KNEE AND ANKLE EXTERNAL JOINT MOMENTS AND KINEMATICS PRE- AND POST-FATIGUE DURING DROP JUMPS IN FEMALE UNIVERSITY SOCCER PLAYERS.

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Abstract

Background: Non-contact knee injuries are common in soccer, with female players at greater risk than males. Fatigue is frequently proposed to increase injury risk, yet findings are inconsistent, and ankle biomechanics under fatigue are less well understood.

Purpose: To compare dominant-leg ankle and knee joint angles and external joint moments at initial contact and mid stance during a drop jump before and after fatigue in female university football players.

Methods: Twelve female players (age 20.4 ± 1.2 years; height 167.4 ± 5.8 cm; body mass 66.2 ± 8.4 kg) completed three drop jumps pre and post fatigue. Three-dimensional motion capture using a CAST lower body marker set quantified ankle and knee kinematics and kinetics. Fatigue was induced using a lower limb exercise circuit continued until a rating of perceived exertion of 9 on the 0 to 10 Borg scale (mean sets completed 10.3; most participants completed 4 to 10 sets; one participant completed 44 sets). Normality was assessed using Shapiro Wilk tests and pre to post comparisons were analysed using paired samples repeated measures statistics.

Results: Single legged countermovement jump height decreased from 11.9 ± 3.9 cm to 9.9 ± 2.8 cm, a 16.6% reduction (P = .002). No significant pre vs post fatigue changes were observed for ankle or knee angles or external moments in any plane at initial contact or mid stance (all P > .05). For example, knee flexion angle at initial contact was 28.48 ± 5.48 degrees pre fatigue and 28.9 ± 6.2 degrees post fatigue (P = .7), ankle dorsiflexion angle at mid stance was 32.6 ± 3.4 degrees pre fatigue and 30.8 ± 5.5 degrees post fatigue (P = .16), and external knee flexion moment at mid-stance was 9.3 ± 3.2 %BW.h pre fatigue and 8.9 ± 3.5 %BW.h post fatigue (P = .58).

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Conclusion: Although the fatigue protocol reduced single-legged countermovement jump performance, no statistically significant pre- to post-fatigue differences were detected in ankle or knee angles or external joint moments during the drop jump in this sample. Given the small sample size and variability in fatigue response, these findings should be interpreted cautiously and do not rule out fatigue related changes. In addition, because the drop jump is a controlled laboratory task that differs from soccer specific jumping and landing demands, future work should use larger, adequately powered cohorts and more soccer-representative tasks and fatigue protocols.

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Preliminaries

Acknowledgements

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List of Abbreviations

Name	Acronym
Anterior cruciate ligament	ACL
Ankle dorsiflexion angle	ADA
Ankle plantarflexion angle	APA
Countermovement jump	CMJ
Drop jump	DJ
Drop vertical jump	DVJ
Fatigue protocol	FP
Fédération Internationale de Football Association	FIFA
Fédération Internationale des Associations de Footballeurs Professionnels	FIFPRO
Injury incidence rate	IIR
Initial contact	IC
Knee flexion angle	KFA
Knee valgus angle	KVA
Landing error scoring system	LESS
Mid-stance	MS
National Collegiate Athletic Association	NCAA
National health service	NHS
Qualisys Track Manager	QTM
Soccer-specific aerobic fatigue test 90	SAFT90
Vertical ground reaction force	VGRF

CHAPTER I

Introduction

Prevalence of non-contact knee injuries in female soccer.

Soccer is one of the biggest sports in the world; however, there are risks that are associated with playing soccer, one of the most burdensome being non-contact knee injuries (Hallén et al. 2024; Waldén et al., 2015). Some studies suggest that female athletes are at greater risk of non-contact knee injuries as opposed to their male counterparts (Chia et al., 2021). Waldén et al., (2011) concluded that female soccer players are at 2-3 times higher risk of an anterior cruciate ligament (ACL) injury than male soccer players. The systematic review with meta-analysis by Chia et al., (2022) analysed ACL injuries across 45 studies covering 13 team ball-sports and concluded that 55% of all injuries were during non-contact scenarios. This issue has infected female soccer, and the effect has been detrimental for female soccer players (Waldén *et al.* 2011). The problem is so prevalent that Fédération Internationale des Associations de Footballeurs Professionnels (FIFPRO), Nike, and Leeds Beckett University have recently launched 'Project ACL' which aims to conduct research with clubs and players in the FA Women's Super League to highlight best practices and propose measures to reduce the occurrence of ACL injuries (Fédération Internationale des Associations de Footballeurs Professionnels, 2024) .

Effects of non-contact knee injuries in female soccer.

Non-contact knee injuries have long-lasting challenges, specifically ACL injuries that often require ACL-reconstruction surgery with many resulting in secondary issues such as bone bruising, reduced knee strength and increased risk of re-injury (Nagelli & Hewett, 2017). These factors restrict athletes at all levels, and for female soccer players, who are already at higher risk than their male counterparts, such injuries can result in prolonged absence from sport. Hallén et al., (2024) reported that ACL injuries impose the greatest injury burden on elite female soccer players, with rehabilitation typically lasting around nine months. However, it is noted that athletes who return to their sport after ACL-reconstruction typically do so within a year (Nagelli & Hewett, 2017). Nagelli & Hewett (2017) suggests that this increased risk of re-injury is elevated for the first 24 months after reconstruction. This means that athletes must make a choice between returning to sport with elevated risks of reinjury, or undergo a two-year absence from competition, which in a professional setting could result in career changing consequences.

Aetiology of ACL injuries.

Waldén et al., (2015) assessed videos from 39 complete ACL tears that occurred in male professional soccer matches and found three distinct mechanisms predominate in non-contact ACL injuries (n = 25); pressing (n = 11), regaining balance after kicking (n = 5, and landing after a header (n = 5). Waldén et al. (2015) reported that landing after a header accounted for 5 of 25 non-contact ACL injury mechanisms in their analysis, accounting for 20 per cent. This video analysis highlights that landing from a header is a typical non-contact ACL injury scenario which supports the use of a standardised drop jump (DJ) to assess fatigue-related changes in non-contact knee injury risk in university female soccer players. Previous studies have assessed lower-

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limb biomechanics during DJs, as these are easily replicable in a motion analysis laboratory and involve jumping and landing patterns like those associated with non-contact knee injuries in soccer (Mok et al., 2016). The DJ is a commonly used manoeuvre to assess lower limb biomechanics as it replicates the style of landing that occurs during soccer matches, which have proven to cause non-contact knee injuries (Cabarkapa *et al.* 2025) and with the use of three dimensional (3D) motion capture, the DJ manoeuvre can provide insight into joint kinetics and kinematics to identify movement patterns that may increase the risk of injury (as shown in Figure 1.1). A common risk factor in non-contact ACL injuries are higher knee abduction angles; Harato et al., (2021) found that fatigue caused increases in knee abduction angles during vertical DJs. This is one of many examples of why a DJ is an appropriate, soccer-related task to assess if fatigue effects risk of non-contact knee injury in university female soccer players.
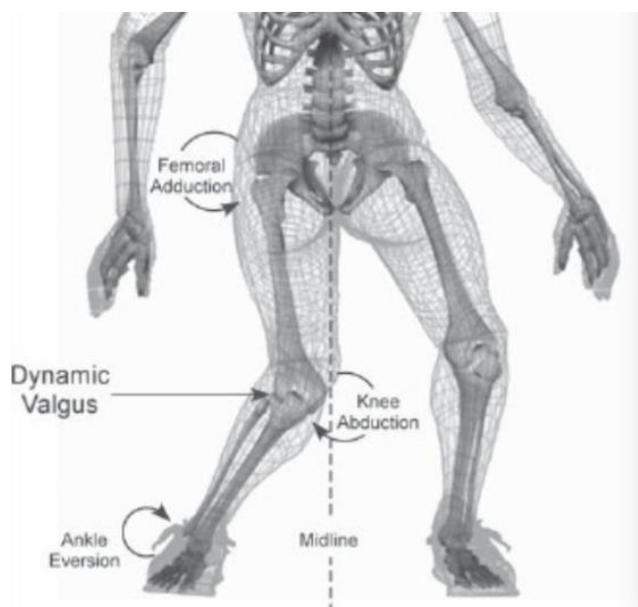
Figure 1.1. Visual demonstration of the common biomechanical risks of ACL injuries during landing in female athletes. Retrieved from: Hewett et al., (2005).

How fatigue influences risk of non-contact knee injury.

Past studies have shown that measurable biomechanical alterations at the knee joint have been shown to occur because of fatigue (Horato et al., 2020).   An example of this is increased peak knee valgus moments, which refers to the highest external torque exerted on the knee causing an inwards bend (Mercurio et al., 2025) , due to fatigue, which causes higher strain on the knee, resulting in increased risk of non-contact knee injury (Abbasi et al., 2025) . However, there is limited support for the idea that this fatigue directly increases the incidence of non-contact knee injuries during soccer matches (Archenback et al., 2024).

There has been extensive research conducted surrounding non-contact knee injuries and the potential biomechanical causes behind such injuries (Straub & Powers, 2025). However, there is still considerable uncertainty around the exact cause of non-contact knee injuries, which are likely multi-factorial in nature. These uncertainties arise from a variety of factors including small sample sizes across studies, lack of standardised methodologies used, and inconsistencies in results when comparing literature (Straub & Powers, 2025). The systematic review by Santamaria & Webster (2010) evaluated the quality and outcomes of published literature that assessed fatigue-induced biomechanical changes during landings and found that inconsistencies often occur as a result of different methodologies used, as studies focus on different variables (e.g. kinematics as opposed to kinetics) or analyse outcomes at various points of a manoeuvre (e.g. initial contact instead of peak values). Santamaria & Webster (2010) highlighted mixed findings in knee kinematics during landings post-fatigue (with three studies showing greater knee flexion angles (KFAs) post-fatigue, one study showing greater KFAs pre-fatigue, and three studies

showing no significant differences in KFA pre- and post-fatigue) and suggested a need for further investigation.

Academically, this study adds to the limited evidence on fatigue related changes in landing biomechanics in female football players by examining both ankle and knee kinematics and kinetics across three planes at defined landing events. This contributes to the interpretation of inconsistent findings in the literature by using standardised biomechanical methods and a clearly defined fatigue criterion. Practically, the findings can help inform injury prevention work by indicating whether fatigue meaningfully alters drop jump landing mechanics, which may guide the emphasis placed on fatigue resistant landing technique, conditioning strategies, and future screening approaches within university and club football settings.

Aims of this study.

The aim of this study was to evaluate the impact of fatigue on knee and ankle biomechanics during DJs in female soccer athletes by analysing knee and ankle moments and angles across the frontal, sagittal and transverse planes pre- and post-fatigue. The findings from this thesis can advance current the current understanding of non-contact knee injury mechanisms in female soccer by clarifying how fatigue alters multiplanar knee and ankle kinetics and kinematics. Academically, the study uses a non-soccer specific FP that is easily replicable and could be used in future studies to refine biomechanical risk markers for non-contact knee injuries in female soccer.

CHAPTER II

Literature review

In this chapter, the relationship between lower limb biomechanics, fatigue, and the risk of non-contact knee injuries in soccer is critically examined, with a focus on female players. Evidence describing the prevalence and burden of non-contact knee injuries is first outlined to justify the importance of this research area. The review then evaluates how drop jump tasks have been used to assess lower limb biomechanics relevant to ACL injury mechanisms in football. Next, research examining fatigue related changes in landing biomechanics is appraised, including the fatigue protocols used and how differences in methodology may contribute to inconsistent findings. Finally, key methodological considerations and gaps in the current literature are identified to justify the aims and design of the present study.

Prevalence of non-contact knee injuries.

Non-contact knee injuries, especially ACL injuries, are highly prevalent among athletes across many team sports such as soccer, basketball, and American football (Chia et al., 2022; Dragoo et al., 2012). Chia et al., (2021) reviewed 2,748 ACL injuries, regardless of age, sex, and participation level, across 42 million player-hours and player exposures. 54% of the injuries reviewed occurred in non-contact scenarios. This alone highlights the severity of the non-contact knee injury epidemic and warrants further investigation.

