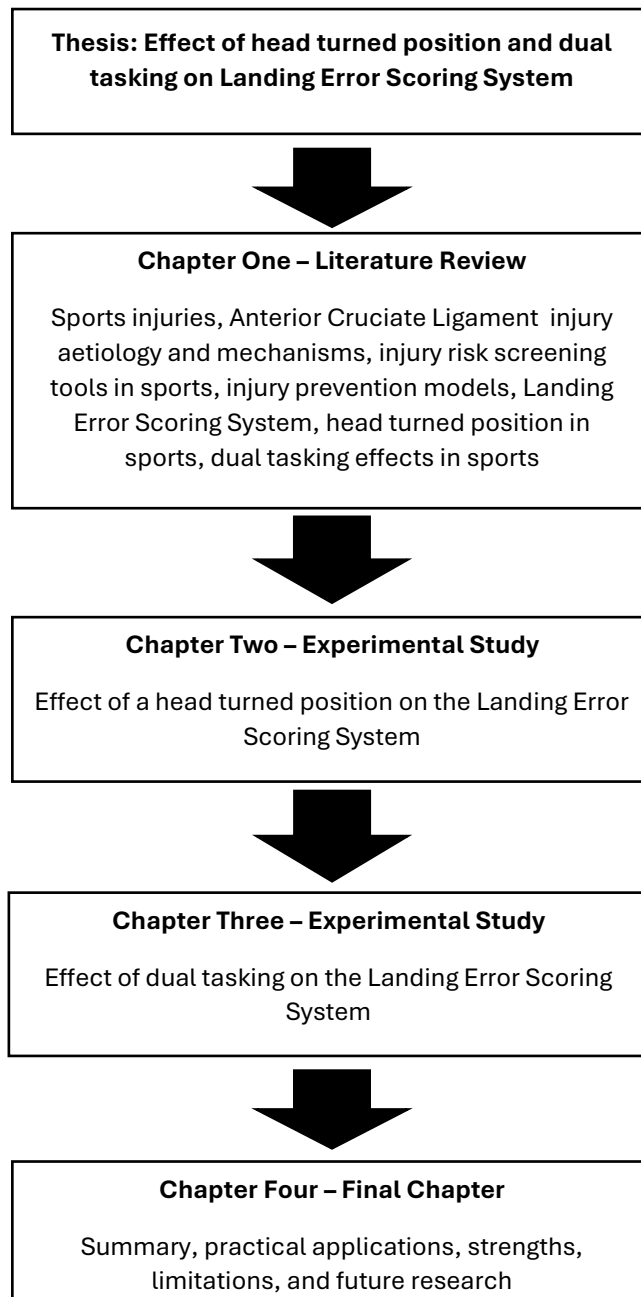


Figure 1. Structure of the Thesis.

Chapter One: Literature Review

Sports injuries

Sport and exercise have many positive benefits to society, most notably positive effects on mental, social, and physical health (Eather et al., 2023). In terms of mental health, participating in sport has been shown to especially benefit individuals in childhood and adolescent years (Doré et al., 2019). With the recent decrease to overall mental health in adolescent groups, the positive effects of sports are becoming increasingly important to harness (Sutcliffe et al., 2023). Fortunately, the overall rate of participation in sport is increasing (Eime et al., 2021; Eime et al., 2016); however, in turn, sport related issues, such as injuries, are increasing. Injuries as a result of sport and exercise limit the potential for sport's positive benefits, and create negative effects such as time off work, long-term musculoskeletal ailments, reduced mental health, and economic burden (Ding et al., 2016).

The New Zealand national health insurance company, Accident Compensation Corporation (ACC), recorded 60,803 moderate-to-serious and serious sporting related injury claims from 2012 to 2016 across netball, cricket, football, rugby union and rugby league, costing NZD\$122,291,313 with a mean price per claim of NZD\$8,284 (King et al., 2019). Of these claims, the knee recorded the most injuries, representing 19,026 injuries over the five-year period. A systematic review investigated the cost effectiveness of injury prevention programmes, such as warm ups, neuromuscular training, and psychological training in a variety of sports and found cost savings between €24 and €462 per player (Lutter et al., 2022). With a large amount of the population participating in sport and the trend towards increasing sport participation (Eime et al., 2021), the potential negative effects of injuries will continue to increase without intervention.

Anterior cruciate ligament injuries

The knee is the largest joint in the human body. Although stable in extension, it becomes considerably mobile in flexion and is often subject to large forces during athletic activities (Patton et al., 2019). The anterior cruciate ligament (ACL) is one of the four major ligaments stabilising the knee, primarily limiting anterior translation of the tibia relative to the femur. Injuries to the ACL are most common in

high intensity sports involving large amounts of jumping, changing of direction, and deceleration, such as basketball, netball, and soccer (Brukner & Khan, 2009; Kobayashi et al., 2010). ACL injuries are common knee injuries in athletes and the general population (Sanders et al., 2016), as well as one of the most severe and burdensome (Chia et al., 2022). The rate of ACL injuries has increased over the last two decades, shown in a longitudinal study by Maniar et al. (2022), where annual ACL injury incidence rates increased significantly for both males (5.2% per year, 95% confidence interval [4.5, 6.0]) and females (6.2% per year, [5.3, 7.1]) based on 228,344 knee injuries recorded in Australia. The highest rate of ACL injury was found in ages 15 to 29 years, however younger individuals aged 5 to 14 years showed the steepest rise in ACL injuries over the 20-year analysis period (Maniar et al., 2022).

Many ACL injuries undergo surgery and are recommended for individuals wanting to return to pivoting sports (Jia et al., 2024). Anterior cruciate ligament injuries require at least five to six months of rehabilitation, with a recommended return to sport time beyond nine months post-surgery to limit reinjury (Kaplan & Witvrouw, 2019). Reinjury rates are considerable, with a retrospective study of 35 collegiate level athletes with previous ACL reconstruction surgeries reporting a reinjury rate of 37% to the graft site or to the opposite knee (Kamath et al., 2014). Long term negative effects of ACL injuries are also of concern, with reported post-traumatic osteoarthritis rates of higher than 50% following ACL injury, decreasing individuals' quality of life and physical ability (Luc et al., 2014; Wang et al., 2020). Altogether, ACL injuries are a widespread issue in sport that considerably burden individuals and society when considering their lengthy recovery periods, extensive rehabilitation, relatively high reinjury rates, and potential for long term consequences. Ideally, strategies would be put in place to foster primary prevention of ACL injuries in sport.

There are some biological and biomechanical risk factors (Belkhelladi et al., 2025; Butcher et al., 2024) that are associated with an increased risk of ACL injury, however up to 70% of ACL injuries are non-contact in nature and potentially preventable (Boden et al., 2000). These non-contact injuries usually result from high risk change of direction cutting mechanisms such as limited hip and knee flexion, or poor landing mechanisms such as landing with minimal hip and knee flexion, or with trunk instability and lateral tilt (Sundberg, 2025). Therefore, non-contact ACL injuries are shown to be preventable with

appropriate preventative interventions (Hewett et al., 2010; Kristianslund et al., 2014). For example, ACL injury risk was reduced by 52% in females and 85% in males when ACL injury prevention programmes were used (Sadoghi et al., 2012). Most effective injury prevention programmes include strengthening and plyometric exercises, focusing on muscles both proximal and distal to the knee (Arundale et al., 2022).

There are many models of injury prevention available to guide injury prevention efforts. One of the earliest is the “sequence of prevention” model by Van Mechelen et al. (1992). The sequence of prevention model (**Figure 2**) is a four-step model, beginning with establishing the incidence and severity of the injury problem, followed by establishing the aetiology and mechanism of the injury, and then introducing preventative measures. Injury screening tasks could be implemented into the sequence of prevention model during step two, helping to identify higher risk populations and individuals prior to introducing preventative measures. Due to high injury and reinjury rates, there is demand for a reliable and practical ACL injury screening task that can be used within injury prevention models. Effectively implementing an ACL injury screening task into an injury prevention model could catalyse the effective use of injury prevention programmes by identifying participants at high risk of ACL injury, decreasing overall injury incidence.

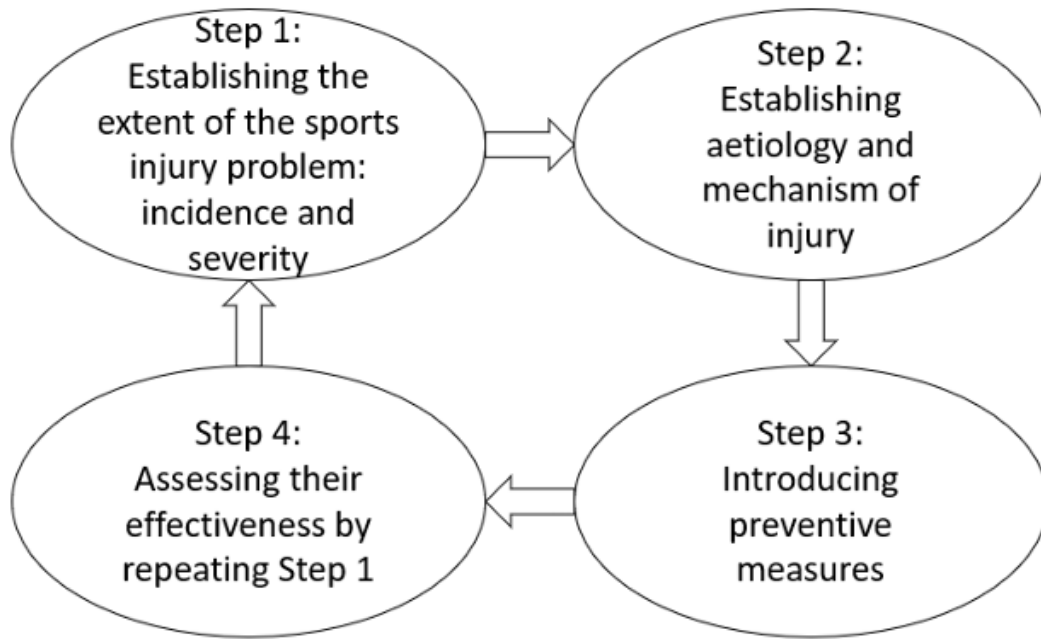


Figure 2. Sequence of prevention model. Developed by Van Mechelen et al. (1992)

Landing Error Scoring System

Injury screening tasks are most often used prior to sporting participation to evaluate an athlete's risk of becoming injured during play or used as a test prior to rehabilitating athletes returning to play. A range of screening tasks have been proposed, including the Functional Movement Screen™, Y-Balance Test, Tuck Jump Assessment, Star Excursion Balance Test, Cutting Movement Assessment Score, and the Landing Error Scoring System (Fox et al., 2016; Schweizer et al., 2022). Out of all of these tasks, the Landing Error Scoring System (LESS) has the most evidence available in terms of predictive ability for ACL injury risk, while remaining practical in a field setting.

The LESS is a screening task used to identify athletes at higher risk of injury, in particular non-contact ACL (Padua et al., 2015) and musculoskeletal injuries (Everard et al., 2018). This task has shown predictive value for non-contact ACL injuries in sport (Padua et al., 2015) and is extensively used in the literature (Arlettaz et al., 2024; Hanzlíková, Athens, et al., 2021; Hanzlíková & Hébert-Losier, 2020a). The LESS involves participants jumping horizontally with both legs from a 30-cm high box, landing at a distance of half their body height, before immediately jumping vertically as high as possible in one motion (Padua et al., 2009). The movement is recorded using cameras in both the sagittal and frontal planes, and then later analysed against standard LESS scoring criteria (Padua et al., 2009). Scoring criteria is shown in **Table 1** and includes knee flexion, hip flexion, trunk flexion, foot rotation, stance width, and symmetry. An overall LESS score is calculated based on the examiner scoring the participants' double-leg jump landing against the 17 different errors shown in **Table 1**. Items 1 to 15 are scored as either zero (no error) or one (error present). Items 16 and 17 are scored on a scale of zero (soft/excellent landing), one (average landing), or two (stiff/poor landing). Higher total scores indicate more movement errors, with the highest potential score being 17, as some errors are mutually exclusive. Scores higher than five indicate 10.7 times greater risk of ACL injury (Padua et al., 2015), and 16 times greater risk of musculoskeletal injury (Everard et al., 2018), and is therefore the generally accepted high risk threshold.