Boden et al., (2000) used a standardised, comprehensive questionnaire on 89 athletes (with a total of 100 knee injuries) regarding their knee injuries, with 71 out of the 100 knee injuries reportedly occurring in non-contact situations. Specifically, most of these occurred at foot-strike when the knee was close to full extension. This study suggests that almost three out of four ACL injuries occur in non-contact scenarios. Although this study suggests that almost three out of four ACL injuries occur in non-contact scenarios, these findings are self-reported with no video footage to support the claims made and therefore further investigation using an objective approach, such as motion analysis, is warranted (Boden et al., 2000). Swenson et al., (2013) calculated knee injury rates and injury proportion ratios from United States (US) high school sports-related injury data collected from 20 sports between 2005/06 and 2010/11 using the National High School Sports-Related Injury Surveillance System, High School RIO[TM]. The study found that during that time frame, 5,116 knee injuries occurred during 17,172,376 athlete exposures: indicating 0.3 knee injuries per 1000 athlete exposures. The primary mechanisms knee injuries were also assessed and categorised as contact with another player, contact with the playing surface (such as landing or falling), or non-contact (e.g. movements occurring without any external impact). The results showed that 22.2% of all knee injuries occurred in non-contact scenarios (Swenson *et al.* 2013). This statistic is lower than reported in other review studies, such as Chia et al. (2021). However, Swenson et al. (2013) examined injuries in more contact-intensive sports, including wrestling and American football, which exhibit substantially higher rates of injuries caused by contact with another person compared with soccer. Gage et al., (2012) found that soccer was a top 5 most common specific cause associated with all knee injuries presented to emergency departments in the United States for females aged 5-14 (7.5% of injuries) and

females aged 15-24 (7.0% of injuries). Although no specifics on how the injuries occurred (e.g. contact vs non-contact) are given, this data shows the prevalence of knee injuries in soccer, especially for females. Using this information alongside research that investigates soccer-specific injuries, it is evident why non-contact knee injuries are such a prominent issue that warrants further investigation.

Are female soccer players at higher risk of non-contact knee injury compared to male soccer players?

Many studies that compare injury incidences between males and females have demonstrated females are more susceptible to non-contact knee injuries compared to their male counterparts (Chia et al., 2021; Swenson et al., 2013; Arendt & Dick, 1995). Chia et al., (2021) highlighted that injury incidence in females (0.20 per 1,000 player-hours, and 0.07 per 1,000 player-exposures) was higher than their male counterparts (0.08 per 1,000 player-hours, and 0.05 per 1,000 player-exposures). In a similar study a year later, Chia et al., (2022) found significant differences in non-contact knee injury incidences per 1,000 player-hours between females (0.14 per 1,000 player-hours) and males (0.05 per 1,000 player-hours). Although there are differences in non-contact knee injury incidences between males and females, a key weakness worth highlighting is that these statistics were collected from multiple studies, and these studies defined knee injuries and non-contact knee injuries differently, for example; some studies used time-loss thresholds to determine an injury whereas others used clinical / imaging confirmation to determine injuries. This can create misclassification and limit comparability with other studies.

Swenson et al., (2013) highlighted differences in the occurrence rates of knee injuries between boys and girls. Girls had higher injury rates per 10,000 athlete exposures than boys in soccer,

volleyball, basketball, swimming and diving, and track and field. In soccer, girls had significantly higher rates of knee injuries (4.53 knee injuries per 10,000 athlete exposures) in comparison to boys (2.65 knee injuries per 10,000 athlete exposures). Across all sports and genders, knee injuries were the second highest in girls' soccer during competition (10.84 knee injuries per 10,000 athlete exposures), only behind American football which was only played by boys. This evidence suggests that females are at significantly higher risk of knee injuries in comparison to males, and when comparing sports that are popular amongst males and females, soccer is the sport that has the highest risk of knee injury. When comparing the nature behind how these injuries occurred, the percentage of injuries caused with no contact were higher in girls' soccer (27.1%) in comparison to boys' soccer (21.7%). Across all sports, the percentage of knee injuries with no contact was significantly higher in females (32.8%) than in males (17.8%) (Swenson et al., 2013).

ACL injury rates are more than double in women's soccer (0.31 ACL injuries per 1,000 athlete exposures) in comparison to men's soccer (0.13 ACL injuries per 1,000 athlete exposures) (Arendt & Dick, 1995). The rate of ACL injuries per 1,000 athlete exposures caused by contact or collision with another player were 0.05 in men's soccer, and 0.10 in women's soccer, and the rate of ACL injuries per 1,000 athlete exposures caused by no apparent contact were 0.05 in men's soccer, and 0.17 in women's soccer, which is a significant difference ($p < 0.01$). These statistics were taken from the NCAA Injury Surveillance System, over a 5-year span (Arendt & Dick, 1995). Although there are more recent studies that show differences between the rates of non-contact injuries in male and female soccer athletes, it is worth highlighting this study as it was undertaken

almost three decades ago yet the issue is still ongoing, and with the increase in popularity of women's soccer (Leslie-Walker & Mulvenna, 2022), even more relevant in present time.

A more recent study also assessed soccer-related knee injuries using the NCAA Injury Surveillance Program and concluded that men's soccer had a lower rate of knee injuries per 10,000 athlete exposures (10.81) in comparison to women's soccer (14.87) (Chandran et al., 2025). The results showed that knee injury rates were higher during competition (32.25 knee injuries per 10,000 athlete exposures) as opposed to during practice (9.22 knee injuries per 10,000 athlete exposures), in women's soccer. In this study, non-contact scenarios made up 26.6% of all knee injuries in women's soccer, which is higher than the 24.1% in men's soccer.

To conclude, multiple related studies have found similar trends that suggest female soccer athletes are at higher risk of knee injury than their male counterparts. Of those knee injuries, many of them occur in non-contact scenarios such as landing from a jumping task and changes of direction (Boden et al., 2000; Waldén et al., 2015; Donelon *et al.,* 2024). Therefore, it is of paramount importance to investigate the causes of these non-contact knee injuries with the goal of helping find prevention methods to lower the risk of injury for female soccer players.

Significance of non-contact knee injuries in female soccer.

The popularity of female soccer has increased over the years, driven by the growth of the Women's Super League in England, from a semi-professional league of eight teams in 2011 to a professional league with multiple divisions today, and competitions such as the FIFA Women's World Cup (Leslie-Walker & Mulvenna, 2022) . There has been rapid growth, specifically in popularity in female soccer as it was reported that the FIFA Women's World Cup 2023[TM] had over

two billion viewers worldwide (Fédération Internationale de Football Association, 2023) . FIFA published the Women's Football: Member Associations Survey Report 2023 and the report showed that 16.6 million girls and women are playing organised football worldwide, which is an increase of 24% since 2019. These statistics indicate a significant increase in both the popularity and participation rates in female soccer. Given the evidence discussed in this literature review, that female soccer players have a higher incidence of non-contact knee injuries than male players, there is a clear need for more gender-specific research to explain this injury-risk discrepancy, which this thesis aims to address.

Non-contact knee injuries can have a range of effects on female soccer athletes, as will be discussed in this section of the literature review. For example, Hallén et al., (2024) found that ACL injuries had the highest injury burden across all recorded injuries in the study, with 100% (n = 33) of ACL injuries resulting in absences greater than 28 days and a median time-loss of 292 days. The purpose of this section is to highlight potential consequences that female soccer players may face because of such injuries, emphasising the significance of these injuries.

Financial effects.

A full ACL rupture is a severe injury, which can result in needing ACL reconstruction surgery, resulting in a financial burden on athletes in countries without free healthcare services. Expenditure on ACL reconstruction for amateur soccer players in Australia over a single year grossed 70 million Australian Dollars (AUD) (£36 million at the time of online publication) with a mean total individual cost of 34,000 AUD (Ross et al., 2023). Australia has a public healthcare service (Medicare) that provides universal coverage for all residents (West et al., 2025); however,

throughout 2023-24, median waiting time for surgery was 82 days. This leaves individuals having to choose between spending a large sum of money to undergo surgery sooner, shortening rehabilitation time, or having to wait long periods of time to get free healthcare or subsidised services.

The United Kingdom has a publicly funded healthcare system called the National Health Service (NHS), and as of December 2nd, 2019, the maximum waiting time for non-urgent treatments were 18 weeks from the day an appointment is booked or when the hospital / service receives a referral letter (National Health Service, 2019) . Although this provides female soccer players free healthcare in England, these waiting times could delay rehabilitation and return to sport.

Physical effects.

There is a long list of physical aftereffects of non-contact knee injuries. Meniscal and cartilage damage is often associated with non-contact knee injuries and can result in increased long-term risk of knee osteoarthritis (Renstrom et al., 2008). Osteoarthritis is a common joint disorder that can cause severe, long-term pain and disability (Lespasio et al., 2017) . Fältström et al., (2016) reported that female soccer players post-ACL reconstruction exhibited reduced knee valgus motion and a lower likelihood of high knee abduction moments during drop jumps compared with knee-healthy peers. Additionally, Fältström et al. (2016) observed decreased performance in the 5-jump test (Chamari et al., 2008) in the post-ACL reconstruction group. Abed et al., (2023) found that National Women's Soccer League players that sustained an ACL tear, and underwent surgery saw a significant decrease in minutes played a year prior to injury in comparison to one-year post-injury ($P = .031$). Forwards and midfielders also had significant decreases in assists (P

= .037) and goals (*P* =.031) post-ACL reconstruction (Abed et al., 2023). These findings suggest that athletic performance is reduced post-ACL reconstruction surgery, and in a professional capacity, this decrease in performance can impact an athlete's career.

Following ACL reconstruction, the incidence of a secondary ACL injury is particularly high among young athletes, with approximately one-third experiencing reinjury within the first two years post-surgery (Nagelli & Hewett, 2017). Nagelli & Hewett (2017) suggested that delaying the return to sports for nearly two years after ACL reconstruction surgery would significantly reduce the risk of reinjury. The issue with this is that the effects of not returning to sport for that long could have serious consequences such as not being able to perform at the level of competition performed pre-injury. In the context of profession soccer, this extended time away from competition could also jeopardise scouting opportunities and contracts, ultimately disrupting career progression.

Psychological effects.

Psychological barriers such as mental fatigue have been proven to negatively impact athletic performance aspects, such as cognitive performance and technical skills, in soccer (Soylu et al., 2022). Kunnen et al., (2023) found that two-thirds of the athletes that took part in a survey related to returning to soccer after ACL injury, mentioned 'fear of re-injury'. Some participants also mentioned that they felt anxiety and self-doubt when returning to soccer after their injury. When relating these negative psychological feelings the players expressed, it suggests a decrease in performance could have occurred. In extreme cases, suffering such injuries can even lead to depression (Kunnen et al., 2023).

Why are female soccer players at higher risk of non-contact knee injury?

There have been many hypotheses surrounding the topic of why female soccer players are at greater risk of non-contact knee injuries when compared to their male counterparts including: neuromuscular imbalances, anatomical differences, hormonal factors, and differences in biomechanical and movement patterns, the main focus of this thesis it to assess the biomechanical factors related to non-contact knee injuries in female soccer players.

Neuromuscular and biomechanical differences.

Parpa & Michaelides (2025) hypothesised that interlimb asymmetries and knee hyperextension may contribute to the occurrence of non-contact knee injuries in female adolescent soccer players, therefore landing from a jump with a more extended knee may be a cause of injury. This is due to the injured population in the study demonstrating statistically significantly greater interlimb asymmetries in knee extensor (P = .03) and knee flexor torque (P = .05) as well as significantly higher knee hyperextension angle values in both the right (P <.05) and left legs (P <.05).

Donelon *et al.,* (2024) systematically reviewed and meta-analysed 17 studies that assessed biomechanical differences between males and females during change of direction tasks (associated with non-contact knee injuries). The meta-analysis showed no significant differences in knee joint loads between males and females; however, females displayed significantly greater knee abduction at initial contact (IC) (P = 0.001), and less peak knee flexion during stance (P = 0.008), both of which are characteristics that have been associated with non-contact ACL injuries (Donelon et al., 2024).

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A recently published systematic review of sex-differences in neuromuscular activation related to non-contact ACL injuries identified inconsistent findings across 15 studies. Specifically, three studies reporting significantly greater activation of the vastus lateralis and vastus medialis in females (during vertical jumps with a single-leg landing and two different types of cutting tasks), whilst two studies observed lower activation of the biceps femoris and semitendinosus (during side-cutting manoeuvres), and the remaining studies finding no significant differences between sexes or even conflicting results (Steiner et al., 2023); the study conducted a comprehensive search across five databases and used a tool for cross-sectional studies to identify key biases such as lack of power calculations. The main weakness of Steiner et al., (2023) is that 73% of the studies used were in the low-moderate category of evidence quality, this limits evidence certainty and increases the risk of biased or unreliable conclusions about sex-specific neuromuscular differences.