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 (acromion processes) at initial contact
8	Stance width (narrow)	Feet are positioned less than shoulder width apart (acromion processes) at initial contact
9	Foot position (toe-in)	Foot is externally rotated more than 30° between initial contact and maximum knee flexion (120°)
10	Foot position (toe-out)	Foot is internally rotated more than 30° between initial contact and maximum knee flexion (60°)
11	Symmetric foot contact at initial contact	One foot lands before the other foot or 1 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, average, stiff
17	Overall impression*	Excellent, average, poor

*Error present (1) or absent (0), except for items 16 and 17: soft/excellent (0), average (1), stiff/poor (2). Template adapted from (Padua et al., 2009)

The LESS is reliable in a clinical setting (Hanzlíková & Hébert-Losier, 2020a), while still practical to complete with minimal personnel and equipment. The LESS does not require the use of expensive three-dimensional motion capture systems or force plates, only requiring two common video cameras. Both expert and novice raters can score the LESS using the scoring criteria, with excellent intra-rater reliability (Hanzlíková & Hébert-Losier, 2020a; Onate et al., 2010). When compared with three-dimensional motion capture systems, the validity of LESS items addressing key knee-injury risk factors is moderate-to-excellent, for specific items (Onate et al., 2010; Padua et al., 2009). While it is not required to measure jump heights for the LESS, jump height is an important measure of performance in many sports (Kobal et al., 2017), and correlates to other athletic movements such as sprinting (He et al., 2025). Therefore, measuring jump height during the LESS could be useful to evaluate any changes in the participants athletic ability and ensure consistency across trials.

While the LESS has shown predictive value in youth football players when using a five error high risk threshold (Padua et al., 2015), other research does not reflect these results. Smith et al. (2012) found no association between LESS scores and non-contact ACL injury in high-school and college athletes. This lack of association may be due to the nature of the double-leg jump landing task performed in the LESS, with Krosshaug et al. (2016) finding no association between a double-leg jump landing task and increased ACL injury risk in players without previous ACL injury (Krosshaug et al., 2016). Age is suggested to have an effect on LESS scores, with the number of errors decreasing as age increases (Hanzlíková, Athens, et al., 2021; Smith et al., 2012). Therefore, the findings by Padua et al. (2015) may not apply to an older cohort. Overall, the LESS has been criticised for a lack of predictive validity in a sporting context (Hanzlíková & Hébert-Losier, 2020a), likely owing to its lack of sport specificity, with further research required to improve the validity of the test.

There has been previous attempts to increase the sporting validity of the LESS by including cognitive load challenges (McWethy et al., 2025), an overhead goal (Hébert-Losier et al., 2023a), and footwear variations (Hébert-Losier et al., 2023b), all with minimal although promising effects on LESS scores and interpretation. Nonetheless, there remains strategies to potentially increase the sport specificity of injury screening tasks that have yet to be explored thoroughly in the context of the LESS.

Head turned position

One manner to potentially increase the sport specificity of the LESS is by considering how non-contact ACL injuries typically occur in a sporting scenario. In a video analysis study of 21 ACL injuries in the sport of netball, where ACL injuries are common, Belcher et al. (2022) found the position of the trunk and the head consistent with other biomechanics related to ACL injury. The most common upper body position related to ACL injury – identified in 16 of the 21 ACL injuries analysed – was players in a head turned position, between 45 and 90° at the time of injury. This position was combined with trunk rotation and flexion (sagittal or frontal) in six cases. A typical injury scenario – identified in 9 of the 21 players – involved landing from a running jump with two feet, a wide base of support, an extended knee position, ankle in dorsi-flexion, and head turned 45 to 90° away from the injured side (Belcher et al., 2022). The head turned position identified is comparable to athletes turning their head to catch a ball or look for the position of their teammates and opponents. These scenarios are presumably applicable to other team ball sports, such as basketball and handball.

In standard LESS tests, participants are given no instruction on where to look and generally look forward or at the landing area with a neutral head position. The effect of a head turned position on LESS scores has not been studied, with potential results unclear. Implementing a 45 to 90° head turned position to the LESS could increase the difficulty of the task in several ways. Firstly, visual feedback could be impacted, with participants missing important landing information, such as the position of the ground. Diminished visual feedback could reduce the participants ability to anticipate ground contact and apply safe landing techniques (Imai et al., 2025). Secondly, turning the head may also illicit a turned or rotated trunk position due and counter action-reaction torque caused by the connective facial slings and neural pathways (Critchley et al., 2020). A rotated trunk has also been connected to biomechanics related to ACL injury, such as increased landing stiffness and lateral trunk flexion (Critchley et al., 2020). Thirdly, implementing a dual tasking scenario by asking participants to focus on a gaze target and jump as high as possible could decrease the performance of both the tasks (Bourke, 1996), potentially increasing biomechanics associated with ACL injury or decreasing jump heights (Hughes & Dai, 2023).

Cognitive load in sports

An alternative method to increase sport specificity of the LESS is to enhance cognitive loads during dynamic tasks. While there are multiple ways to increase cognitive load during a jumping or cutting task, including working memory (Biese et al., 2019), arithmetic (Dai et al., 2018), reaction time (Norte et al., 2020), and decision making tasks (Almonroeder et al., 2018), each have strengths and weaknesses. Mental arithmetic tasks may not be challenging enough for some participants while many working memory and decision making tasks require visual attention, therefore changing the participants ability to perceive the environment. One cognitive loading task that shows promise that has not yet been used in combination with the LESS is auditory tone counting. Tone counting tasks have been shown to decrease performance in other sports, such as kayaking (Blakely et al., 2022), climbing (Blakely et al., 2021), and running (Blakely, Simon, et al., 2016). A recent study by McWethy et al. (2025) examined the difference between a control LESS and a LESS with number memory tasks. In one condition participants were given the numbers visually, and in the other condition numbers were given verbally. Visual based cognitive load was found to increase total LESS scores significantly, but audio based cognitive load was not (McWethy et al., 2025). There is potential that a more difficult auditory task such, as a tone counting, will illicit changes in LESS outcomes, as interference with the primary task will increase. In the dual tasking literature, increases in cognitive load have been shown to decrease jump performance (Dai et al., 2018). Hence, a decrease in jump height alongside worsening of LESS scores could be anticipated during tone counting.

Research statement

Therefore, this Thesis has two experimental chapters (**Figure 1**). Chapter Two of this Thesis compares LESS outcomes between a control LESS and a LESS performed with a head turned position. Chapter Three of this Thesis compares LESS outcomes between a control LESS and a tone-counting LESS condition. In both experimental chapters, the primary outcomes were LESS scores, risk categorisation based on a five error threshold, and the occurrence of specific LESS errors. A secondary outcome was jump height given the relevance of maximal jump heights in a sporting context.

It was hypothesised that in both chapters, introducing the head turned or tone counting task to the double-leg jump landing task would involve higher overall LESS scores, a greater number of individuals categorised at high risk of injuries, and decreased jump height compared to performing the LESS task under control conditions. We also predicted that scores would increase further in scoring items that related to landing stiffness, specifically items 12, 13, and 14. This research was inspired by real life sporting situations where ACL injuries occur, and we hypothesised that increasing the sport specificity would increase landing errors and measurable biomechanics related to ACL injury risk during the LESS.

Overall, the results from this Thesis are intended to improve the effectiveness and use of the LESS in the context of identifying individuals and populations at higher risk of ACL injury in sports. Using scenarios commonly seen in sports, the potential increased difficulty of the LESS task could increase its sport specificity and validity. The results may affect the implementation of the LESS and potentially assist in injury risk identification in large-scale prospective studies.

Chapter Two: Head Turned Experiment

Introduction

The ACL is one of the four major ligaments in the knee, and provides stability to the knee, predominantly by limiting anterior translation of the tibia relative to the femur. The ACL is vital to the knee during sporting activities, as the knee is often subject to high forces (Patton et al., 2019). These high forces often strain or rupture the ACL, and stem from non-contact mechanisms that are common during high intensity sports involving deceleration, landing, and turning (Boden & Sheehan, 2022). Unfortunately, ACL injuries are one of the most common and severe types of knee injuries in sport (Yu & Garrett, 2007), with injury incidence rates increasing over the last 20 years (Maniar et al., 2022). Surgical (Jia et al., 2024) and conservative non-surgical rehabilitation programmes improve knee function (Ahn et al., 2010; Grindem et al., 2014; Park et al., 2021), although there is no consensus on what approach is gold standard for treating ACL injuries. For both approaches require, extensive rehabilitation lasting 19 to 32 weeks, with limited sporting participation during this time (Kotsifaki et al., 2023). Unfortunately, even with surgery, one in five athletes sustain a reinjury to their ACL, either on the ipsilateral or contralateral side (Barber-Westin & Noyes, 2020).

Injury prevention programmes aim to reduce an athlete's risk of injury when participating in sport and often involving strength, plyometric, agility and balance training (Huang et al., 2020). Despite variations between the specific exercises and format of many programmes, injury prevention programmes were found to reduce injury rates by 53% (Huang et al., 2020). Programme effectiveness was strongly related with the duration, frequency, and athlete's adherence to the programme (Arundale et al., 2022). Screening for risk of injury is used alongside injury prevention programmes, usually involving athletes performing movements during which their biomechanics are observed. Screening tasks are used to identify athletes who are likely to benefit from injury prevention programmes and to assess the effectiveness of these programmes in altering biomechanics linked with ACL injury.

The Landing Error Scoring System (LESS) is a screening task used to assess landing patterns in relation to ACL injury mechanisms (Padua et al., 2009). The LESS involves performing a double-leg jump

landing task from a 30cm box to 50% of body height and jumping vertically for maximal height upon landing (Padua et al., 2009). The LESS has the benefit of requiring minimal time, space, and equipment, making it practically useful in team sports involving multiple players. The test has shown predictive value in 11 to 18 year old football players, with athletes scoring more than five errors having 10.7 times greater odds of ACL injury incidence (Padua et al., 2015) and 16 times greater risk of musculoskeletal injury (Everard et al., 2018). The LESS has, however, been criticised for lacking predictive validity of ACL injury in student athletes (Smith et al., 2012) and sport specificity to ACL and other knee injury mechanisms (Hanzlíková & Hébert-Losier, 2020a; Kristianslund & Krosshaug, 2013). In the sport of netball where ACL injury is common (Downs et al., 2021), players sustaining a non-contact ACL injury were observed to have their head turned towards their injured side at time of injury, such as when catching a ball or looking for teammates (Belcher et al., 2022). Similarly, video analysis of ACL injuries in basketball identified that players were looking at the ball, basket rim, or opponent in all but four of the 39 injuries (Krosshaug et al., 2007). The athlete's head position and where they are looking are potentially important, but overlooked, factors in ACL injury risk screening assessment.

From a biomechanical perspective, athletes focusing on heading a soccer ball during a double-leg jump landing task (Akbari et al., 2023) or a stop-jump task (Weinhandl et al., 2024) were more likely to demonstrate biomechanics consistent with ACL injury mechanisms, compared to when jumping with no ball present. These biomechanical patterns linked with ACL injuries included decreased knee flexion angle and displacement (Della Villa et al., 2020), lateral trunk flexion (Hewett & Myer, 2011), and leg stiffness (Beaulieu et al., 2023), and increased vertical ground reaction forces (Belkheili et al., 2025). Trunk rotation, presumably associated with head rotation during sporting manoeuvres, is linked to decreased knee flexion, increased ground reaction forces and increased knee abduction moments during a double-leg jump landing task (Critchley et al., 2020), and these factors have been shown to increase risk of ACL injury (Boden & Sheehan, 2022). Visual feedback is also important for motor control (Grooms et al., 2018), and reliance on visual feedback has been found to increase after ACL reconstruction (Tortoli et al., 2024). Visual feedback could be reduced safely during the LESS task by introducing a head turned aspect, as the participant will be unable to look at their landing area or lower

leg. Incorporating a head turned position during the LESS has the potential to increase its sport specificity and relevance to ACL injury mechanisms, recognising that adding complexity to the task might compromise performance (Akbari et al., 2023), here being maximal jump height.

Therefore, we aimed to compare overall LESS scores, injury risk categorisation based on a five error threshold, occurrence of specific LESS errors, and jump heights between head turned and control LESS conditions. We hypothesised that adding head rotation to the double-leg jump landing task would involve higher overall LESS scores, lead to greater number of individuals categorised at high risk of injuries, and influence specific LESS errors (items 1, 6, 11) compared to performing the LESS task without head rotation. We also anticipated lower jump heights when the head was turned.

Increasing the sport specificity of the LESS via the incorporation of a head turned position may increase the difficulty of the task and relevance to athletes. Therefore, we aimed to examine biomechanics related to non-contact ACL injury using the LESS, in a head turned position, to potentially increase the difficulty of the LESS task, in turn increasing sport specificity and validity.

Methods

Experimental approach

The study was a randomised cross-over experimental design to moderate any effect of learning or fatigue during the study. This design was used to examine the effect of the head turned condition on LESS scores, LESS risk categorisation, jump heights and differences in specific LESS errors. The condition to be completed first was randomly selected. Sample size calculations were performed *a priori* using G*Power 3.1.9.7. A standard two-tailed hypothesis with 80% power ($\beta = 0.20$), 5% significance level ($\alpha = 0.05$), and moderate effect size difference (Cohen $d = 0.50$) between conditions for paired data indicated that 34 participants were required. This effect size difference would align with a one-error LESS difference defining a clinically meaningful change (Hanzlíková, Athens, et al., 2021; Padua et al., 2009), and a 2-error standard deviation of the difference in paired means, which is reasonable based on previously published data comparing between two LESS experimental conditions (Scarneo et al., 2017).

Participants

Thirty-five participants (22 males and 13 females) were recruited from a convenience sample of healthy university students who volunteered to participate in the study. Their demographic characteristics are represented in **Table 2**. Most participants (83%) participated in sport, of which most (69%) were court or field sports (e.g., rugby, netball, hockey). Other sports included Olympic weightlifting, swimming and running. Three male and three female participants competed in their sport at national level or higher with all remaining participants ranging from recreational to regional level. All participants were free of injury, illness or conditions that may have affected their movement or landing mechanics. Participants with injuries to their lower extremity, back or pelvis regions within the last 3 months were excluded from the study. All participants signed an informed consent form prior to participating in the study, that explained the risks associated (e.g., chance of injury due to physical activity participation). The University of Waikato Human Research Ethics Committee (HREC(HECS)2023#43 approved the research project prior to data collection, which adhered to the Declaration of Helsinki.

Table 2. Demographic characteristic of participants in head turned condition.

Characteristics	Females (<i>n</i> = 13)	Males (<i>n</i> = 22)	Total (<i>n</i> = 35)
Participants			
Age (y)	19.8 ± 1.3	20.6 ± 1.9	20.3 ± 1.8
Height (cm)	167.8 ± 6.8	179.9 ± 8.2	175.4 ± 9.7
Mass (kg)	68.2 ± 10.8	81.1 ± 9.37	76.3 ± 11.6
BMI (kg/m ²)	24.1 ± 2.9	25.0 ± 1.8	24.7 ± 2.3
IPAQ (high:mod:low)	11:2:0	19:2:0 ^a	30:4:0 ^a

Notes. ^aMissing data from one participant. BMI, body mass index; IPAQ, International Physical Activity Questionnaire; mod, moderate.

Procedures

Prior to participating in the study, participants completed a standard International Physical Activity Questionnaire (IPAQ) to categorise their daily physical activity levels as low, moderate or high. All participants (100%) were categorised as having high or moderate daily activity levels. The participant's height was measured using a stadiometer (seca model 0123, Medical Measuring Systems and Scales, Mount Pleasant, South Carolina), and weight measured using piezoelectric force plates (Kistler Piezoelectric force sensor, Switzerland). The study aims were made clear to the participants prior their participation. Landing Error Scoring System testing and scoring was completed in accordance with original LESS testing protocols (Padua et al., 2009), except in the head turned condition where a gaze target was added. Participants jumped horizontally with both legs from a 30-cm high box to a distance of half their body height, before landing and jumping vertically as high as possible in one motion. In the head turned condition, participants were asked to maintain eye contact with an 'X' positioned on the wall 2 meters above and 4 metres to the right of the DLJL landing distance, resulting in the head being turned to approximately 65 to 90° during the task. The landing distance was marked on the floor using tape. Tests were invalid and not included if the participant did not land at the correct distance, jumped with one foot at a time, did not maintain balance throughout the task, or, in the head turned condition, did not maintain eye contact with the 'X (external visual focus of attention)'. Prior to completing the LESS test, participants were allowed up to three trials for familiarisation if they wished. The order of conditions was randomised, with participants completing the familiarisation and three experimental trials for one condition before moving on to the other. Three valid LESS tests were

recorded for each condition, with any invalid tests being repeated a maximum of two times. No participant completed more than five tested invalid or valid jumps in each condition. No feedback on performance was given to the participant unless the task was being performed incorrectly to avoid influencing results (Hanzlíková & Hébert-Losier, 2020b). Between trials, each participant was given up to one minute to rest, with up to five minutes rest given between conditions.

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 and eye gaze. 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 0.9.5, 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/s²), and t is the flight time (s).

Statistical analysis

The effect of the head turned condition on LESS scores, LESS risk categorisation (high risk \geq five errors, low risk $<$ five errors), jump height and differences in specific LESS errors were examined. A single rater (BA) completed all analyses after receiving training from an expert rater (KHL). The average of participants' three trials was used for analysis in line with the original LESS (Padua, 2009) and the most common method used when analysing jump height and individual LESS errors (Hanzlíková & Hébert-Losier, 2021). Differences between group LESS errors and jump heights

between head turned and control conditions were analysed using mean differences, two tailed paired t-tests and Cohens *d* effect sizes for paired samples using average variance with 95% confidence intervals. Cohens *d* effect sizes were categorised as *small*, *medium*, *large*, at 0.2, 0.5 and 0.8 respectively. A Cohen's *d* effect size of less than 0.2 was categorised as *trivial*. McNemar's test and odds ratio was used to determine statistical significance between individual LESS errors and risk categorisation. The odds ratio (OR) reflects the number of participants exclusively at high risk in one condition. Therefore, an OR of higher than one shows a higher proportion of at-risk participants in the head turned condition. Furthermore, the number of individuals that exhibited a meaningful change in LESS score (1 error or more) between conditions were counted.

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 except for when analysing individual LESS errors where Bonferroni correction was applied to account for multiple comparisons ($P \leq 0.003$), which were conducted using Microsoft Excel for Microsoft 365 MSO (version 2109, Microsoft Corp, Redmond, WA, USA).

Results

Group mean LESS scores were significantly higher in the head turned (range: 3.7 to 9.7 errors) than the control (range: 3.3 to 9.7) condition, with the mean difference of 0.4 errors being *small* (Cohen's $d = 0.27$ [0.51, 0.03]). The control and head turned conditions had 29 and 31 high risk participants respectively, with no significant difference in the odds of being categorised at risk between conditions ($P = 0.625$, *odds ratio* = 3.00 [0.312, 28.8]). One participant was at risk exclusively in the control condition, three exclusively in the head turned condition, and 28 participants in both conditions, with the remaining three at low risk in both conditions (**Figure 3**). Eighteen participants had a meaningful

change in LESS score (1 error or more) between conditions, with 13 having a meaningful increase and 5 having a meaningful decrease in the head turned compared to the control condition. Average jump heights were significantly lower in the head turned (range: 17.0 to 59.7 cm) than the control (range: 18.6 to 59.2 cm) condition, with the mean difference of 2.1 cm being *small* (Cohen's $d = 0.2$ [0.07,0.34]).

Table 3. Comparison of group level Landing Error Scoring System means, risk percentages and jump heights in control and head turned conditions.

Data are means \pm standard deviation and differences with 95% confidence intervals [lower, upper].

Outcome	Control	Head turned	Difference ¹	<i>P</i> -value
LESS score (errors)	6.4 \pm 1.4	6.8 \pm 1.5	0.4 [0.1, 0.7]	0.027 ^{†*}
High risk (%)	82.9	88.6	5.7	0.625 [‡]
Jump height (cm)	34.8 \pm 10.3	32.7 \pm 10.2	-2.1 [-3.4, -0.8]	0.002 ^{†*}

Note. ¹Difference calculated as head turned minus control. [†]*P*-value from paired t-tests and mean differences. [‡]*P*-value from McNemar's test and odds ratios. *Significant difference ($P \leq 0.05$) between conditions.

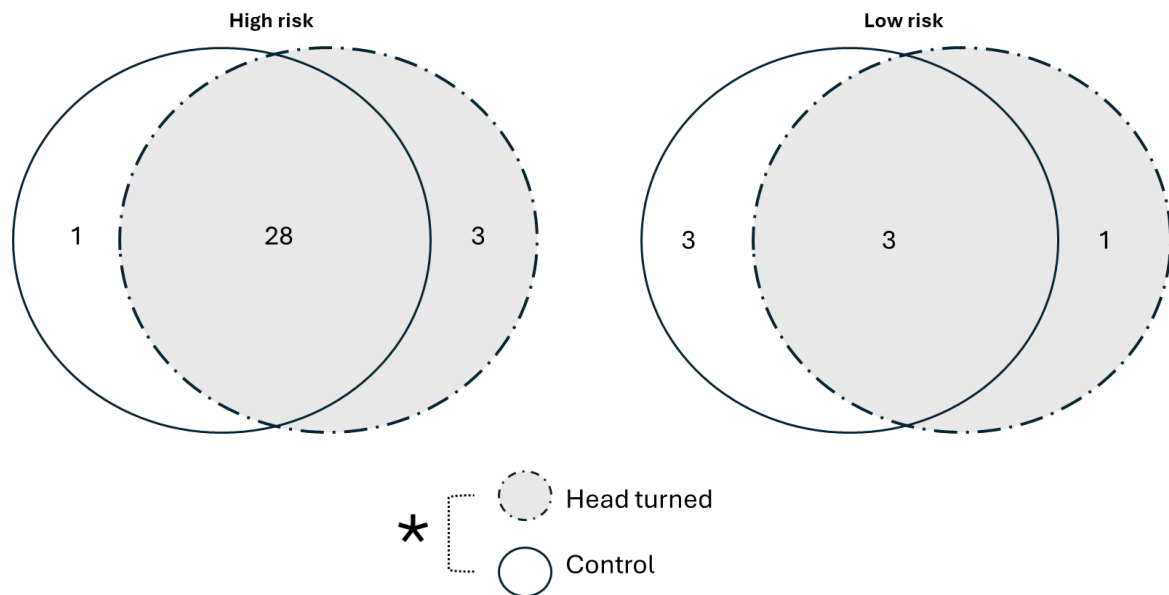


Figure 3. Venn diagrams of high risk and low risk participants in the head turned and control conditions. *Note: Venn diagrams are not to scale.*

LESS scores for specific errors are shown in **Table 4**. When considering the individual LESS errors, there was a significant difference in the occurrence of errors for two items only: item six, lateral trunk flexion at initial contact, and item seven, stance width at initial contact (wide). The percentage of participants who scored an error for item six increased by 34% ($P = 0.002$), and item seven increased by 23% ($P = 0.002$).

Table 4. Landing Error Scoring System specific errors for 35 participants in control and head turned conditions.