Anatomical differences.

Research shows that males and females have multiple anatomical differences that effect risk of non-contact knee injuries in soccer. Hedt et al., (2022) found that there were significant differences in pelvic width below femoral head (male = 15.3 ± 1.4cm; female = 16.8 ± 0.8cm ($P =$ < 0.001)) but no significant differences in greatest pelvic width between elite male and female soccer players.

The Q (quadricep) angle, an angle formed by a line drawn between the anterior superior iliac spine (ASIS) and the midpoint of the patella and a line drawn between the tibial tubercle to the

midpoint of the patella (Figure 2.1), is another anatomical variant that has shown to differ between males and females (Malone & Pfeifle, 2017) .
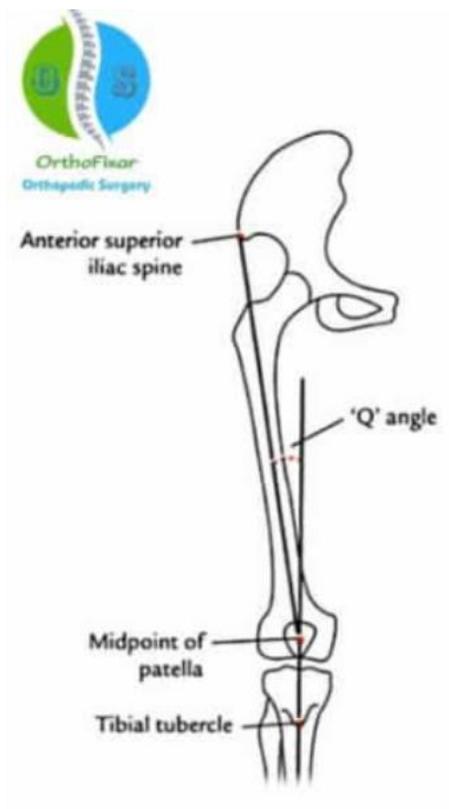
Figure 2.1. Illustration of the Q angle of the knee. Retrieved from:

https://orthofixar.com/special-test/knee-q-angle-definition/.

Mitani (2017) found that female university athletes had significantly larger Q-angles than male university athletes (males = 11.3 ± 4.8°, females = 15.0 ± 5.1°; P = <0.01). A significantly larger proportion of the female athletes had history of lower limb sports injuries. These connections suggest that female athletes may be at increased risk of injury due to anatomical differences. On

the contrary, Mohamed et al., (2012) found that there were no significant differences in knee injuries depending on pelvic width, Q-angle, and intercondylar notch width; however, the study was relatively small (n = 24) and only compared non-injured vs injured female soccer players as opposed to male and female soccer players. Wahl et al., (2012) found that females and males (that have sustained non-contact knee injuries) had similar lateral knee geometry. This geometry was defined by a shorter tibial plateau relative to the femur, and more curved articulating surfaces on the tibia and femur. These factors were associated with non-contact knee injury risk, as they were observed in injured male and female participants. However, their presence in uninjured females but not males may suggest reason as to why injury prevalence is higher in female soccer players.

Hormonal factors.

Balachandar et al., (2017) , undertook a systematic review that assessed the effects of the menstrual cycle on lower-limb biomechanics, neuromuscular control, and ACL injury risk, and found that female athletes are at the most risk of ACL injury during the preovulatory phase of the menstrual cycle (8 out of 10 studies reviewed reported significantly greater risk of injury during the preovulatory phase).

Bell et al., (2014) assessed lower limb biomechanics during the loading phase of jump landings by female athletes who have recovered from ACL reconstruction at both the menses and ovulation phases of the menstrual cycle. During the menses phase, participants demonstrated greater peak vertical ground reaction forces (VGRF) (menses: 1968.3 ± 623.8 N; ovulation: 1775.8 ± 642.9 N; P = .04) and during the ovulation phase, participants demonstrated increased peak

knee valgus moments (menses: -0.02 ± 0.03; ovulation: -0.06 ± 0.06; *P* = .01) (Bell et al., 2014) .

These results may indicate that female athletes demonstrate biomechanical variables associated with increased risk of non-contact knee injury in two different stages of the menstrual cycle (Bell et al., 2014; Podraza & White, 2010; Hewett et al., 2005).

How these injuries occur.

Video analysis of 27 separate ACL injuries found that most non-contact ACL injuries occur when the knee is close to extension when landing and when there is a sharp deceleration (Boden et al., 2000). Waldén et al., (2015) found that there were three main scenarios for non-contact ACL injuries in soccer, these were: gaining balance after kicking a soccer ball, landing after a header, and pressing. Pressing typically refers to when a defender makes a side-step cut to reach the ball or to make a tackle (Walden et al., 2015). Alentorn-Geli et al., (2009) identified that non-contact knee injuries frequently occur during side-stepping or cutting manoeuvres, specifically when these actions occur with a sudden deceleration.

In soccer, landing is a clearly reported mechanism for non-contact ACL injury. Waldén et al. (2015) reported that landing after a header accounted for 5 of 25 non-contact ACL injury mechanisms in their analysis, which is 20 per cent. This supports the use of drop jump tasks within laboratory research, as drop jumps replicate the rapid landing and stabilisation demands present during aerial duels, while allowing controlled assessment of multiplanar joint biomechanics. Analysing ankle and knee joint angles and external joint moments in the frontal, sagittal, and transverse planes at initial contact and mid stance provides insight into landing mechanics that are

commonly implicated in ACL injury risk, including reduced knee flexion, increased knee abduction loading, and altered transverse plane control.

Although football is the primary focus of this thesis, video analyses in other jumping based sports further highlight landing as a high-risk scenario for non-contact knee injury. For example, Krosshaug et al. (2007) reported that a large proportion of recorded knee injury cases occurred during landing, reinforcing the importance of evaluating landing biomechanics using controlled laboratory tasks. However, due to differences between sports in movement demands and force application strategies, football specific evidence remains most relevant when interpreting injury mechanisms and fatigue related changes.

Although the injuries occur during similar conditions, research suggests that soccer and basketball players have clear differences in vertical force application patterns, such as soccer players using a deeper countermovement and generating higher propulsive impulse over a longer duration whereas basketball players typically use faster, stiffer jumps (Chalitsios et al., 2019). This consistent occurrence of non-contact knee injuries during jumping manoeuvres across different sports, even when there are clear differences in application patterns, supports the need for further research surrounding lower limb biomechanics when jumping and landing.

Biomechanics of drop jumps.

 The DJ manoeuvre consists of the following four phases: (i) the subject steps off a box (set to a predetermined height) with their designated test leg, (ii) lands with both feet on the floor, (iii) then jumps as high as they can, minimising ground contact time, and (iv) landing again on the surface with both feet (Bishop et al., 2019) . DJs are a common manoeuvre used to assess lower

limb biomechanics in sports science. The DJ is relevant in studies analysing lower limb biomechanics in relation to non-contact knee injuries in soccer (Ma et al., 2022). The manoeuvre replicates the actions such as landing and immediate propulsion, which occurs when jumping for a header, which was previously highlighted as a common scenario where such injuries occur in soccer (Waldén et al., 2015). DJs have also been used in research when assessing risks of other injuries that occur due to inappropriate jump-landing technique such as ankle instability (Herb et al., 2018).

Biomechanical variables associated with non-contact ACL injuries include knee joint angles such as KFA and knee valgus angle (KVA) which can be commonly analysed during a DJ under various conditions such as pre- and post-fatigue, single-legged, or with a sports-specific header involved (Briem et al., 2017; Nakahira et al., 2022; Akbari et al., 2023) . Nakahira et al., (2022) compared KFA and KVA at initial contact (IC), maximum knee flexion and toe-off between the dominant and non-dominant legs of female soccer players during DJs. Nakahira et al., (2022) found no significant differences between KFA at any point of the DJs and KVA only statistically differed at IC, where KVA was greater in the non-dominant leg (non-dominant = 0.8° ± 5.2°; dominant = -0.9° ± 4.9°; P = <.01).

Other biomechanical variables associated with non-contact knee injuries can occur at the ankle joint. Malloy et al., (2014) reported both negative and positive correlations in female collegiate soccer players, where reduced ankle dorsiflexion flexibility was associated with multiple knee joint biomechanical parameters indicative of poor landing mechanics and increased risk of non-contact knee injuries, including greater peak knee abduction angles (r = 0.355) and lower peak knee flexion angles (r = -0.385). The work by Malloy et al., (2014) indicates that ankle joint angles

during DJs influence risk of injury. However, there is a lack of research that involves the analysis of such metrics (Malloy et al., 2014). Akbari et al., (2023) measured ankle dorsiflexion range of motion and assessed landing patterns during a soccer-specific jump-landing task. Akbari et al., (2023) presented significant negative correlations between ankle dorsiflexion range of motion and landing errors (r = -0.450, P = 0.006) and decreased ankle dorsiflexion ROM was associated with greater landing errors. The landing errors were defined using the landing error scoring system (LESS), developed by Padua et al., (2015), which quantifies faulty jump-landing biomechanics such as insufficient knee / hip flexion, and stance width asymmetry during a double-leg drop-jump task. The LESS procedure is described in greater detail later in this thesis and was used as part of the current study's protocol.

Mancini et al., (2022) used 3D motion capture to assess lower-limb landing kinematics in healthy female soccer players during drop vertical jumps (DVJs) and soccer-specific vertical jumps from a height of 0.31 m. Trunk, hip, knee, and ankle range of motion, trunk flexion at initial contact (IC), peak hip flexion, hip flexion at IC, peak and IC knee flexion angles (KFA), peak ankle dorsiflexion angle (ADA), and ankle plantarflexion angle (APA) at IC were measured as potential biomechanical risk factors for ACL injury. Significant kinematic differences were observed between jump types (P < 0.05), including increased APA (P = 0.005) and lower peak KFA (P = 0.002) during soccer-specific vertical jumps compared with DVJs.

Typical kinetic variables analysed during drop jumps.

Malloy et al., (2014) compared the association between ankle dorsiflexion flexibility and knee joint biomechanics during a DVJ in 23 female collegiate soccer players. The results produced from

Malloy et al., (2014) found a significant negative correlation between ankle dorsiflexion flexibility and peak external knee abduction moments (r = -.442; *P* = .017), this finding is important in relation to risk of injury as greater knee abduction moments have been associated with an increased risk of non-contact knee injuries (Ma et al., 2022**).** Leppänen et al., (2017) used 3D motion capture analysis on 171 female basketball and floorball athletes to assess hip, knee and ankle biomechanics in the sagittal plane during DJs in relation to non-contact ACL injuries**.** In Leppänen et al. (2017), 15 non-contact knee injuries were recorded, with greater peak knee flexion moment (KFM) significantly associated with increased injury risk (hazard ratio per 10 N·m increase in KFM: 1.21; 95% CI, 1.04–1.40; *P* = 0.01). The study assessed peak external KFM and peak external hip flexion moments but did not analyse peak external ankle dorsiflexion or plantarflexion moments.

Although ankle dorsiflexion factors such as range of motion / flexibility have been assessed in relation to knee biomechanics during DJs (Malloy et al., 2014), in relation to non-contact knee injuries in soccer, there is a lack of research that directly assesses ankle joint moments (especially in all three planes of motion) during DJs.

Fatigue and how it influences the risk of non-contact knee injuries in soccer.
Fatigue is a subjective experience which is characterised as the feelings of tiredness and exhaustion which can interfere with an athlete's ability to perform physical and mental tasks (Billones et al., 2021). Neuromuscular fatigue refers to exercise-induced reductions in the force or power-generating capacity of muscles (Weavil & Amann, 2019), and can be characterised by

shorter endurance duration, increased perceived effort, lower force steadiness, and higher electromyographic activity (Tyagi & Mehta, 2021).

As highlighted by Yousif et al., (2019), combining objective measures such as force plate analysis with subjective measures such as rating of perceived exertion (RPE) scales can provide a more comprehensive evaluation of neuromuscular fatigue and its effects on injury risk. Achenbach et al., (2024) assessed 37 ACL injuries during women's professional soccer matches and found there was a difference in distribution of injuries between the two halves of the match (first half = 35% of injuries, second half = 65% of injuries), however this difference was insignificant, and nearly half of all non-contact knee injuries occurred within the first 15 minutes of play. Although the difference in injury distribution between halves were not statistically significant, the greater proportion of injuries occurring in the second half (65%) suggests that fatigue may exacerbate biomechanical risk factors, thereby increasing susceptibility to non-contact knee injuries in female soccer players.