No.	Item	Number of errors (% participants)		Difference [§]	P-value [‡]
		Control	Head turned		
1	Knee flexion at initial contact	69%	74%	6%	0.727
2	Hip flexion at initial contact	0%	0%	0%	1.000
3	Trunk flexion at initial contact	0%	0%	0%	1.000
4	Ankle plantar flexion at initial contact	23%	23%	0%	1.000
5	Knee valgus at initial contact	66%	80%	14%	0.063
6	Lateral trunk flexion at initial contact	20%	54%	34%	0.002*
7	Stance width at initial contact (wide)	23%	46%	23%	0.002*
8	Stance width at initial contact (narrow)	29%	23%	-6%	0.688
9	Foot position (toe in)	3%	14%	11%	0.125
10	Foot position (toe out)	0%	0%	0%	1.000
11	Symmetrical foot contact at initial contact	34%	49%	14%	0.267
12	Knee flexion at maximal knee flexion	20%	9%	-11%	0.219
13	Hip flexion at maximal knee flexion	3%	0%	-3%	1.000
14	Trunk flexion at maximal knee flexion	23%	20%	-3%	1.000
15	Knee valgus displacement	83%	86%	3%	1.000
16	Joint displacement	74%	80%	6%	0.500
17	Overall impression	100%	97%	-3%	1.000

Note [§]Difference calculated as head turned minus control. [‡]P-values from McNemar's test.

*Bonferroni corrections were applied to calculate significant difference ($P \leq 0.003$).

Discussion

We examined the effect of head position on LESS performance, specifically head turned with premise of increasing the complexity and sport specificity of this injury risk screening task. Agreeing with our hypothesis, mean LESS scores were significantly greater in the head turned compared to the control condition, but the corresponding increase of 0.4 errors was *trivial* and smaller than the meaningful change threshold of one error or more (Hanzlíková, Athens, et al., 2021). Therefore, the clinical meaningfulness of this change is debatable, especially given the non-significant difference in group level risk categorisation. Also agreeing with our hypothesis, the average jump height was 2.1 cm lower in the head turned condition, with the *small* significant difference indicating compromised performance. This difference in jump height can be considered clinically meaningful because it is more than the 2 cm error usually associated with this measurement (Gallardo-Fuentes et al., 2016; Markwick et al., 2015). At an individual level, 13 of 35 participants (37.1%) had a meaningful increase (one or more) in LESS score errors under the head turned condition and five participants (14.3%) had a meaningful decrease, with the remaining 17 participants exhibiting no meaningful change between conditions. Individual risk level categorisation was inconsistent for four participants (11.4%). Overall, the data indicate no meaningful impact of head position on LESS outcomes or interpretation at a group level and, although some individuals demonstrated meaningful changes in LESS scores between conditions, individual risk categorisation is minimally affected. The interpretation of these findings should consider that most participants were already categorised at risk in the control condition based on the five error threshold previously reported (Padua et al., 2015). Furthermore, individuals who exhibited worse LESS scores during the head turned task could represent a subset of individuals who are reliant on vision and are pre-disposed to injury when in cognitively challenging environments, especially in sports that involve elements of reaction time, decision making, or dual tasking.

Incorporating a head turned aspect to the LESS task was based upon previous ACL injury research identifying a head turned position as a potential risk factor for ACL injuries and ACL injury related biomechanics (Belcher et al., 2022). We anticipated that with loss of visual cues and increased torso rotation via head turning, overall LESS performance would deteriorate, resulting in greater errors.

Although a significant increase in overall LESS errors was seen, this increase was *trivial*. More prominent differences might have surfaced between tasks should a single-leg jump be used rather than a double-leg one. For instance, a preliminary scoring template of a modified LESS has been proposed which incorporates a single-leg jump and rotation to make the task more biomechanically challenging (Hanzlíková et al., 2022). The *trivial* increase in LESS scores in the head turned condition compared to control may be due to the reliance of LESS scoring on gross observable movement rather than using more sensitive tools like 3D motion capture systems to detect change in movement. Furthermore, a large proportion of participants were at risk under the control condition. The LESS may have a ceiling effect, whereby despite the head turned condition being more complex, errors were already present and further errors were not expressed. For example, an error is present for item six when any level of lateral trunk flexion is present at initial contact. Therefore, if the amount of lateral flexion increases between conditions, this increase cannot be identified if the participant already presents an error under the control condition. In this scenario no change would be found between conditions, despite an increased level of lateral trunk flexion leading to increased injury risk.

Belcher et al (2022) performed video analysis of 21 ACL injuries sustained by elite level netball players, and found that in 16 scenarios, the athletes head was turned 45-90 degrees away from their injured knee. This upper-body positioning was the most common upper-body position in the ACL injury scenarios studied (Belcher et al., 2022). Stuelcken et al. (2016) also performed video analysis on elite netball players, and found similar injury scenarios, although also identified mid-flight trunk perturbations or lateral trunk flexion without realignment of the feet as common injury scenarios. Therefore, the LESS under a head turned condition should be relevant to ACL injury mechanisms, and result in greater errors or participants identified at high risk. The lack of meaningful difference found between the control and the head turned condition reflect results from prior studies examining variations in the LESS protocol, such as with and without footwear (Hébert-Losier et al., 2023b) or with and without an overhead goal (Hébert-Losier et al., 2023a). Collectively, these results highlight an overall lack of sensitivity of the LESS to varying conditions, especially in cohorts where a large proportion of individuals are identified at risk based on a five error threshold in the control condition.

Participants in the current study jumped on average 2.1 cm lower in the head turned condition when compared to control, which may have influenced their biomechanics (Belkhelladi et al., 2025; Ford et al., 2005). Imai et al. (2025) found increased vertical ground reaction forces and decreased hip and knee flexion when vision was reduced during a single-leg jump landing task. In both conditions, participants were asked to jump as high as possible, which is standard in LESS testing (Padua et al., 2009). Assuming that participants were jumping as high as possible, the decrease in jump height may be due to greater uncertainty and inability to see the landing area, resulting in compromised balance upon landing and decrease in subsequent force production. Perception of the environment is essential, as movement is the result of the athlete perceiving their environment and then acting in a context that is shaped by its constraints (Newell et al., 1989). Including this ecological constraints approach in injury screening and prevention research ensures that results are generalisable to wider sporting contexts (Bolt et al., 2024). A reductionist approach examines biomechanics precisely, although often misses important information about the adaptability and natural variability of human movements (Bolt et al., 2024), especially sporting environments. The use of force plates during landing would have assisted in verifying speculations movement differences, as a result of participant's decreased perception, with greater precision than via video analysis. Analysing LESS biomechanics using 3D motion capture and force plates would increase accuracy of LESS scoring (Onate et al., 2010; Padua et al., 2015), allow assessment of joint moments and biomechanical factors linked with ACL injury occurrence (Butcher et al., 2024), as well as help identify the biomechanical factors impacting jump height.

Having an external focus promotes self-organisation of motor skills, and increases movement effectiveness, such as balance, muscular activation, and force production (Wulf, 2013). Internal focus is described in the literature as focusing on the movement of one's own body, with an external focus being a focus on external cues and results. However, it is difficult to verify whether participants in the head turned or control conditions had a predominantly external or internal focus during the task, and whether their focus shifted from an internal focus during the control condition to an external focus during the head turned condition or inversely. Merely looking at a target does not eliminate the possibility of participants internally focusing on a specific aspect of their jump or body during the LESS

task. Similarly, the external visual focus used in the head turned condition is not relevant to the jumping movement, and therefore is less likely to benefit movement fluency and performance compared to an internal focus (Dai et al., 2018). Kahneman's (1973) capacity model of attention may be more suited to this context, which suggests that everyone has a limited capacity of attention that can be allocated to tasks, with attentional capacity and demands varying between individuals and tasks respectively. When attention is allocated to task relevant cues, the attention is used more effectively, and performance can be maximised. Future research could increase the visual attention and cognitive demand required during the task by using an external visual-cognitive task as the gaze target. This strategy could increase the difficulty of the head turned task by ensuring higher levels of external focus and attentional resources, potentially leading to greater changes in biomechanics and LESS scores and increasing sports specificity.

On an individual level, the effect of the head turned position had contrasting effects, with differences in mean LESS score between conditions ranging from positive two to negative two. It is possible that participants who scored higher in the head turned condition are more reliant on vision when performing challenging tasks. It is known that visual reliance increases in double and single-leg balance tasks, as well as hopping tasks, after ACL reconstruction (Tortoli et al., 2024). Despite this, there is no research to our knowledge exploring whether visual reliance is a risk factor for ACL injury. Dynamic tasks, such as the LESS, that incorporate visual constraints could be beneficial for injury prevention and rehabilitation programmes. The individuals that showed a negative change in performance are potentially those that are of greater concern, and at the highest risk of injury in a sporting scenario. Ultimately, a prospective study is required to determine the predictive value of the head turned LESS and if it has superior injury predictive value than the control LESS due to the increased visual constraint.

Item specific LESS errors remained largely unchanged, although there was a statistically significant difference in number of errors for item six, lateral trunk flexion at initial contact, and item seven, stance width at initial contact (wide), seen in **Table 4**. Lateral trunk flexion has been linked to increased ACL loading and injury risk (Della Villa et al., 2020; Song et al., 2023) and is a common functional movement in a sporting environment. Lateral trunk flexion can also shift the centre of mass, and shift the load to

predominantly one leg, increasing risk of ACL injury. (Stuelcken et al., 2016; Waldén et al., 2015). Landing with an overly wide base of support is often used in an attempt to improve lateral balance, however Belcher et al. (2022) observed during video analysis that 17 of 21 double-leg ACL injuries occurred when the participant landed with a wide base of support. Needing to control lateral trunk flexion and reduce asymmetries during jumping and landing could not only increase the sport specificity of the LESS but also increase its potential as a rehabilitation or training tool. Interestingly, lateral trunk flexion and wide stance width were not accompanied by noticeable changes in other LESS items. Participants may have compensated for the lateral trunk flexion in ways that were not detected by the LESS, such as increased force production on the loaded side, or increased ground contact time. Performing LESS tests, with and without a head turned aspect, could be used in injury rehabilitation or neuromuscular training programmes to provide different stimulus and to identify improvements or compensations in jump-landing biomechanics. Further research is required into the effect of the head turned position on specific biomechanics related to ACL injury to further verify its use as a rehabilitation exercise, return to play test, or musculoskeletal training tool.

Limitations

There are limitations to the current study, most notably that gaze behaviour was not reliably measured during the head turned condition. Participants were asked to look at the mark on the wall, and this stimulus was sufficient to elicit a head turned position and show slight differences between conditions. Despite the limited gaze behaviour, the validity of the head turned aspect is low, as the participants could have looked at other factors of the environment for further visual information, such as position of the landing platform. Monitoring gaze behaviour, using eye tracking technology or a visual task, would ensure validity and reliability between participants in future studies. Another limitation during the head turned condition was only performing the task looking to the right hand side and therefore there is a missed opportunity to examine imbalances and asymmetries that may have been found if the test was completed with participants looking to both sides. Many sports, especially field and court sports, involve rotating the body and turning the head in both directions. Although practicality would

slightly reduce, performing the head turned condition for both sides to examine asymmetries would be more sport specific, and could be an area for future research.

Greater differences between control and head turned conditions may have surfaced in a cohort of participants with lower LESS scores during the control condition. Group mean LESS scores in the control condition were 6.4 ± 1.4 , higher than comparable studies (Hanzlíková & Hébert-Losier, 2020a). Hanzlíková and Hébert-Losier (2020a) completed a systematic review containing nine moderate to strong quality LESS studies with varying populations to examine LESS reliability. This review's weighted mean LESS score was 5.2 ± 1.7 errors, with only one study (Beese et al., 2015) reporting group mean LESS scores of higher than 6.4, although these participants had an average age of 15.2 ± 1.2 years, more than 5 years younger than ours (20.3 ± 1.8 years). A study with a similar methodology, sample population and comparable participant information (age: 20.0 ± 2.3 , height: 175 ± 9.1 , mass: 77.1 ± 17.6 , IPAQ: 56:19:2) reported similar LESS scores (6.2 ± 1.5) and high risk percentage (77.5%), suggesting the high LESS scores are a result of the sample population (Hébert-Losier et al., 2023b). Although the current studies' participants were all physically active (IPAQ: 30:4:0), with 83% of participants involved in sport, the level of sporting participation was low. Only three male and three female participants competed in their sport at national level or higher with all remaining participants ranging from recreational to regional level, participating once or more a week. A large amount of LESS research is performed on high level athletes, as this provides the most reliable population for research, and is valuable for sporting organisations and teams. This small difference in LESS scores between the control and head turn conditions would result in a bigger difference of risk categorisation if control scores were lower. Further research using a head turned LESS with higher level athletes may demonstrate greater differences in LESS scores and justify the use of a head turned LESS in an elite and professional level sporting environment.

Conclusion

Overall, performing the LESS with and without a head turned position had a clinically significant difference on jump heights and group mean LESS scores, with *small* effect sizes, although 13 participants had a meaningful increase in LESS score. The only individual LESS items significantly

affected by the head turned condition were item six, lateral trunk flexion at initial contact, and item seven, wide stance width at initial contact, and there was no significant difference between individual level risk categorisations. Performing the LESS with a head turned position is deemed to increase the difficulty of the task and increase sport specificity. Hence, the LESS with a head turned position may be useful for injury risk screening and rehabilitation from injury, to identify individuals with potential predisposed risk of injury in a head turned condition due to high visual reliance. It is important to note that the reliability of the LESS to predict ACL injuries with a head turned condition included in the task has not been assessed. Further research is required to identify reliability of the LESS when including the head turned condition before this can be implemented into clinical and practical settings.

Chapter Three: Tone Counting Experiment

Introduction

Anterior cruciate ligament (ACL) injuries are common and serious injuries in sport, despite many being non-contact in nature and considered largely preventable with appropriate injury risk screening and injury risk reduction tasks (Arundale et al., 2022). Unfortunately, there is no gold standard ACL injury risk screening task, with several current tasks criticised for the lack of cognition required to complete the task (Gokeler et al., 2021). ACL injury risk screening task's environments and tasks are critiqued as being too standardised and not reflective of usual sporting environments (Bolt et al., 2024). During sports, athletes must process multiple different external stimuli to make decisions, often with time pressure, while still performing the required skill successfully and safely. An effective injury risk screening task should aim to recreate these challenges in a standardised environment and implement them effectively in a clinical setting.

The Landing Error Scoring System (LESS) is one of the most commonly used ACL injury risk screening tasks (Hanzlíková & Hébert-Losier, 2020a), which involves participants jumping from a 30 cm box with both feet to 50% of their body height, then immediately rebounding upwards for maximal vertical height. The task is recorded using two video cameras and scored against seventeen scoring criteria, with scores of five or more showing a greatly increased risk of ACL injury (Padua et al., 2015). Although this task was initially shown to present predictive value for ACL injury in elite youth soccer athletes (Smith et al., 2012), subsequent studies have failed to confirm the LESS's predictive value. Without a cognitive task to complete during the LESS, athletes predisposed to injury under cognitively challenging conditions may not be identified (Avedesian et al., 2022). Considering only how an athlete moves, without addressing the environment the player inhabits is overly reductionistic as it neglects key information about the athlete-environment relationship, such as perception and decision making (Bolt et al., 2024). It is therefore important that the LESS, and other injury risk screening tasks, include an element of cognitive challenge to attempt to recreate the complex athlete-environment relationship of sports and more accurately predict each athlete's risk of injury.

Literature exploring the relation between cognition and musculoskeletal injuries is still relatively sparse, but the literature generally identifies that decreased cognitive performance is linked to musculoskeletal injuries (Avedesian et al., 2022). Much of the traditional cognitive load literature is based on balance, gait, and postural control tasks in injured or elderly populations, although cognitive load is now also being implemented in injury reduction and rehabilitation research (Almonroeder et al., 2018; Biese et al., 2019; Dai et al., 2018; Gokeler et al., 2025; Hughes & Dai, 2023; McWethy et al., 2025). A traditional way to increase cognitive load is to complete a secondary or dual task in combination with the primary task (Sweller et al., 2011). This secondary task is often a decision making, memory, or reactive task (Sweller et al., 2011), such as counting backwards in sevens (Dai et al., 2018), counting the number of high and low pitched audio tones (Blakely et al., 2021), and remembering the order of colours played on a screen (i.e., Stroop colour word test) (Biese et al., 2019). Based on the capacity model of attention proposed by Kahneman (1973), the total amount of attention a person can deploy at any one time is limited, and therefore higher cognitive load due to a secondary task can reduce performance of the primary task and vice-versa (Wickens et al., 2021). Kahneman's (1973) model of attention is a capacity limited model, whereby each person's ability to process information is limited by the capacity of the wider mental resources of the brain (Kuchinsky et al, 2024). In contrast, structural bottleneck models of attention suggest that specific parts of the information processing chain may limit processing ability, such as the ability to perceive the information with the eyes, process the information in the brain, or act on the information with the nervous system (Kuchinsky et al, 2024). Information can be obtained through visual, auditory or haptic cues, and retained in the working memory for a short period of time (Kimura et al., 2017). Working memory consists of an active storage component and a processing component that allows information to be processed to perform a given task (Baddeley, 1992). Research has shown that performing a secondary task with a jumping task reduces the performance of both the jumping and secondary task (Dai et al., 2018).

Non-contact ACL injuries often occur when an athlete's attention is focused on the opponents, the ball, or the goal based on video analysis (Belcher et al., 2022; Krosshaug et al., 2007). These video analyses justify the potential benefit of incorporating a dual task in clinical settings when assessing or

rehabilitating sports movements to recreate the attentional component of the athlete-environment relationship. Much of the previous dual tasking research in the ACL injury space has been completed using visual cognitive loading (Hughes & Dai, 2023) as it is the most practical. However, an alternative manner to load cognition is auditory tone counting, and this type of loading may impact movement differently. Tone counting tasks have been used in previous research with other exercise modalities such as running to measure the cost of cognition to the athlete's ability (Blakely, Simon, et al., 2016; Blakely, Wilson, et al., 2016), finding that increased cognitive load decreased running speed. Tone counting performance decreases when dual tasking with complex movements, such as kayaking and climbing, as athletes prioritise maintaining movement quality over the secondary tone counting task (Blakely et al., 2021; Blakely et al., 2022).

Specifically in the context of the LESS, a recent study found that performing a visual number memory secondary task increased LESS errors, but performing an auditory number memory secondary task did not (McWethy et al., 2025). These findings suggest that introducing a secondary task to the LESS, specifically one that is visual-based, can increase the overall difficulty of the double-leg jump landing movement, its sport specificity, and its potential value in injury risk screening. Whether an auditory task creates similar cognitive demands to a visual task, and therefore has a similar impact on LESS performance metrics, has not been demonstrated.

Therefore, we aimed to compare overall LESS scores, injury risk categorisation based on a five error threshold, occurrence of specific LESS errors, and jump heights between a control LESS condition and a LESS including an auditory tone counting task. We hypothesised that introducing a tone counting task to the double-leg jump landing task would involve higher overall LESS scores, lead to greater number of individuals categorised at high risk of injuries, and decreased jump heights when compared to performing the LESS task under control conditions. We also predicted that scores would increase further increase in scoring items that related to landing stiffness, specifically items 12, 13 and 14. The potential increased difficulty of the LESS task would increase sport specificity and validity.

Methods

Experimental approach

The study was a randomised cross-over experimental design to moderate any effect of learning or fatigue during the study. This design was used to examine the effect of the tone counting condition on LESS scores, LESS risk categorisation, jump heights and differences in specific LESS errors. The condition to be completed first was randomly selected. Sample size calculations were performed *a priori* using G*Power 3.1.9.7. A standard two-tailed hypothesis with 80% power ($\beta = 0.20$), 5% significance level ($\alpha = 0.05$), and moderate effect size difference (Cohen $d = 0.50$) between conditions for paired data indicated that 34 participants were required. This effect size difference would align with a one-error LESS difference defining a clinically meaningful change (Hanzlíková, Athens, et al., 2021; Padua et al., 2009), and a 2-error standard deviation of the difference in paired means, which is reasonable based on previously published data comparing between two LESS experimental conditions (Scarneo et al., 2017).

Participants

Forty-one participants (20 males, 19 females, and 2 others) were recruited from a convenience sample of healthy university students who volunteered to participate in the study. Their demographic characteristics are represented in **Table 5**. All participants (100%) participated in sport, of which almost half (49%) were court or field sports (e.g., rugby, netball, hockey). Other sports included Olympic weightlifting, swimming and running. Ten participants (4M, 5F, 1O) competed in their sport at national level or higher with all remaining participants ranging from recreational to regional level. All participants were free of injury, illness or conditions that may have affected their movement or landing mechanics. Participants with injuries to their lower extremity, back or pelvis regions within the last 3 months were excluded from the study. All participants signed an informed consent form prior to participating in the study, that explained the risks associated (e.g., chance of injury due to physical activity participation).

The University of Waikato Human Research Ethics Committee (HREC(HECS)2023#43) approved the research project prior to data collection, which adhered to the Declaration of Helsinki.

Table 5. Demographic characteristic of participants in tone counting condition.

Characteristics	Females ($n = 19$)	Males ($n = 20$)	Other ($n = 2$)	Total ($n = 41$)
Participants				
Age (y)	20.7 ± 4.0	20.1 ± 4.0	18.4 ± 0.0	20.3 ± 3.07
Height (cm)	168.5 ± 6.5	183.2 ± 5.8	166.5 ± 0.7	175.5 ± 9.6
Mass (kg)	69.9 ± 9.6	81.6 ± 12.9	64.0 ± 2.1	75.8 ± 12.1
BMI (kg/m ²)	24.7 ± 3.7	24.2 ± 3.3	23.1 ± 0.9	24.5 ± 2.9
IPAQ (high:mod:low)	15:2:1 ^a	18:0:1 ^a	2:0:0	35:2:2 ^b

Notes. ^aMissing data from one participant. ^bMissing data from two participants. BMI, body mass index; IPAQ, International Physical Activity Questionnaire; mod, moderate.

Procedures

Prior to participating in the study, participants completed a standard International Physical Activity Questionnaire (IPAQ) to categorise their daily physical activity levels as low, moderate or high. Most participants (85%) were categorised as having high daily activity levels. The participant's height was measured using a stadiometer (seca model 0123, Medical Measuring Systems and Scales, Mount Pleasant, South Carolina), and their weight was measured using piezoelectric force plates (Kistler Piezoelectric force sensor, Switzerland). The study aims were made clear to the participants prior to their participation. LESS testing and scoring was completed in accordance with original LESS testing protocols (Padua et al., 2009) for the control condition. The tone counting cognitive task was included in the tone counting condition but not the control. In both conditions participants jumped horizontally with both legs from a 30-cm high box to a distance of half their body height marked on the floor using tape, before landing with both feet and jumping vertically as high as possible in one motion. In the tone counting condition, participants were asked to mentally count a random series of high and low pitched tones during the double-leg jump landing task and repeat the number of each to the scorer after completing each trial. A tone was played each second with a duration of one second and a 1:1 ratio of high and low pitched tones. Tone counting began prior to the jump, with four to six tones being delivered. The researcher would instruct "jump", at which time participants initiated their double-leg

jump-landing task. Tones were stopped after participants completed the LESS, and participants were asked to relay the number of high and low pitched tones to the experimenter. An average of eight to ten tones were delivered per jump. Tests were repeated if the participant did not reach the 50% of body height landing distance, jumped with one foot at a time, or did not maintain balance throughout the task. Prior to completing the LESS test, participants were allowed up to three trials for familiarisation if they wished. The order of conditions was randomised, with participants completing the familiarisation and three experimental trials for one condition before moving on to the other. Three valid LESS tests were recorded for each condition, with any invalid tests being repeated a maximum of two times. No participant completed more than five tested invalid or valid jumps in each condition. No feedback on performance was given to the participant unless the task was being performed incorrectly to avoid influencing results (Hanzlíková & Hébert-Losier, 2020b). Between trials, each participant was given up to one minute to rest, with up to five minutes rest given between conditions.