Previous literature has shown different effects fatigue has on lower limb biomechanics (Cortes et al., 2014; Kamitani et al., 2023). Fatigue can cause increased knee abduction angles during dynamic tasks such as vertical DJs, which is a known critical factor in ACL injury mechanisms (Harato et al., 2021). Cortes et al., (2014) analysed lower extremity biomechanics during crossover cutting tasks until fatigue was reached, with fatigue resulting in significantly decreased knee adduction angles (pre-fatigue = 9° ± 5°, 100% fatigue = 6° ± 4°; P = 0.006) and knee flexion angles (pre-fatigue = 32° ± 9°, 100% fatigue = 29° ± 11°; P = <0.001) at IC of the crossover cutting manoeuvres which could contribute to higher risks of non-contact knee injury. Cortes et al., (2014) assessed hip flexion and abduction angles at IC, knee and hip flexion at peak stance, and

knee and hip adduction moments but found no significant differences between fatigue levels in any of these variables. Kamitani et al., (2023) used a high-intensity ergometer FP to induce fatigue in Japanese Women's Soccer League players and evaluate the effects of fatigue on landing posture during drop vertical jumps (DVJs). Kamitani et al., (2023) found no significant differences in KFA pre- and post-fatigue (from 50.0° ± 5.9° to 49.1° ± 6.1° [P = .91]) and ADA was reduced significantly post-fatigue (from 26.4° ± 3.9° to 20.0° ± 3.7° [P = <.001]).

Fatigue protocols in similar studies.

Soccer specific fatigue protocols are often considered the most ecologically valid approach because they replicate the intermittent running, accelerations, decelerations, and changes of direction that occur during match play. However, these protocols can be time and resource intensive, requiring large spaces, lengthy testing sessions, and complex set ups, which can reduce feasibility within laboratory-based biomechanics studies. As a result, many studies adopt alternative protocols that prioritise experimental control and repeatability, while still targeting the lower limb musculature and movement demands relevant to landing and deceleration. This trade-off between ecological validity and feasibility informed the design choice in the present study.

Multiple studies have examined lower-limb biomechanics before and after fatigue. These studies often employ sport-specific fatigue protocols to replicate the physical and physiological demands of the sport, producing data that closely reflects what would be expected during or after actual competition (Alimoradi et al., 2024). Alimoradi et al., (2024) shows how a generic FP can result in different movement quality outcomes when compared to a soccer-specific FP. Alimoradi et al.,

(2024) compared the effects of a generic FP (Bruce treadmill test) and a soccer-specific FP (Soccer-specific Aerobic Fatigue Test 90 [SAFT90]) on movement quality during anticipated and unanticipated change of directions in female soccer players. The results of this study indicate that participants who completed the soccer-specific fatigue protocol exhibited greater changes in cutting motion assessment scores, reflecting poorer movement quality post-fatigue compared with those who completed a generic protocol. However, the study did not evaluate the effects of the two protocols on lower-limb kinetics or kinematics using 3D motion analysis, limiting insights into how fatigue may influence risk factors for non-contact knee injuries. This indicates that the type of FP used in an experiment is a key component when wanting to mimic specific sporting scenarios.

Numerous studies have used the Bruce treadmill test to induce fatigue (Alimoradi et al., 2024; Güler et al., 2020), starting at 0.8 m/s with a 0% incline and increasing speed and incline by 2% every three minutes until either 2.7 m/s at 10% incline or volitional exhaustion was reached, with RPE scores recorded at each stage. Kwon and Williams (2018) employed the same protocol but capped the final speed at 2.5 m/s. While the Bruce treadmill test is effective, quick, and simple to administer, its inability to replicate soccer-specific fatigue patterns limits its validity for studies examining fatigue-related risk factors for non-contact knee injuries.

The SAFT90 protocol has been used in multiple studies, effectively induces fatigue whilst replicating a soccer match scenario (Small et al., 2010; Lehnert et al., 2018). Alimoradi et al., (2024) described it as a course consisting of a 20-metre shuttle run with four poles for the participants to navigate via walking, jogging, side-stepping, and sprinting (common manoeuvres in soccer). Participants would run backwards or side-step around the first pole and then run

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forwards, weaving between the remaining three poles. An audio track controls the movement and intensity, creating a 15-minute sequence that was repeated six times over 90 minutes (split into two 45-minute halves with a 15-minute break in between). The SAFT90 protocol creates a realistic fatigue simulation, incorporating 1269 changes in speed and 1350 changes in direction throughout the 90 minutes, which are similar demands to a real soccer match (Small et al., 2010). However, the FP is extremely time and resource intensive as it requires 90 minutes to complete and a complex setup. These findings informed the present study by highlighting the value of standardising fatigue induction while maintaining feasibility, so that post fatigue landing biomechanics could be measured promptly under controlled laboratory conditions.

Kamitani et al., (2023) used a cycle ergometer to induce fatigue in elite female soccer players, the FP consisted of eight, ten-second pedalling sets at maximum anaerobic power, with 30s rest periods between sets. A positive from using the cycle ergometer to induce fatigue is that it can easily be used and replicated for testing in future studies. However, the biomechanical changes found by Kamitani et al., (2023), mentioned previously in this thesis, may not accurately indicate the changes that would typically occur during a female soccer match (Alimoradi et al., 2024). Harato et al., (2021) used double-legged, bodyweight squats to a depth of 90° knee flexion. In this instance, fatigue was defined as the point where a participant could not complete another squat.

A key reason for conflicting findings across fatigue studies is variation in methodology. Studies differ in the type of fatigue protocol used (for example, treadmill running, cycling, or strength-based circuits), how fatigue is defined (for example, performance decrement, heart rate thresholds, or perceived exertion), and which landing task is assessed (for example, drop jumps,

drop vertical jumps, or cutting). In addition, biomechanical outcomes are reported at different time points such as initial contact, peak values, or mid stance, which can lead to different interpretations even when the same task is used. These methodological differences reduce comparability across studies and support the need for research using clearly defined events and consistent outcome measures.

Khazaee et al. (2021) developed an exercise circuit consisting of 10 single leg squats to 90 degrees knee flexion, 20 single leg vertical jumps, and step ups and downs on a 31 cm step, with fatigue defined when participants reported a Borg score of 10 on the 0 to 10 scale. Although this protocol is not soccer specific, it targets the lower limb muscle groups and single leg loading patterns that underpin landing control and deceleration, which are relevant to common non-contact ACL injury scenarios in soccer. Importantly, this type of circuit is practical to implement within a laboratory session and can enable rapid transition into post fatigue biomechanical testing, reducing the likelihood of recovery masking fatigue effects. For these reasons, and to balance ecological relevance with experimental control and replicability, a modified version of this circuit was selected for the present study with a clearly defined perceived exertion-based stopping criterion.

It is acknowledged that non soccer specific fatigue protocols may not reproduce the full physiological and cognitive demands of match play, therefore findings from laboratory studies should be interpreted in this context.

Methodological considerations.

Harato et al., (2022) tested how biomechanical features of DVJ are different among various female sporting groups (including basketball, soccer, and volleyball). The results found that peak

knee flexion angle was significantly larger in soccer players compared to the other athletes. Knee abduction angle at IC, peak knee abduction angle, knee internal rotation angle, and knee abduction moment within 40ms from IC were significantly smaller in soccer players when compared to the basketball players. These findings suggest that soccer players are at less risk of non-contact knee injury; however, factors such as fatigue are not mentioned in this study.

The soccer players also had better landing error scoring system (LESS) scores than the other athletes. Padua et al., (2009) suggests that the LESS procedure identifies athletes presenting high-risk biomechanical patterns during a jump-landing task. The LESS procedure is a commonly utilised tool used to identify athletes that present high injury-risk biomechanical patterns when jumping and landing (Hanzlíková & Hébert-Losier, 2020). Padua et al., (2015) completed baseline LESS testing for 829 elite-youth soccer athletes (male and female) and follow-ups were taken throughout the seasons for ACL diagnoses. During the follow-up period, seven participants sustained ACL injuries. Injured participants exhibited higher LESS scores (6.24 ± 1.75) compared with uninjured participants (4.43 ± 1.71), P = 0.005. Analysis of the receiver operating characteristic curve indicated that a LESS score of 5 was the optimal cut point for identifying athletes at increased risk of injury. Therefore, the purpose of this thesis is to use both motion analysis and the LESS scores to profile female soccer players' risk of injury when in a fatigued state compared to a pre-fatigued condition and compare results between athletes that have significantly different LESS scores to see how jumping ability effects lower limb biomechanics pre- and post-fatigue. The LESS procedure relies on a DJ-landing task (explained step-by-step in the methodology of this thesis), scored for movement errors.

Akbari et al., (2023) assessed the differences in trunk and lower extremity biomechanics when heading a soccer ball and performing DJs. The study found that when performing the header during DJs, there was significantly reduced peak knee flexion angle (KFA) (Δ = 5.35°; P = .002) as well as other kinetic and kinematic changes including decreases in knee flexion displacement (Δ = 3.89°; P = .015) and hip flexion angle at IC (Δ = -2.84°; P = .001), and increased knee joint stiffness (Δ = 0.002 N*m/kg/deg; P = .017), all of which suggest increased risk of ACL injuries when compared to the standard DJ task. Mok et al., (2017) also tested the effect of an overhead target on lower limb biomechanics during DJs in elite female athletes. However, the results showed that all changes in kinematics and kinetics were clinically insignificant. The methodology in the Mok et al., (2017) study used a horizontal bar as the overhead target, around 30cm ahead of the athlete. The bar height was set based on previous jump tasks and if the athlete was able to reach the bar with their head, the bar height was increased by 5cm or less. This methodological difference may explain the contrasting biomechanical and movement patterns in comparison to the Akbari et al., (2023) study, which had participants heading a stationary soccer ball at a height determined by their maximum jumping performance. This change of target could be a contributing factor as to why the two studies found contradicting results. Implementing heading a soccer ball during DJs was not possible in this thesis, however this change in methodology would provide a closer, sports-specific insight into the context behind non-contact knee injuries in soccer.

Summary and identification of gaps.

Despite extensive research into non-contact ACL injury risk, important gaps remain within soccer specific fatigue biomechanics literature, particularly in female players. Findings on fatigue related

changes in knee biomechanics are inconsistent, partly due to differences in fatigue protocols, fatigue definitions, landing tasks, and the events selected for analysis. In addition, while ankle dorsiflexion range of motion has been linked to landing quality and knee loading, there is comparatively limited research directly assessing ankle joint moments across the frontal, sagittal, and transverse planes during drop jumps under fatigue. Therefore, further research is needed that evaluates both ankle and knee kinematics and external joint moments in multiple planes at clearly defined landing events, such as initial contact and mid stance, to better clarify whether fatigue meaningfully alters landing mechanics associated with non-contact knee injury risk in female football players.

Thesis purpose.

The purpose of this study was to determine whether fatigue alters ankle and knee biomechanics during drop jumps in female university football players. Specifically, ankle and knee joint angles and external joint moments were analysed in the frontal, sagittal, and transverse planes at initial contact and mid stance before and after fatigue. This design addresses key limitations in the literature by using clearly defined landing events and including ankle biomechanics alongside knee biomechanics, which is less commonly reported in fatigue related landing studies. Findings from this study may help clarify whether fatigue meaningfully changes landing mechanics linked to non-contact knee injury risk, supporting future research and informing applied injury prevention practice in football settings.

To conclude, the aim of this study was to ascertain whether there were any differences in knee and ankle biomechanics in female soccer university soccer players pre- and post-fatigue, utilising

a FP that targets the same muscles that influence non-contact knee injuries in female soccer, to try and create solid connections between lower limb biomechanics and fatigue. Results from this study may help improve knowledge surrounding increased risk of non-contact knee injuries in female soccer players and aid in the development of injury prevention plans, resulting in fewer injuries during competition and training.

Research questions.

The study hypothesis was that ankle and knee angles and moments in the frontal, sagittal, and transverse planes at initial contact and mid-stance of the first phase of DJs would be significantly altered at post-fatigue; highlighting biomechanical parameters associated with risk of non-contact knee injury in female soccer players.