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 and eye gaze. 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 0.9.5, 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/s²), and t is the flight time (s)

Statistical analysis

The effect of the tone counting condition on LESS scores, LESS risk categorisation (high risk: LESS \geq five errors, low risk: LESS < five errors), jump height and differences in specific LESS errors were examined. The average of each participant's three trials were used when analysing jump height and individual LESS errors, to reflect the participants average performance of the LESS. A single rater (BA) completed all analyses after receiving training from an expert rater (KHL). The average of participants' three trials was used for analysis in line with the original LESS (Padua, 2009) and the most common method used when analysing jump height and individual LESS errors (Hanzlíková & Hébert-Losier, 2021). Differences between group LESS errors and jump heights between tone counting and control conditions were analysed using mean differences, two tailed paired t-tests and Cohens *d* effect sizes for paired samples using average variance with 95% confidence intervals. Cohens *d* effect sizes were categorised as *small*, *medium*, *large*, at 0.2, 0.5 and 0.8 respectively. A Cohen's *d* effect size of less than 0.2 was categorised as *trivial*. McNemar's test and odds ratio was used to determine statistical significance between individual LESS errors and risk categorisation. The odds ratio (OR) reflects the number of participants exclusively at high risk in one condition. Therefore, an OR of higher than one shows a higher proportion of at-risk participants in the tone counting condition. Furthermore, the number of individuals that exhibited a meaningful change in LESS score (1 error or more) between conditions was counted.

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 or more 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 except for when analysing individual LESS errors where Bonferroni correction was applied to account for multiple comparisons ($P \leq 0.003$), which were conducted using Microsoft Excel for Microsoft 365 MSO (version 2109, Microsoft Corp, Redmond, WA, USA).

Results

LESS score outcomes are reported in **Table 6** for both control and tone counting conditions. Group mean LESS scores were not significantly different between the tone counting (range: 1.7 to 9.3 errors) and control (range: 2.7 to 9.3 errors) conditions, with the mean difference of -0.2 errors being *trivial* (Cohen's $d = 0.13$ [-0.09, 0.34]). The control and tone counting conditions both had 35 high risk participants (85.4%), with no significant difference in the odds of being categorised at risk between conditions ($P = 1.000$, *odds ratio* = 1.00 [0.20, 4.95]). Three participants were at risk exclusively in the control condition, three exclusively in the tone counting condition, 32 at risk in both conditions, and the remaining three at low risk in both conditions (**Figure 4**). Ten participants had a meaningful change in LESS score (1 error or more) between conditions, with four having a meaningful increase, and six a meaningful decrease in the tone counting compared to the control condition. Average jump heights were significantly lower in the tone counting (range: 13.5 to 50.6 cm) than the control (range: 17.6 to 51.0 cm) condition, with the mean difference of -4.2 cm being *small* (Cohen's $d = 0.48$ [0.30, 0.66]).

Table 6. Comparison of group level Landing Error Scoring System means, risk percentages and jump heights in control and tone counting conditions. Data are means \pm standard deviation and differences with 95% confidence intervals [lower, upper].

Outcome	Control	Tone Counting	Difference ¹	P-value
LESS score (errors)	6.2 \pm 1.5	6.0 \pm 1.3	-0.2 [-0.5, 0.1]	0.255 [†]
High risk (%)	85.4	85.4	0.0	1.000 [‡]
Jump height (cm)	32.0 \pm 8.6	27.8 \pm 8.8	-4.2 [-2.9, -5.5]	≤ 0.001 ^{†*}

Note. ¹Difference calculated as tone counting minus control. [†] P-value from paired t-tests and mean differences. [‡] P-value from McNemar's test and odds ratios. *Significant difference ($P \leq 0.05$) between conditions.

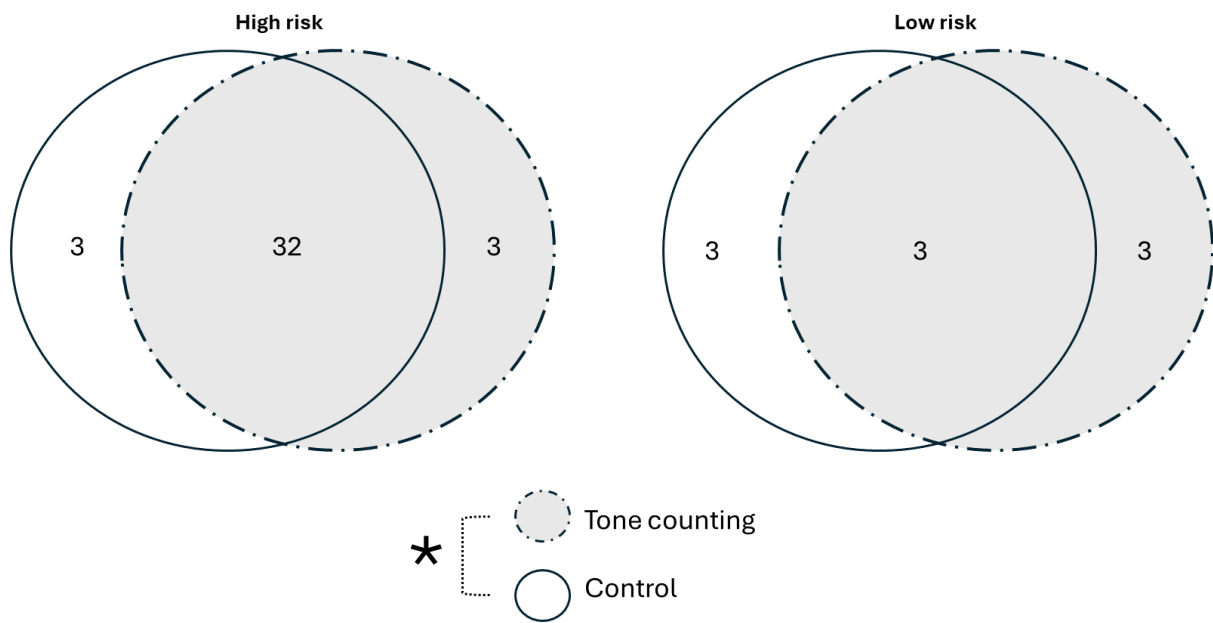


Figure 4. Venn diagrams of high risk and low risk participants in the tone counting and control conditions. *Note: Venn diagrams are not to scale.*

Item specific LESS scores are displayed in **Table 7** for both control and tone counting conditions. When considering the individual LESS items' scores, there was no significant difference in the occurrence of errors for any items. The largest percentage differences were observed for item 5 (knee valgus at initial contact), and item 11 (symmetrical foot contact), with the frequency of errors decreasing approximately 7% and 12% respectively.

Table 7. Landing Error Scoring System specific errors for 41 participants in control and tone counting conditions.

No.	Item	Number of errors (% participants)		Difference [§]	P-value [‡]
		Control	Tone counting		
1	Knee flexion at initial contact	80%	85%	5%	0.727
2	Hip flexion at initial contact	0%	0%	0%	1.000
3	Trunk flexion at initial contact	0%	0%	0%	1.000
4	Ankle plantar flexion at initial contact	17%	20%	2%	1.000
5	Knee valgus at initial contact	78%	71%	-7%	0.453
6	Lateral trunk flexion at initial contact	12%	7%	5%	0.687
7	Stance width at initial contact (wide)	2%	2%	0%	1.000
8	Stance width at initial contact (narrow)	54%	56%	2%	1.000
9	Foot position (toe in)	51%	59%	7%	0.549
10	Foot position (toe out)	0%	0%	0%	1.000
11	Symmetrical foot contact at initial contact	44%	32%	-12%	0.332
12	Knee flexion at maximal knee flexion	7%	5%	-2%	1.000
13	Hip flexion at maximal knee flexion	0%	0%	0%	1.000
14	Trunk flexion at maximal knee flexion	7%	10%	2%	1.000
15	Knee valgus displacement	80%	76%	-5%	0.625
16	Joint displacement	71%	63%	-7%	0.549
17	Overall impression	98%	98%	0%	1.000

Note [§]Difference calculated as tone counting minus control. [‡]P-values from McNemar's test. Bonferroni corrections were applied to calculate significant difference ($P \leq 0.003$).

Discussion

We examined the effect of cognitive load on LESS performance, specifically increased cognitive load using a tone counting task, with the intention of augmenting the complexity of the task to enhance sporting validity. In contrast to our hypothesis, inclusion of the tone counting task had no significant effect on overall LESS scores. There was also no significant difference in group level risk categorisation based on a five error threshold, with 35 participants (85%) having the same risk profile in both conditions. Overall, our results suggest no meaningful change in LESS performance and interpretation when adding a tone counting task to the LESS at a group level. However, although overall scores and

risk categorisation did not significantly change, it is possible that jump-landing biomechanics at a more granular level were different between conditions, but the LESS is not able to identify these changes as only gross movements are assessed. At an individual level, risk categorisation changed in six individuals (15%), with half of them being at risk in the control condition only and the other half in the tone counting condition only. It is possible that these six individuals are more susceptible to changes in their environment and task constraints and would benefit from varying the cognitive load challenges during standard training and rehabilitation. In terms of the secondary performance outcomes, agreeing with our hypothesis, jump heights decreased significantly with tone counting, with the mean decrease of 4.2 cm considered clinically meaningful as more than the 2.0 cm test-retest error usually associated with this measurement (Gallardo-Fuentes et al., 2016; Markwick et al., 2015). Jump height is not systematically recorded during LESS performance, although provides potential insight on athletic performance given that maximal vertical jump heights are linked to key performance indicators in sports such as sprinting (He et al., 2025; Washif & Kok, 2022). The decrease in jumping performance observed indicates the tone counting task did increase the cognitive load during the LESS, and therefore performance is decreased when a tone counting task is present.

Performing the LESS with the inclusion of a tone counting task was based on previous research demonstrating that injuries are more likely in cognitively challenging environments (Almonroeder et al., 2018; Gokeler et al., 2021). Research has also shown that increasing cognitive load in a jump landing task increases landing stiffness and movement patterns related to increased ACL strain (Almonroeder et al., 2020). On the basis of increased ACL strain under cognitive load, we hypothesised that introducing tone counting to the double-leg jump landing task would increase overall LESS scores, especially in items relating to landing stiffness, such as items 1, 2, 4, and 16 (**Table 7**). However, overall LESS scores and the occurrence of specific errors did not significantly change between tasks, which may be due to how the tone counting task was implemented in terms of speed, duration, and timing, potentially not challenging participants in a manner that alters their biomechanics during the task.