CHAPTER III

Methodology

Background.

This chapter outlines the design and methodology employed to assess lower-limb biomechanics during DJs in pre- and post-fatigue conditions in university soccer players.

All motion capture data was collected at the University of Kent's Biomechanics Laboratory as part of a Master's by Research and Thesis project. The participant pool comprised of healthy female soccer players; a population identified as being at an elevated risk for lower limb injuries during high-impact activities in comparison to their male counterparts (Arendt and Dick 1995). Ethical approval for the study was granted by the University of Kent, Sport, Exercise, and Rehabilitation Research Ethics Advisory Group. All participants were provided with written informed consent forms prior to data collection.

Although soccer specific fatigue protocols can replicate the physical demands of match play more closely, many require prolonged testing time and a large running area, which can reduce feasibility within a single laboratory visit. Therefore, the present study prioritised a controlled and repeatable method of inducing lower limb fatigue that could be implemented efficiently in the biomechanics laboratory while still targeting movement patterns relevant to soccer, including repeated single leg loading, stepping, and jumping actions.

At the start of each day of testing, the lead experimenter worked through a checklist that listed all equipment necessary for testing. This included a Lode (Lode BV; Groningen , Netherlands) Corival cycle-ergometer for the warm-up, an Output Sports device (Output Sport, Dublin, Ireland) to measure single-legged CMJ height), a 12" platform to perform the drop jumps (DJs), foam blocks to adjust the single-leg box squat height performed during the fatigue protocol, an L-frame, a 750.7mm calibration wand to calibrate the cameras, all retro-reflective markers necessary, two Sony 4K FDR-AX53 Camcorder's (Sony, Japan) for the LESS procedure, a stadiometer to measure height, and a scale to measure body mass. Under the circumstance where a participant was unable to follow the instructions to any of the tasks, they were to be deemed ineligible for testing.

Data collection.

Twelve healthy University female soccer players across three levels of competition volunteered to take part in this single-visit observational study. The demographic characteristics of the participants are summarised in Table 3.1. To provide greater clarity regarding the sample, participants were recruited from three levels within the University of Kent Women's Football programme. Three participants were members of the 1st Team, six participants were members of the 2nd Team, and three participants were members of the 3rd Team. The 1st and 2nd Teams competed in BUCS leagues with weekly fixtures, while the 3rd Team served as a development squad that primarily played non-competitive friendly fixtures.

Table 3.1. Demographic characteristics of study participants.

	Age (years)	Height (cm)	Mass (kg)
n = 12	20.4 ± 1.2	167.4 ± 5.8	66.2 ± 8.4

The inclusion criteria were healthy female collegiate soccer players who regularly train as part of a university soccer team (minimum 2 times per week) and have not participated in strenuous exercise within 24 hours prior to testing. The exclusion criteria was a history of lower limb surgery, lower limb injury within the last 8 weeks leading up to testing that led to an absence from sport for more than 28 days, pregnant, have been told they have high blood pressure (>140/90 mm Hg), cardiovascular disease, metabolic disease, uncontrolled respiratory disease (exacerbation in past 3 months), joint problems that would impair full functional movement, viral infections/illness within the past 2 weeks, or were unable to understand instructions to take part in the study assessments.

Informed consent and questionnaire.

All participants received a digital copy of the Participant Information Sheet (PIS) (Appendix A) at least three days prior to their laboratory visit. The PIS explained the purpose of the study, the inclusion and exclusion criteria, the procedure, and how the data would be anonymised and stored.

Upon arriving to the laboratory, the participant was given an additional copy of the PIS and given the opportunity to ask the researcher any questions. After which, the participant signed an

informed consent form (Appendix B) followed by a pre-activity readiness questionnaire (PAR-Q) form (Appendix C).

Clothing.

All participants were asked to wear tight-fitting, non-reflective sportswear (such as leggings and a t-shirt) to allow full movement to perform the jumping tasks and to ensure the passive retro-reflective markers were always visible. Except for the warm-up and LESS procedure, all remaining tasks were performed in an unshod condition. This was to standardise the potential effect of footwear during the jumping tasks (Hébert-Losier et al., 2023). However, testing participants barefoot may limit external validity of the findings in relation to soccer play, where non-contact knee injuries typically occur during manoeuvres performed in soccer cleats. Using an unshod condition improved internal validity by removing variation introduced by differences in shoe type, sole stiffness, and cushioning across participants, which can influence ground reaction forces and lower limb joint mechanics during landing. This standardisation allowed observed changes to be attributed more confidently to the fatigue condition rather than footwear differences.

Although unshod testing improves standardisation, it may reduce ecological validity because soccer is typically performed in boots. Therefore, findings from the present study are interpreted as representing fatigue related changes in controlled landing mechanics rather than direct replication of match play conditions. This trade off was considered appropriate given the study aim to quantify biomechanics under standardised laboratory conditions.

Anthropometric and background data.

The participants' age (years), height (cm) and mass (kg) were recorded. The participant was then questioned on their sporting history (years played, positions played, team history etc), what their dominant leg is (as this is the leg that would be targeted in during the fatigue protocol), food and drink consumption on the day of testing and basic menstrual cycle questions to gauge phase of cycle on the day of testing.

Lower limb assessment.

Two distinct multi-camera configurations were used for data collection during this study. For the initial cohort of five participants, a configuration made up of eleven Qualisys (Qualisys, Sweden) (refer to Appendix D for the list of camera models used) cameras was used to record the position of the retro reflective markers in 3D space. For the subsequent seven participants, data collection was conducted under an eight-camera setup, this was due to other ongoing studies at the University. Figure 3.1 shows a screenshot taken from QTM that displays the original, eleven-camera setup. The decrease in cameras used for data collection did not affect the results of the study as both configurations achieved comparable data quality, consistently achieving residual errors below 1.0mm during wand calibrations prior to each day of testing.
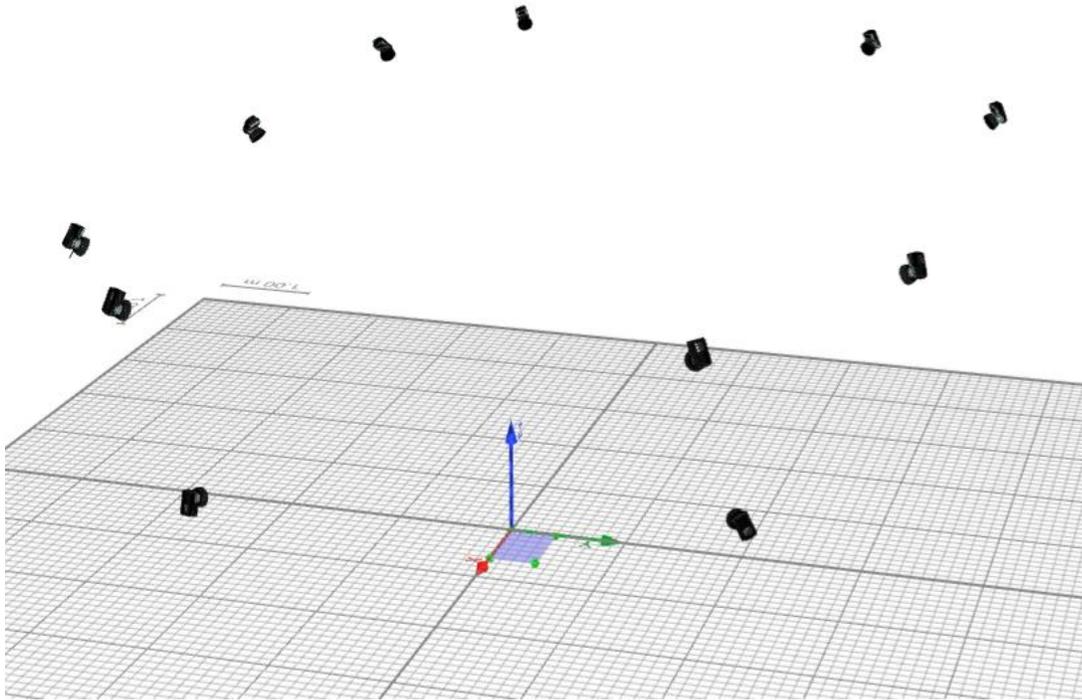
Figure 3.1. Diagram of the original, eleven-camera motion capture set up.

Calibration.

Prior to a data collection session, all motion capture cameras were calibrated. For this study, Qualisys Track Manager (QTM) version 2025.1 was used. A calibration wand with a 750.7mm marker separation and an L-frame (77.47cm x 58.42cm) was used to calibration the area of interest in the laboratory.

The L-frame was placed on the bottom-right corner of the force plate, aligned with the jumping direction. The calibration wand was waved throughout the area that is used during the DJs for 90 seconds to ensure full coverage. Upon completion, QTM reported the residual errors for each

camera, reflecting the difference between expected and observed wand marker positions. If any residual was greater than 1.0mm, the calibration process was repeated to ensure accurate marker tracking. Figure 3.2 illustrates what an acceptable calibration and a rejected calibration would look like.

Force was simultaneously captured with the motion capture system. An AMTI BMS400600 force plate (AMTI, Massachusetts, USA) was imbedded into the ground on the DJ landing area and was used to measure ground reaction forces throughout the DJs at a frequency of 1000 Hz. The force plate was located on QTM by placing a retro-reflective marker at the end of each corner of the force plate, then taking a short recording, identifying the four individual markers and using them to locate the position and orientation of the force plate within the global coordinate system of the laboratory.

(a) An accepted calibration   (b) A rejected calibration

Figure 3.2. Screenshots of (a) an accepted calibration, and (b) a rejected calibration.

Assessment preparation.

20 individual retro-reflective markers alongside four clusters made up of four retro-reflective markers (as shown in Figure 3.3) were used for motion capture data collection. Prior to each participants arrival, double-sided tape was applied to all individual markers, and the clusters were checked to ensure they were ready for use. Double-sided tape was applied to additional individual markers to save time if markers had to be re-applied after the fatigue protocol. This additional preparation meant that participants were given minimal rest periods before undergoing the post-fatigue tests.
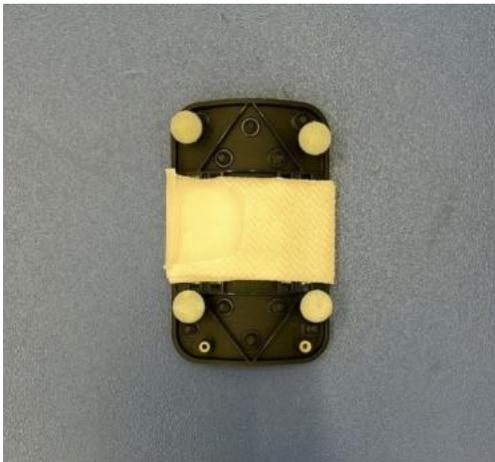
Figure 3.3. Image of a marker cluster, made up of four retro-reflective markers, used to track limb movement using 3D motion capture software.

Retro-reflective marker placement and marker set.

Marker placement followed the CAST lower body marker set (Cappozzo et al., 1995) as shown in Figure 3.4. Anatomical markers were used to define segment dimensions. The tracking markers were used to calculate how segments translate and rotate in relation to each other. Markers connected by a bold line indicated a cluster. A minimum of three tracking markers had to be identified throughout an entire trial for the calculation of joint rotations and translations in the three planes (sagittal, frontal and transverse). If this minimal marker requirement was not met, that trial was discarded.
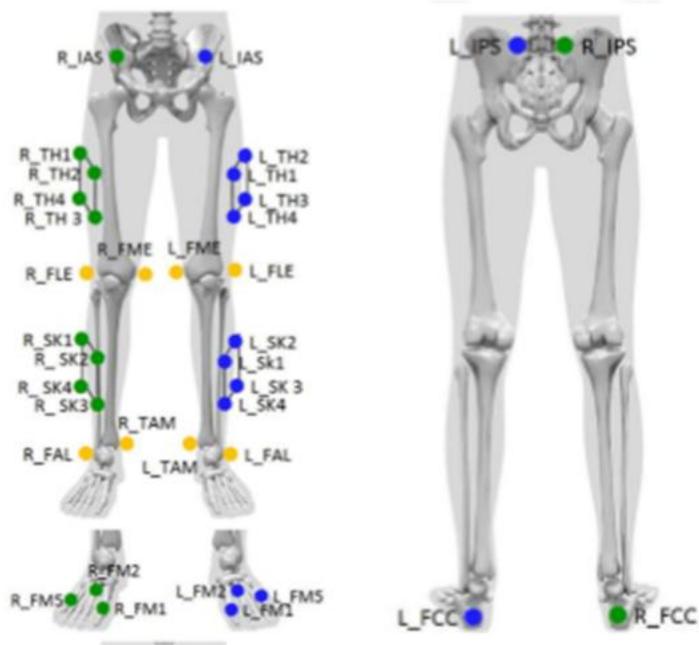
Figure 3.4. Lower body marker set taken from Cappozzo et al., (1995), used to define lower-limb segments.

Assessments.

After a standardised warm-up (including a 5-minute cycle at a moderate intensity and dynamic stretches), participants performed the Landing Error Scoring System (LESS) procedure, which after a demonstration meant the participant: (a) Jumped forward off a 12" platform with both feet, landing with both feet simultaneously beyond the target line (positioned half the participant's height ahead of the platform to ensure forward momentum); (b) Immediately jumped vertically for maximal height; and (c) landed with both feet. Steps a-c was repeated three times. Figure 3.5 shows screenshots of the LESS procedure at key points of the manoeuvre.
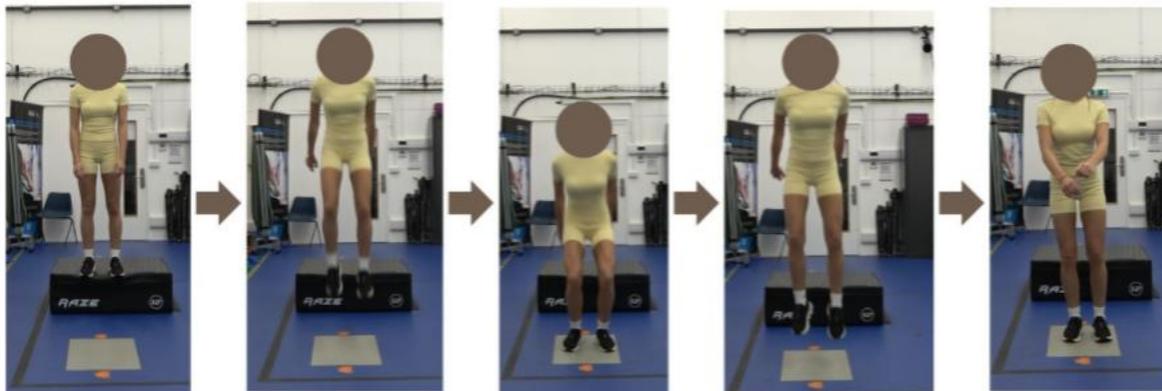
Figure 3.5. Visual demonstration of the LESS jump-landing procedure used in this study.

Two cameras were set up to record the jump in both the sagittal and frontal plane, with the cameras placed at a height of 1m and at a distance of 3.048m from the landing area. There are multiple analysis methods including manual video review (Padua et al., 2015), real-time (live)

scoring (Schwartz et al., 2020), and automated marker-less system analysis (Mauntel *et al.* 2017). As it is a low cost, easily accessible and validated analysis method, the manual video review method was chosen for this study. LESS scoring was conducted using the standardised criteria described by Padua et al. (2015). Each participant completed three LESS trials, and each trial was scored for observable landing technique errors using the standard LESS item criteria across sagittal and frontal plane video footage. The mean LESS score across the three trials was calculated for each participant and used in subsequent analysis. Participants were categorised as lower risk (LESS score less than 5) or higher risk (LESS score 5 or greater), consistent with previously proposed thresholds. The interpretation of the recordings was completed by the lead experimenter, based on standardised criteria (Padua et al., 2015), after the laboratory session was completed.

The participant was then instructed to complete three, maximal effort, single-legged countermovement jumps (CMJs), unshod and with hands on hips throughout. Participants then repeated these jumps following completion of the fatigue protocol. The highest jump out of the three scores was used going forward. Likewise for the post-jump scores. The difference in maximal jump height between the pre- and post-fatigue CMJs were compared and used as an indicator as to whether fatigue had been induced. A reduction in single leg CMJ height following the fatigue protocol was used as an objective manipulation check to support the subjective fatigue criterion, consistent with recommendations to combine subjective and performance-based indicators of fatigue.

Static calibration.

After applying all retro-reflective markers and clusters, a static trial was recorded. The participant was asked to stand upright on the force plate with feet, shoulder-width apart with arms extended horizontally at a 90° angle from the torso, palms facing down, forming a 'T' shaped pose, for at least three seconds. This recording was required for data processing in Visual3D (C-Motion, Maryland, USA) and anatomical landmarks were defined using the markers placed on anatomical landmarks and captured during the static calibration trials. This process was completed before the pre-fatigue DJs and after the fatigue protocol, right before the post-fatigue DJs.

Drop jump trials.

Six successful DJs were recorded pre- and post-fatigue. Participants would continue to repeat the manoeuvre until six successful DJs were recorded. Six trials were collected per condition to improve the reliability of the biomechanical measures, as landing mechanics can vary across repetitions even within the same participant. Collecting multiple trials reduces the influence of outlier performances and provides a more reliable estimate of typical landing mechanics at initial contact and mid stance. Only trials that met the predefined success criteria were retained to ensure consistent force plate contact and marker tracking quality. For each participant, the mean of the retained successful trials was used for statistical analysis to represent typical performance within each condition. The 12" platform was moved to line up against the force plate (but without contact to the force plate). Participants were designated time to familiarise themselves with the manoeuvre before the pre-fatigue trials. This DJ sequence is visualised in Figure 3.6. A successful DJ is as described:

a. The participant would stand on the edge of the platform.

b. The participant dropped forward from the platform, landing simultaneously with both feet (dominant leg on the force plate, non-dominant leg off) to assess dominant leg vGRFs (however this analysis was not conducted due to time constraints).

c. When landing, the participant would bend their legs and propel themselves vertically as high as they could. Unlike during the CMJs, the participants were encouraged to swing their arms when jumping to replicate a typical style of jumping often carried out in soccer matches.

d. The participant would then land again, landing with both feet simultaneously but with their dominant leg on the force plate.
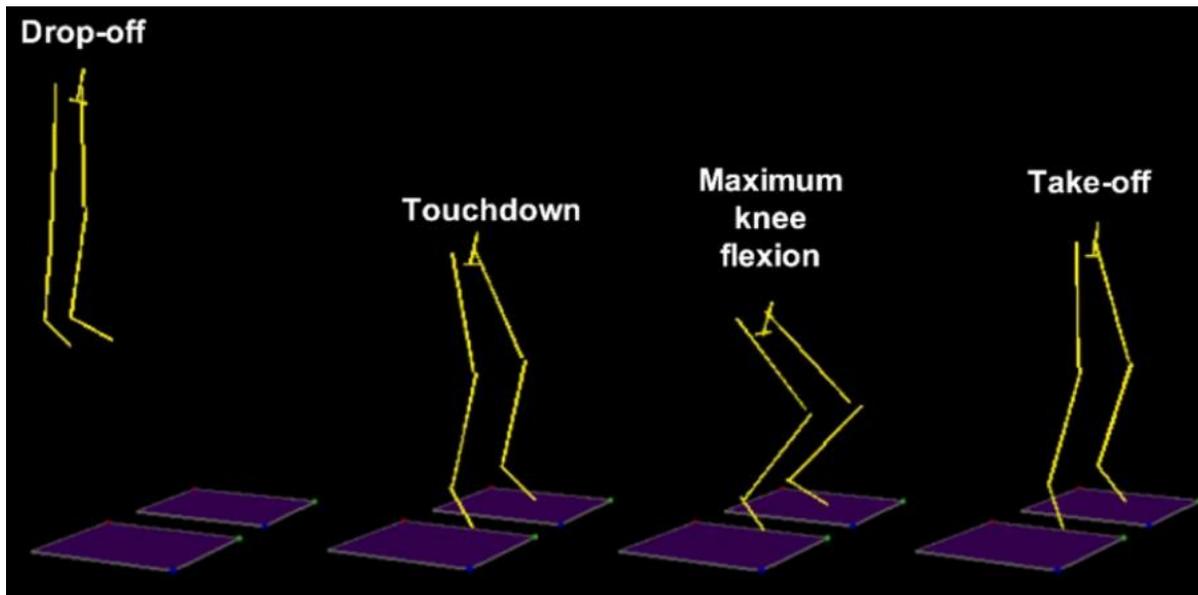
Figure 3.6. Visual representation of a successful DJ manoeuvre, Retrieved from: Alonzo et al., (2020).

A DJ was considered unsuccessful, and therefore invalid, if: the participant's dominant foot did not land fully on the force plate during both landings; if both feet contacted the force plate at any time during the manoeuvre; or if the manoeuvre was not completed as explained (i.e. the participant only landed on one foot). The decision to use a 12" (30.48cm) box for the DJs was influenced by trends found when comparing recent literature with similar objectives (Mancini et al., 2022). Drops from this height also provided a balance between detecting biomechanical changes and safety for participants, allowing for repeatability of the test with minimal levels of risk for the participants.

These procedures were designed to maximise measurement quality and internal validity by ensuring consistent task execution, reliable force plate contact, and adequate marker visibility across trials. While this controlled approach supports accurate estimation of joint angles and moments, it is acknowledged that laboratory-based DJs are a simplification of soccer specific landing scenarios, and this is considered when discussing the applicability of the findings.

Fatigue protocol.

The fatigue protocol used in this study was a modified exercise circuit adapted from Khazaee et al. (2021) and was selected to induce lower limb neuromuscular fatigue in a controlled and repeatable manner. While not soccer specific, the circuit targeted single leg strength and landing related demands relevant to soccer and was feasible to implement within a single visit laboratory protocol. The original circuit goes as followed:

   a. 10 repetitions of single-legged squats up to 90° knee flexion.

   b. 20 vertical jumps with a single leg.

    c. One repetition of a step-up and down on a 30cm box.

The modified version used in this study goes as followed:

    a. 10 repetitions of a single-legged box squat up to 90° knee flexion.

    b. 10 vertical jumps with a single leg.

    c. 10 repetitions of a step-up and down on a 12" box/platform.

Soccer specific fatigue protocols, such as match simulation or shuttle-based protocols, were considered because they can replicate frequent changes in speed and direction. However, these protocols can be time intensive and require large spaces and complex set ups, which can limit practicality within laboratory based biomechanical testing. In contrast, the present circuit-based approach was chosen to balance ecological relevance with experimental control by directly fatiguing the lower limb musculature involved in landing and stabilisation, while enabling rapid transition into the post fatigue biomechanical trials with minimal recovery time.

All single leg exercises were performed on the participant's dominant leg and in an unshod condition. At the end of each full circuit, the participant rated exertion using the Borg 0 to 10 scale (Figure 3.7). Fatigue was deemed to have been reached when the participant reported a Borg score of 9 or above, or when the participant was unable to complete a repetition of any exercise within two consecutive attempts. If a score lower than 9 was reported, the participant repeated the circuit until a score of 9 or above was achieved. There was no planned rest period between circuits, although participants were permitted to pause briefly for water if required. This stopping criterion was selected to standardise the fatigued condition across participants, while maintaining a practical testing workflow that limited recovery before post fatigue measurements.

Once fatigue was induced, the participants repeated the CMJ protocol again, which consisted of three maximal effort single-legged CMJs (unshod), this was done to compare maximum CMJ heights pre- and post-fatigue to observe changes in single-legged CMJ heights as an indicator of fatigue induction. Any markers that fell off during the fatigue protocol were replaced and a static calibration trial was recorded once again, before going into the post-fatigue DJs.

1 - 10 Borg Rating of Perceived Exertion Scale	
0	Rest
1	Really Easy
2	Easy
3	Moderate
4	Sort of Hard
5	Hard
6	
7	Really Hard
8	
9	Really, Really, Hard
10	Maximal: Just like my hardest race

Figure 3.7. 0-10 Borg Scale, used by participants to rate perceived exertion between each round of the fatigue circuit.

This approach was informed by literature highlighting that fatigue related biomechanical changes vary depending on how fatigue is induced and how fatigue is defined. The present protocol was therefore designed to fatigue the lower limb in a way that is relevant to landing control, while using a clear and reproducible stopping criterion and allowing immediate post fatigue drop jump assessment to reduce the likelihood of recovery masking fatigue effects. Although the protocol was not soccer specific, it was chosen to prioritise experimental control, feasibility, and replicability, and this limitation is considered when interpreting the findings.