Auditory tone counting tasks are infrequently used in combination with discrete sporting movements, and more commonly used with cyclical movements, such as in running (Blakely, Simon, et al., 2016;

Blakely, Wilson, et al., 2016) or kayaking (Blakely et al., 2021). Cyclic movements tend to be slower in nature, with the addition of tone counting requiring sustained mental attention to correctly identify tones. However, the double-leg jump landing task of the LESS is discrete and fast, taking roughly 1.2 seconds to complete. Given the short timeframe, participants heard no more than two tones during the jumping portion of the task, allowing them to momentarily focus on jumping instead of tone counting, subsequently guessing the missed tones. These switches of attention between jumping and counting tasks, and movement task prioritisation may explain the lack of significant difference in LESS scores between conditions, as participants can prioritise each task individually. Task prioritisation occurs when two tasks occur simultaneously, and one task is more important to the individual than the other, often resulting in a decrease in performance in the unprioritised task (Wickens et al., 2021). Secondary tasks, such as mathematics and tone counting, are not given priority when used in combination with movement tasks, especially movements involving injury risk, such as climbing (Blakely et al., 2023) or jumping from a height. Therefore, a tone counting task may not be useful to increase cognitive load during a short dynamic task like jumping. Blakely et al. (2021) used two different difficulty levels of a tone counting task, count one of three pitched tones (low load) and count all three pitched tones (high load), finding that increased cognitive load increased interference and decreased performance of the movement task. Increasing the frequency or number of different tones may increase interference, resulting in greater differences in LESS outcomes than were observed in our study. Future research may also record the accuracy of each participant's secondary task, to evaluate how effectively the participant could perform both aspects of the dual task. The correlation between low accuracy in the secondary task could then be connected to LESS outcomes, to determine if higher prioritisation of the primary task reduced the dual tasking effects from the secondary task

Furthermore, the frequency of the tone counting task was the same across participants, which does not account for different levels of baseline cognitive ability. Kahneman's (1973) capacity model of attention explains that there is a limit to each individual's capacity to perform mental work, with different activities using different amounts of attentional resources. When demand on one task increases, more of the individual's attentional capacity is used, decreasing their ability to perform dual tasks. Each

individual has a different capacity of attention, therefore, increasing or decreasing the difficulty of the secondary task, based on their baseline cognitive ability, could ensure that each individual is challenged equally. Previous research has found that lower levels of baseline neurocognitive ability correlate to higher rates of knee kinematics related to ACL injury (Herman & Barth, 2016). Future research may seek to explore whether individualising the level of cognitive challenge is beneficial for injury risk screening purposes, ensuring that each individual is cognitively challenged to the same extent.

Strengths

A benefit of using tone counting to increase cognitive load is that tone counting does not rely on vision, allowing participants to use their vision during the task as they would normally. Therefore, any differences seen between a control and experimental tone counting task are more likely to result from changes in cognitive load rather than changes in visual constraint. For example, cognitive load tasks that involve visual cues, such as the Stroop colour word test (Biese et al., 2019), limit the participants' ability to perceive their environments, like the position of the ground, and therefore limit their ability to perform the alternate movement task effectively. Our findings of no significant difference in LESS outcomes between control and tone counting conditions agree with those recently reported elsewhere whereby a number memory secondary task did not influence LESS scores, but a visual one did (McWethy et al., 2025). Visual occlusion or changes in visual attention during a landing task can hinder balance and safe landing biomechanics (Imai et al., 2025). Therefore, when a visual based task is used, LESS errors may increase as a result of increased visual constraint, rather than increased cognitive load (Almonroeder et al., 2018).

The tone counting secondary task included in this condition is not directly relevant to the double-leg jump landing task, which is important in the context of internal and external focus. Historically, allocating attention to external task relevant cues, such as sounds or the position of objects, can benefit jump landing mechanics and motor performance (Lohse et al., 2014; Wulf et al., 2010). However, when performing the tone counting task during the LESS, the tone counting task is not relevant to the double-leg jump landing movement, and therefore performance of the LESS task should not increase as a result of the participants external focus of attention on the auditory tones.

Supporting this, jump performance in the tone counting condition meaningfully decreased with the addition of the tone counting task. This decrease reflects that at least some attentional resources were dedicated to the tone counting task rather than solely to the jump-landing task. Similarly, Dai et al. (2018) used a counting backwards task during a jump landing movement and found significant decreased jump heights. Although mean LESS scores did not differ, decreased jump heights show a decrease in athletic performance during dual tasking scenarios, which may have a corresponding effect on injury risk.

Limitations

Pre-programming movements has long been used as a strategy in sports to enhance focus, reduce anxiety, and improve movement patterns (Cotterill, 2010). Englander et al. (2019) suggests that when a landing can be pre-planned, an athlete may be able to anticipate ground contact and increase their knee flexion as a protective mechanism to reduce injury risk. Pre-planning movements usually occurs in anticipated scenarios, where the athlete can focus solely on the movement task. In the tone counting condition, participants were asked to focus on counting tones even before jumping, and were told to jump at an unanticipated time, reducing the chance of participants pre-programming movements. This reduction in pre-planning could be valuable in injury risk screening tasks such as the LESS, because sporting injuries most commonly occur during reactionary scenarios, where the athlete does not have the attentional resources available to pre-planning movements (Wilkerson, 2012). A systematic review concluded that tasks that do not allow participants to pre-plan their movements promote knee mechanics consistent with increased risk of injury (Almonroeder et al., 2015). That said, the LESS task potentially does not require much pre-programming for successful execution given the phylogenetic nature of the task. Previous research has identified a lack of association between LESS scores and movement specific reinvestment, this finding could be due to the phylogenetic nature of the LESS task and general low-pressure testing environment (Hanzlíková, Masters, et al., 2021). Unlike ontogenetic tasks, which require people to learn them, phylogenetic tasks (such as jumping) typically can be performed by anyone who is healthy, with minimal conscious processing (Poolton et al., 2007). Therefore, a lack of pre-planning can exert a minimal effect on phylogenetic task

performance (Poolton et al., 2007), such as the double-leg jump landing task involved in the LESS. In contrast, ontogenetic tasks require more cueing and attentional resources, and are therefore more susceptible to disruption (Poolton et al., 2007). Using tone counting during a more ontogenetic task, such as sidestep cutting (Almonroeder et al., 2015), or a single-leg LESS task (Hanzlíková et al., 2022) may create greater changes in gross movement due to interfering with pre-planning of the movement. Further detailed biomechanical analyses of the jump-landing tasks via 3D motion capture, force plate, electromyography (EMG) or inertial measurement units (IMU's) might have revealed different movement patterns and changes than possible using 2D video analysis.

A considerable proportion of participants (85.4%) were categorised at high risk of injury in the control LESS condition based on a five error threshold, which presents as a key limitation of the tone counting experiment. Therefore, there may exist a ceiling effect whereby further challenging individuals does not lead to increasing errors and cannot shift injury risk. Our mean score of 6.2 errors is nonetheless consistent with previous studies conducted on similar population groups, reporting means of 5.6 (Hanzlíková & Hébert-Losier, 2021), 6.6 (Hanzlíková & Hébert-Losier, 2020b) and 6.9 (Garbenyté-Apolinskienė et al., 2018). Individuals who present lower LESS errors at baseline and are generally more proficient at executing the task may show greater biomechanical changes with the addition of cognitive loading. The five error threshold used in this study to categorise ACL and musculoskeletal injury risk, originally derived from young elite soccer players (13.9 ± 1.8 years) (Padua et al., 2015) is a further limitation. A five error high risk threshold may not apply to our young adult population (20.3 ± 3.1 years) involved in a range of sport, aligning with findings from Smith et al. (2012) where a five error threshold did not predict incidence of non-contact ACL injuries in young adults (age = 18.3 ± 2.0).

Another consideration is that success rates for the tone counting task was not actively monitored as secondary outcome, although anecdotally, the correct identification of low and high pitches was infrequent (i.e., less than 5% of jumps). These figures suggest that participants did not allocate sufficient attentional to the tone counting task for its successful completion. Furthermore, the audibility of tones was sometimes compromised when emitted at the same time as participants landed. It is possible that LESS scores and jump height would be further compromised should the tone counting task be

prioritised over the landing task and the successful identification of tones be a requirement for completion. Future studies with such requirements would ensure further differentiation between control and experimental conditions.

Conclusion

Overall, performing the LESS with secondary tone counting task significantly decreased jump heights with a *small* effect size difference compared to completing the LESS without the secondary task, corroborating an increased cognitive load during testing that impaired jump performance. However, there was no significant difference in group mean LESS scores, group level risk categorisation, and occurrence of individual LESS errors potentially due to that lack of sensitivity of the LESS to identify small changes in biomechanics or ineffectiveness of tone counting to divert attentional resources during a discrete, rapid movement. Despite the limited change in LESS scores we observed, the addition of tone counting during a double-leg jump landing task may still be useful in training and for rehabilitation to alter task constraints. It may also benefit individuals more susceptible to changes in movements when their environment or task constraints are altered.

Chapter Four: Final Chapter

Summary

This Thesis on the LESS had two main aims. First, it aimed to examine the effect of a turned head position on the LESS; and second, to examine the effect of increased cognitive load via tone counting on the LESS. In Chapter Two, a study was conducted to examine the impact of a head turned position on LESS scores, risk categorisation, specific LESS errors, and jump heights. In agreement with the hypothesis, LESS errors increased significantly with a *small* effect size, jump heights decreased with a *small* effect size, and occurrence of specific LESS errors (item 6 and item 7) increased significantly by 34% and 23%, respectively. Thirteen of the 35 participants' LESS scores increased by one or more error, which is deemed to reflect a meaningful increase (Padua et al., 2009). However, the number of participants categorised at high or low risk based on a five error risk threshold was not significantly different between conditions. Overall, it appears that performing the LESS with a head turned position has the potential to increase the complexity of the double-leg jump landing task primarily due to participants not looking at the landing area. This increased challenge has possible implications in neuromuscular training programmes or return to sport protocols to solicit different adaptations and landing strategies. However, in clinical practice, performing the LESS without the head turned position is still recommended because the ability for the head turned LESS to predict ACL or musculoskeletal injury has not yet been studied.

In Chapter Three a study was conducted to examine the impact of a tone counting task on LESS scores, risk categorisation, specific LESS errors, and jump heights. Disagreeing with the hypothesis, overall LESS scores did not significantly increase, with no significant difference between the two conditions. There were also no significant differences in the occurrence of specific LESS errors or in group level risk categorisation based on a five error risk threshold, with six participants having a meaningful decrease in LESS scores and four having a meaningful increase (Padua et al., 2009). However, jump heights decreased significantly between conditions with a *small* effect size, suggesting that there was a dual task cost associated with the tone counting task. However, in a clinical setting, the standard LESS

test is still recommended, as the predictive ability of the LESS with a tone counting condition has not been established. Regardless of the similar results between control and tone counting conditions, including a tone counting task to the LESS demonstrates future potential in a clinical setting as a manner of identifying specific individuals at particularly higher risk of ACL injury during cognitively demanding scenarios. Further research is required to identify the most valid and reliable method of increasing cognitive load during the double-leg jump landing task, as well as the predictive ability of the LESS with a tone counting task in terms of ACL and musculoskeletal injury.

Practical implications

The LESS remains a relevant tool for practitioners and coaches to use in the field, with or without modifications to increase sport specificity. The head turned and the tone counting condition can each be implemented into the double-leg jump landing task without drastically increasing costs or time requirements. The LESS requires minimal equipment, is easy to set up, can be performed outdoors, and can be used to assess many participants quickly, making it practical for use in sports teams and larger groups. Although three-dimensional motion capture is more accurate than two-dimensional video analysis, the costs associated with the former are often a limiting factor to assess movement. Therefore, screening tasks like the LESS remain in use by practitioners and coaches.

The results from this Thesis imply that incorporating dual tasking conditions, such as a head turned position or a tone counting task, to mimic sport specific scenarios, increased LESS scores and could therefore be useful in training and rehabilitation settings. Increased LESS errors in the head turned condition suggests a reduction in safe landing mechanics and shows potential for use in injury prevention programmes and injury rehabilitation. Teaching athletes to land safely during these tasks, such as increasing knee flexion and rotating their entire body during landing, may assist in preventing ACL injuries. Decreased jump heights during the tone counting condition suggests that the increased cognitive load limited athletic performance, with tone counting challenging athletes. Training programmes and injury rehabilitation exercises should aim to include aspects of cognitive load to challenge athletes' ability and require them to react quickly while still performing maximally.

Strengths

A strength of this Thesis is the achieved sample size in both head turned and tone counting conditions. Both studies were sufficiently powered to 80% ($\beta = 0.20$) for detecting a medium effect size difference (Cohen's $d = 0.50$) 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.

Both males and females participated in this Thesis, and therefore the results of both experiments represent both sexes. Much of the previous ACL research has focuses on particular sporting groups (Padua et al., 2015) or only one sex (Almonroeder et al., 2020). However, this Thesis has an approximately even number of males and females, with more than ten different sports represented at a wide variety of competition levels from social to international. The inclusion of both sexes in this Thesis increases the relevance to a broad population.