Marker tracking.

Marker location data (with x,y,z coordinates) was captured during all trials in QTM (Qualisys, Sweeden). This is relevant for the static trials as the locations of each marker was identified and labelled and then used to define an Automatic Identification of Markers (AIM) model which was then applied to that participants' DJ trials. This made identifying the trajectories of all markers semi-automated.

Once that AIM model was applied to the successful DJ trials, any marker gaps would be filled if the marker dropout was >20 frames. If a marker did not have a 100% fill level, this was noted on an Excel spreadsheet (as shown in Appendix E) so that individual marker could be disregarded during the data analysis if there were at least 3 other markers in that segment with a 100% fill level. If a dominant leg segment or the pelvic segment could not be made due to a lack of eligible markers, that trial was disregarded. Once all QTM files were labelled and gap-filled, they were batch processed and exported as .c3d for analysis in Visual3D (C-motion, Maryland, USA) (visual comparison of a trial in QTM and Visual3D can be seen in Figure 3.8).
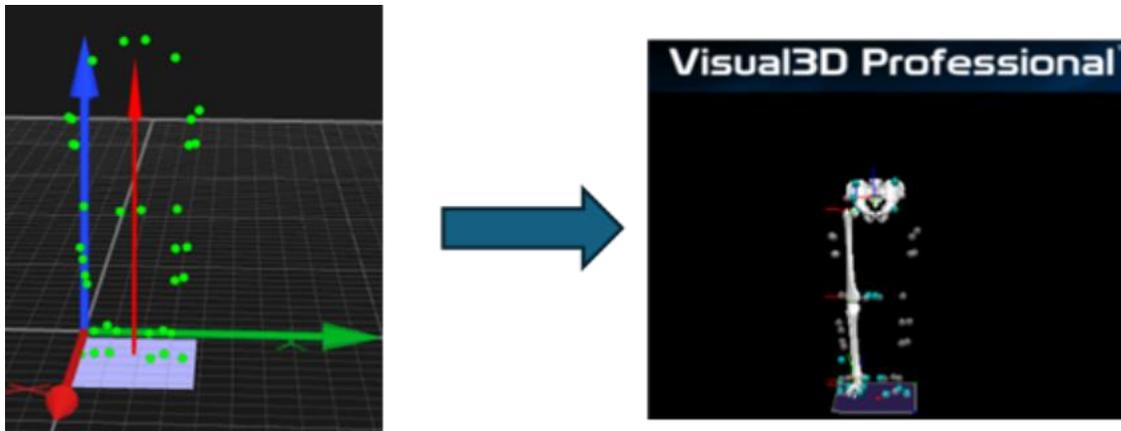
Figure 3.8. Visual comparison of how the markers are displayed in QTM (left) and used to create segments in Visual3D (right).

Variables and measurements.

This was measured with the use of Qualisys (Qualisys, Sweden) motion capture equipment. The Qualisys cameras used utilise spherical infrared markers to track movement in a 3D space. The markers reflect infrared light, which is emitted by the cameras which is recorded, allowing for precise tracking of the position of each individual marker. The cameras captured data at a frequency of 100 Hz. Knee and ankle external moments at IC and MS in the transverse, sagittal and frontal planes were measured alongside knee and ankle joint rotations at IC and MS in the transverse, sagittal and frontal planes. Ankle and knee joint kinematics were defined as joint angles of the distal segment relative to the proximal segment and are reported in degrees (°) in the sagittal, frontal, and transverse planes. Kinetic variables were defined as external joint moments, representing the net external torque acting about the joint due to the ground reaction force and segment dynamics, calculated using inverse dynamics in Visual3D. External joint moments are reported as normalised values expressed as body weight multiplied by height

(%BW.h) to allow comparison between participants of different sizes. Ground reaction forces were recorded in Newtons (N) and were normalised to body weight (%BW) where reported. Initial contact was defined as the instant the dominant limb first contacted the force plate during the analysed landing phase, and mid stance was defined as the mid-point of the stance phase for the analysed landing, determined from the vertical ground reaction force time series within Visual3D.

Data processing.

Marker trajectories were labelled in Qualisys Track Manager (QTM). Gaps of 20 consecutive frames or fewer were filled in QTM, while larger dropouts were left unfilled. Trials were retained only when the pelvis and dominant limb segments could be defined throughout, requiring a minimum of three valid tracking markers per segment. Retained trials were exported as .c3d files and processed in Visual3D (C Motion, Maryland, USA) using a custom pipeline to compute kinematics, kinetics, and vertical ground reaction force.

Force plate data only were filtered within Visual3D prior to kinetic calculations, while marker trajectory data were not filtered. A six degree of freedom model was created for each participant from the static calibration trial, with segment coordinate systems defined using anatomical and tracking markers and inertial properties estimated from recorded anthropometrics.

Knee and ankle joint centres were defined as the midpoints of the femoral epicondyles and malleoli, respectively. External ankle and knee joint moments were calculated using inverse dynamics from segment kinematics, ground reaction forces, and centre of pressure, then extracted at initial contact and mid stance and normalised to body weight multiplied by height

(%BW.h). Joint angles were calculated using a Cardan or Euler X Y Z rotation sequence consistent with ISB recommendations, with angles defined as the orientation of the distal segment relative to the proximal segment.
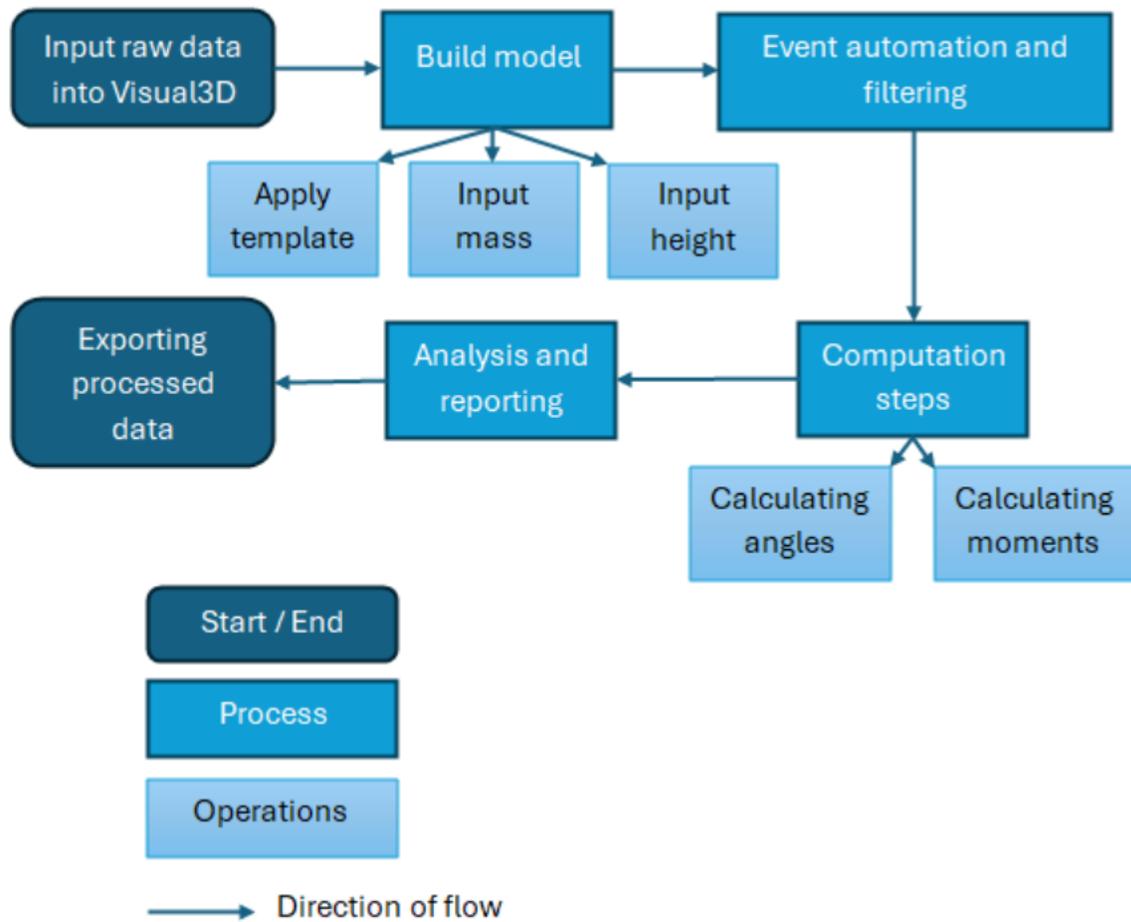
Figure 3.9. A flow chart illustrating the stages of the Visual3D pipeline used to process and export ankle and knee kinetic and kinematic data during drop jumps.

Analysis.

After the data was processed via Visual3D, 24 discrete dependent variables were then exported

to a Microsoft Excel spreadsheet (shown in appendix F). From there, the variables were imported

into Statistical Package for the Social Sciences (SPSS) (SPSS, Chicago, Illinois) document, ready for

statistical testing. In SPSS, all biomechanical parameters were paired (pre- and post-fatigue), and

a Shapiro-Wilk test of normality was performed. For any parameters that were normally

distributed (P = >.05), a paired samples t-test was performed, and for any parameters that were

not normally distributed, a Wilcoxon non-parametric test was performed. This process was

repeated twice, once with the data collected from all the participants (n = 12), and then only

those who demonstrated objective evidence of fatigue (n = 9) because the fatigue manipulation

did not affect all participants uniformly. Although all participants completed the fatigue protocol,

a reduction in single leg CMJ height was used as an objective manipulation check of fatigue

induction.

Accordingly, the full-sample analysis (n = 12) reports overall pre vs post changes for the whole

cohort and avoids selectively excluding participants, while the subgroup analysis (n = 9) provides

a more internally valid test of the study's primary question by focusing on participants for whom

fatigue was confirmed. This second analysis reduces the likelihood that any null or attenuated

effects are driven by non-responders who may not have been meaningfully fatigued at the time

of post testing. I have clarified this rationale in the Methods/Analysis section and have tempered

interpretation by treating the fatigued-only results as a sensitivity analysis rather than the

primary outcome.

Ethical considerations.

Data collection commenced only after approval from the University of Kent's Sport, Exercise, and Rehabilitation Sciences Research Ethics Advisory Group (December 2024). Participants were anonymised using unique codes (e.g. P_011), and all sensitive documents were securely stored in a locked cabinet. Digital files were saved on a cloud-based drive and a password-protected laptop, with access restricted to the research team.

CHAPTER IV

Results

The study cohort comprised twelve female soccer players (mean age: 20.4 ± 1.2 years; mean height: 167.4 ± 5.8 cm; mean body mass: 66.2 ± 8.4 kg) recruited from three competitive levels within the University of Kent Women's Football programme. Two teams competed in British Universities and Colleges Sport (BUCS) leagues with weekly fixtures, while the third team played non-competitive friendly matches.

Landing error score system (LESS) procedure.

The mean LESS score across the three jumps for each participant was calculated and used for analysis. Participants were categorised as low risk (LESS score less than 5) or high risk (LESS score of 5 or greater) in line with Padua et al. (2015). Ten of the twelve participants were classified as low risk, while two participants were classified as high risk (Figure 4.1).
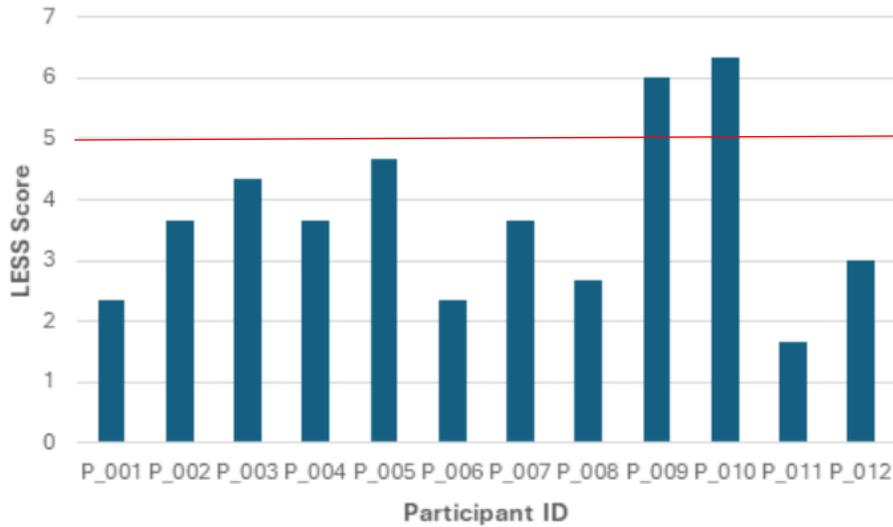
Figure 4.1. Bar graph of each participants' LESS score.