Previous research has highlighted the increased risk of ACL injury in a head turned position (Belcher et al., 2022) and biomechanics susceptible to ACL injury risk when increasing the cognitive load (Dai et al., 2018). This Thesis supports both of these findings. Introducing a head turned position, using an 'X' marked on the wall to the right of the participant, led to significantly increasing the occurrence of specific LESS errors. Similarly, introducing the tone counting task decreased jump heights significantly, providing evidence for a decrease in overall performance, and potentially movement fluency during increased cognitive load. Decision making and dual tasking scenarios are common in sport and have also been shown to increase the occurrence of biomechanics related to ACL injury (Hughes & Dai, 2023). Both the head turned and tone counting dual task protocols in this Thesis increased the complexity of the LESS task in a way that is relevant to sporting contexts, while maintaining relative practicality compared to other screening tasks, making the LESS a valuable tool in screening for risk of injury and assessing movements.

Limitations

The five error threshold used in this Thesis has previously been shown as sensitive for predicting non-contact ACL injuries. However, this threshold may not be suitable to the participants in this Thesis, as the five error threshold is derived from a study of young elite soccer players (13.9 ± 1.8 years) (Padua et al., 2015). The five error threshold may not be an accurate predictor of non-contact ACL or musculoskeletal injury in our non-elite and older population of young adults (20.3 ± 3.1 years). In agreement with this proposition, a five error threshold was unable to predict incidence of non-contact ACL injury in a population similar to the current studies' population in age (18.3 ± 2.0 years) and sporting participation (Smith et al., 2012). Future studies should be careful when considering the use of the five error threshold, as its appropriateness may well depend on factors influencing LESS scores, such as training status, age, and sex (Hanzlíková, Athens, et al., 2021)

Baseline levels of cognition were not examined in this Thesis and could have an impact on the difficulty of the tone counting task for each participant (Herman & Barth, 2016). Future studies may choose to test baseline cognition levels and adjust the difficulty level of the secondary task accordingly. This adjustment could lead to more consistent changes across participants and therefore examine the true dual task cost associated with the secondary task.

Sex influences the risk of ACL injury, with females more susceptible to injury than males (Belcher et al., 2022; Montalvo et al., 2019). Sex differences were not examined in this Thesis. To account for any sex differences, both males and females were recruited for each study and were relatively equally represented. Previous research demonstrated a relationship between a head turned position and ACL injury in elite female netball players (Belcher et al., 2022), although no similar study has been performed in males.

When completing two tasks simultaneously, one task will be prioritised. The level to which the secondary task is prioritised will vary between participants, creating variance in LESS outcomes and jump heights. Due to the nature of the study and information provided to participants, the secondary task should have been prioritised, although this prioritisation cannot be confirmed via our results.

Therefore, future research is required to determine the prioritisation of task and the dual task cost of these two tasks during a LESS test. McWethy et al. (2025) concluded that the traditional LESS is sensitive enough to identify the dual task cost of landing errors when combined with a visual dual task, although our findings do not support this sensitivity for tone counting dual tasking.

Future directions

Previous studies have examined the occurrence of a head turned position in relation to ACL injury (Belcher et al., 2022), although no study has attempted to implement a head turned position into a screening or neuromuscular training task (Chapter Two). To our knowledge, this project is also the first study to perform the LESS with a tone counting condition (Chapter Three). Future studies are required to determine the predictive ability of the LESS when including these dual tasking scenarios, in terms of both ACL and musculoskeletal injuries.

Further research may also aim to implement more challenging primary tasks, such as single-leg, rotational or cutting movements, with the intention of more accurately representing movements commonly seen in ACL injury scenarios. As discussed in the limitations section, baseline levels of cognitive ability could also be examined to identify any relationship with changes in biomechanics under increased cognitive load. Sex differences could also be examined in both head turned and tone counting conditions to determine whether sex influences the magnitude of the effects observed. Additionally, three-dimensional motion capture, markerless motion capture systems, or force plates could be used to identify more precise changes in biomechanics related to a head turned or tone counting condition than is possible via the LESS. In order to increase sport specificity, future research may include elements of reaction or other sport specific skills. An example of this could be requiring participants to track the movement of a player or trajectory of a ball, possibly displayed on a screen, during the jump, such as suggested in by Dai et al., (2018).

Overall, future research should focus on finding practical, effective, and low-cost manners to accurately screen for risk of injury. For the LESS, increasing the challenge and sport specificity of the task appears important, notably via recreating sporting manoeuvres and environments where cognitive demands are

high and likely to lead to ACL injury. Increasing the validity of the LESS is vital to provide practitioners with a better injury screening tool that involves high levels of cognitive load and effectively recreates the environment of sports where ACL injuries most commonly occur.

Conclusion

Overall, this Thesis provides evidence that performing the LESS with a head turned position or tone counting task increases the difficulty of the task and increases sport specificity. Hence, the LESS with head turned or tone counting conditions may be useful for injury risk screening and rehabilitation from injury. The ability of the LESS to predict ACL injuries when including a head turned position or a tone counting task requires future research before widespread use.

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Appendix One – Ethics Approval

The University of Waikato
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0800 WAIKATO (924 528)

HECS Human Ethics Committee
Brett Langley
Telephone +64 77 838 4060
Heecs-ethics@waikato.ac.nz



4 August 2023

Kim Hebert-Losier
Steve Finlayson
Merel Hoskens
Liis Uiga
Ivana Hanzlikova

Re: HECS Ethics Approval of Application HREC(HECS)2023#43 "Landing error scoring system: Effect of head position and dual tasking"

Dear Kim:

Thank you for submitting your amended application HREC(HECS)2023#43 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Recruitment of approximately 48 physically active and healthy male and female (>16 years of age) participants for a study that aims to examine the influence of head position and dual tasking on the Landing Error Scoring System (LESS) scores.
- Have participants complete a baseline data collection form.
- Have participants complete a cognitive test.
- Have participants jump from a 30-cm box, and immediately jump upwards for maximal height. This will be done three times for each of three conditions (control, head turned to the right, or while performing a dual task -counting backwards- that enhances cognitive load) and recorded using 2D video capture and force plates.
- In total, the entire session should take approximately 35 minutes to complete.

Please contact the committee by email (hecs-ethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

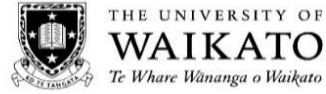
We wish you all the best with your research.

Kind regards,

Brett Langley, PhD
Chairperson
HECS Human Ethics Committee
University of Waikato

Appendix Two – Participant Information Sheet

Participant Information Sheet





Title – Landing error scoring system: Effect of head position and dual tasking

Aim – Our goal is to explore the influence of testing conditions on clinical methods used to assess movements in sport.

Overview – Should you agree to participate, you will be asked to sign an informed consent document and complete a baseline questionnaire and cognitive tasks. You will be familiarised with the testing equipment and procedures, and be given sufficient time to practice the jump task.

For testing, you will be asked to jump from a 30-cm box, and immediately jump upwards for maximal height. You will be asked to perform this task three 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 up to 2 minutes of rest between jumps. You will be asked to perform the same protocol under two conditions. One condition is the control. In the other condition, you will be asked to either turn your head to the right during jumping or count backwards during jumping. The entire session (including 15 minutes rest) should take 35 minutes.

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 associated with performing physical activities. Although the injury risks are considered minimal, we cannot guarantee your safety. If harm does occur during study participation, the research team will offer immediate first aid and support you in accessing medical attention as required. If an injury does happen during testing, costs are likely to be covered – at least in part – by Accident Compensation Corporation.

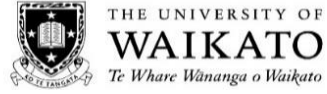
What will happen to the information collected – The information collected will be used by the research team to write research reports, give scientific presentations, and help in educating students at the University of Waikato and the wider community. The information could be used in postgraduate student projects and thesis dissertations. Only the research team will have direct access to the notes, documents, and recordings, or vetted research associates who sign a non-disclosure agreement. 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;
- 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, refuse to do any particular activity, and to withdraw from the study at any time;

Appendix Three – Participant Consent Form

Consent Form for Participants



Title – Landing error scoring system: Effect of head position and dual tasking

I have read the Participant Information Sheet for this study and have had the details of 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 question or to refuse to do any particular activity.
- I can withdraw any information I have provided up to two weeks after participating in the research activities by contacting the principal investigator.
- 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.

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:	Researcher:
Signature:	_____	_____
Name:	_____	_____
Date:	_____	_____

Additional Consent to Use Images and Videos (Optional)

I agree to my images and videos being used in their original (unaltered) form for publication, scientific presentation, and/or education purposes. I understand that anonymity cannot be preserved.

	Participant:	Researcher:
Signature:	_____	_____
Name:	_____	_____
Date:	_____	_____

ID number: _____

NAME: _____

DIRECTIONS: Below are a number of statements about your movements. The possible answers go from 'strongly agree' to 'strongly disagree'. There are no right or wrong answers so circle the answer that best describes how you feel for each question.

1 I rarely forget the times when my movements have failed me, however slight the failure.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

2 I'm always trying to figure out why my actions failed.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

3 I reflect about my movement a lot.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

4 I am always trying to think about my movements when I carry them out.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

5 I'm self conscious about the way I look when I am moving.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

6 I sometimes have the feeling that I'm watching myself move.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

7 I'm aware of the way my mind and body works when I am carrying out a movement.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

8 I'm concerned about my style of moving.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree


9 If I see my reflection in a shop window, I will examine my movements.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

10 I am concerned about what people think about me when I am moving.

strongly disagree moderately disagree weakly disagree weakly agree moderately agree strongly agree

Appendix Four – Participant Data Collection Sheet

<i>Participant Data Collection Sheet</i>		 THE UNIVERSITY OF WAIKATO <i>Te Whare Wānanga o Waikato</i>
ID number		
NAME		
DATE OF BIRTH (dd/mm/yyyy)		
SEX (please tick)	<input type="checkbox"/> MALE <input type="checkbox"/> FEMALE <input type="checkbox"/> OTHER: _____	
FOOTEDNESS (foot used to kick a ball)	<input type="checkbox"/> RIGHT <input type="checkbox"/> LEFT	
ETHNICITY		
SPORT		
What sport do you play?		
What level do you play?	<input type="checkbox"/> school <input type="checkbox"/> club <input type="checkbox"/> national <input type="checkbox"/> other _____	
How many times a week do you play?		
How many hours a week do you play?		
How many years have you been playing?		
During the past 12 months, how much do you move or exert yourself physically during leisure/play time (overall)?		
<input type="checkbox"/> Hardly no physical activity (reading, watching TV, using the computer)		
<input type="checkbox"/> Mostly sitting, sometimes walk, easy tasks/play		
<input type="checkbox"/> Light physical activity for about 2 – 4 hours a week, like fishing, talking, dancing		
<input type="checkbox"/> Moderate exercise 1 – 2 hours a week, like jogging, swimming, gymnastics		
<input type="checkbox"/> Moderate exercise at least 3 hours a week, like jogging, swimming, gymnastics		
<input type="checkbox"/> Hard or very hard exercise regularly and several times a week, during which the physical exercise is great, like jogging, rugby, football		
INJURIES		
Are you in good general health?	<input type="checkbox"/> YES <input type="checkbox"/> NO	
Do you have any current or recent injuries (3 months)? <i>Please provide detail (e.g., right Achilles tendon)</i>	<input type="checkbox"/> YES <input type="checkbox"/> NO	
Have you suffered any injuries in the past? <i>Please provide detail (e.g., right ACL tear 2015)</i>	<input type="checkbox"/> YES <input type="checkbox"/> NO	
PHYSICAL ACTIVITY IN THE LAST 7 DAYS		
During the past 7 days , please tell us how much time you have spent in each category of activity.		
Vigorous physical activities 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, school, and home, walking from place to place, and any other walking that you have done for recreation, sport, exercise.		
Sitting includes time spent sitting at work, at school 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.		
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