**Red line indicates threshold for the high-risk category (Padua et al., (2015).

Fatigue protocol.

Participants completed the fatigue protocol until they reported a rating of perceived exertion of 9 on the 0 to 10 Borg scale. No participant was stopped due to failure to complete repetitions. The mean number of circuit sets completed was 10.3. Eleven participants completed between 4 and 10 sets, while one participant completed 44 sets (Appendix G).

Single-legged CMJs.

Eleven participants completed three maximal effort single-legged CMJs pre and post fatigue to assess the presence of fatigue. The highest CMJ height from the three trials was retained for each condition. After confirming normality using the Shapiro Wilk test, pre and post fatigue values were compared using a paired samples t test. CMJ height decreased significantly from 11.91

(3.87) cm pre fatigue to 9.93 (2.76) cm post fatigue, representing a 16.6 per cent reduction (P

= .002) (Table 4.1). Two participants demonstrated higher CMJ height post fatigue and one

participant did not complete CMJs, therefore individual values are presented for n = 11 (Figure

4.3).

Table 4.1. Paired samples t-test results, indicating statistically significant changes in single-legged CMJ performance pre- and post-fatigue.

	Pre-fatigue Mean (std)	Post-fatigue Mean (std)	Percentage change	Pre- vs post-fatigue *P* value
CMJ height (cm)	11.91 (3.87)	9.93 (2.76)	16.6% decrease	.002**

Two participants showed an increase in maximum single-legged CMJ height post-fatigue, and a

third participant did not complete the single-legged CMJs pre- or post-fatigue. Figure 4.3

illustrates individual maximum heights pre- and post-fatigue for all participants that completed

them (n = 11).
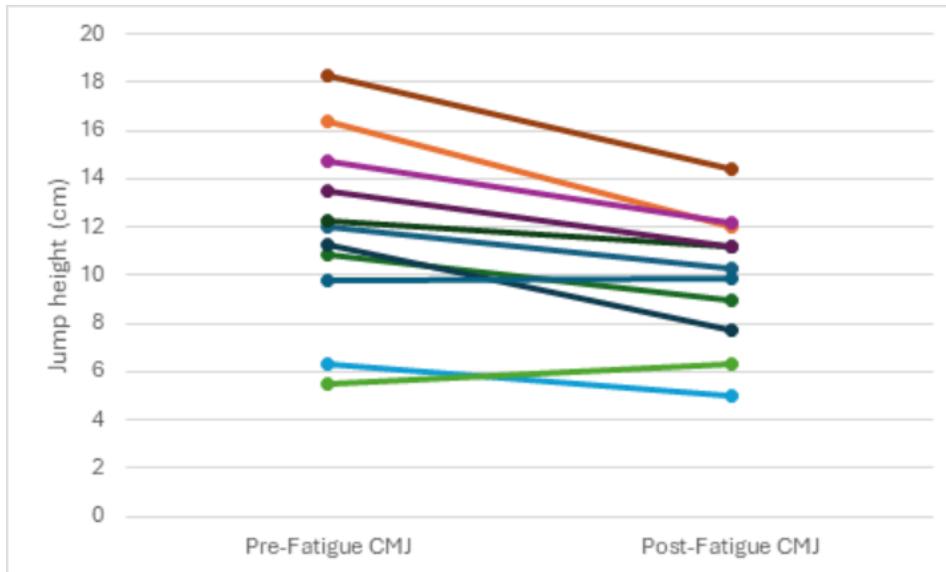
Figure 4.3. Line graph illustrating each participant's maximum single-legged CMJ, pre-and post-fatigue.

Visual 3D Outputs.

External ankle and knee joint moments and joint angles were extracted at initial contact and mid stance during drop jumps for the dominant leg. Across all 24 dependent variables, there were no statistically significant differences between pre and post fatigue conditions (all P greater than .05). While no statistically significant differences were observed, the small sample size limits statistical power, and therefore non-significant findings should not be interpreted as evidence that fatigue has no effect on ankle or knee biomechanics. For example, ankle dorsiflexion angle at mid stance was 32.64 (3.35) degrees pre fatigue and 30.78 (5.54) degrees post fatigue (P = .162) (Table 4.2.1), and knee flexion angle at initial contact was 28.48 (5.48) degrees pre fatigue and 28.94 (6.20) degrees post fatigue (P = .663) (Table 4.2.3). Similarly, external knee flexion moment at mid

stance was 9.26 (3.17) %BW.h pre fatigue and 8.93 (3.54) %BW.h post fatigue (P = .577) (Table 4.2.4), and external ankle dorsiflexion moment at mid stance was 6.63 (2.32) %BW.h pre fatigue and 6.31 (2.06) %BW.h post fatigue (P = .356) (Table 4.2.2).

An example of a participant (participant 7, pre-fatigue) biomechanical assessment is shown below from a customed Visual 3D Report:
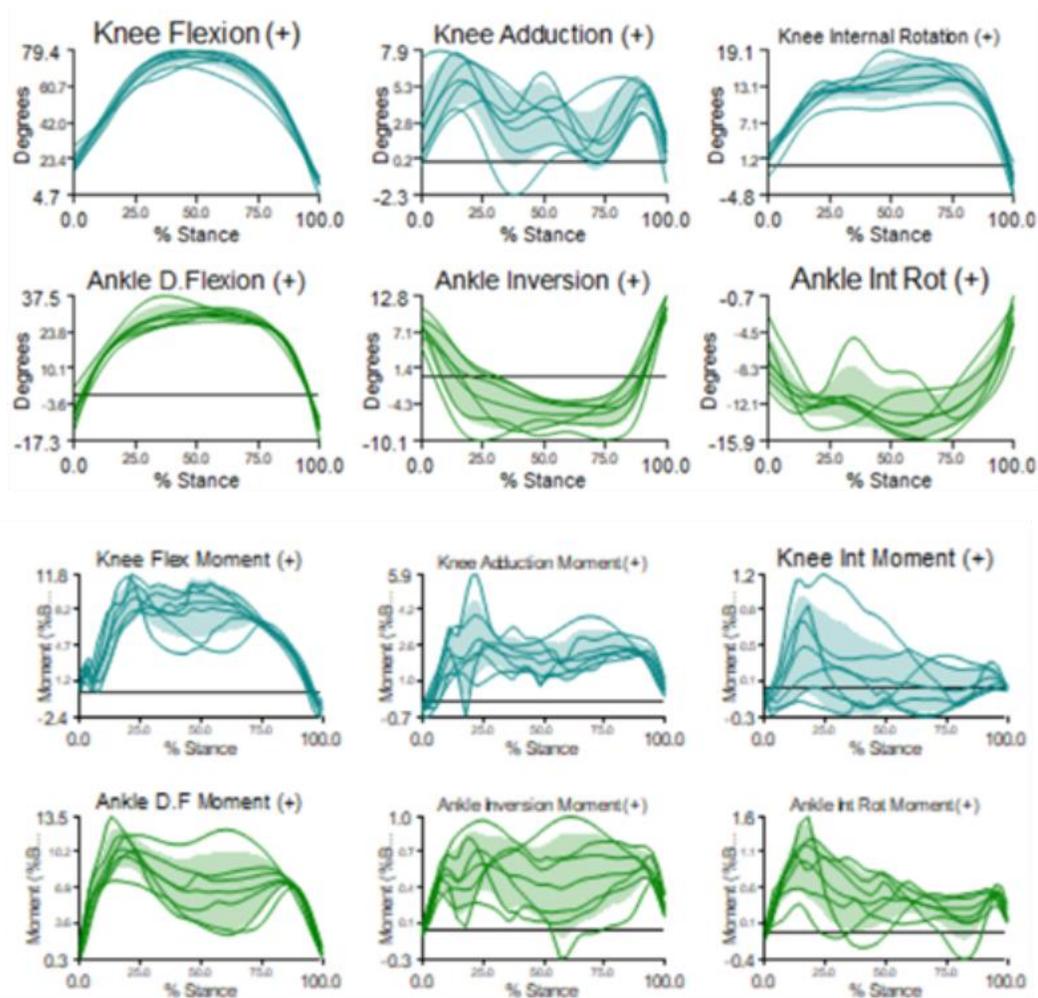
Figure 4.4. Screenshots showing an example of a Visual3D biomechanical assessment report after all pipeline commands were run. This specific figure displays participant 7's pre-fatigue data.

All raw ground reaction force (GRF) data were processed using a fourth-order, zero-lag Butterworth high-pass filter with a cut-off frequency of 30 Hz. The choice of filter and cut-off was guided by the signal characteristics of jumping biomechanics. Vertical GRF signals contain high-frequency components associated with impact transients during take-off and landing, which can

be masked by low-frequency drift or baseline artefacts inherent in force plate recordings. A high-pass filter at 30 Hz effectively removes slow-varying trends and offsets, while retaining the rapid fluctuations that are mechanically relevant to explosive jumping movements.

Previous biomechanical research has demonstrated that cut-off frequencies in the range of 10-50 Hz are appropriate when analysing ballistic tasks such as jumping, drop landings, and cutting manoeuvres, since these actions involve short-duration, high-force impulses with substantial high-frequency content (e.g., Challis, 1999; Kristianslund et al., 2012). The 30 Hz threshold was therefore selected as a balance between attenuating low-frequency noise and preserving the fidelity of the force signal required for reliable identification of key performance metrics such as peak GRF, rate of force development, and impulse. Using a zero-lag (bidirectional) filter ensured that no phase shift was introduced into the time-domain signals, which is critical for accurate determination of temporal events including jump onset and take-off.

Figure 4.5. shows the effect of filtering analogue data with a low pass 30 Hz Butterworth filter. Both screenshots show knee flexion moments during DJs in the same participant.
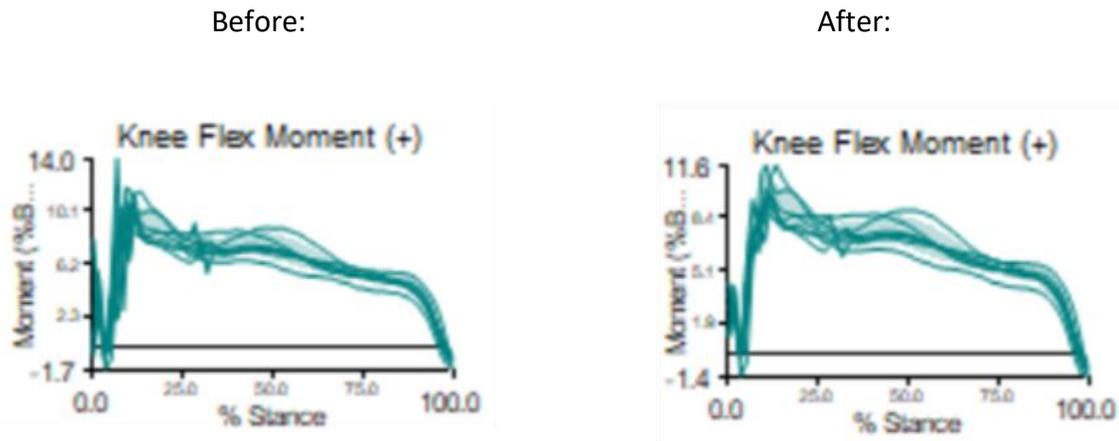
Before: After:

Figure 4.5. Example of before and after filtering analogue data with a low pass 30 Hz Butterworth filter for a single participant's external knee flexion moment.

All statistical analysis performed on the 24 dependent variables in this thesis are outlined in tables 4.2.1 to 4.2.4 below. Table 4.2.1 displays the pre- and post-fatigue mean (std) values of ankle joint angles in the frontal, sagittal, and transverse planes at IC and MS. Of importance, all variables statistically analysed were non-significant ($P > 0.05$).

To help interpretation, ankle and knee joint angles are reported in degrees (°) and external joint moments are reported as normalised values (%BW.h), where %BW.h represents body weight multiplied by height. Values are presented as mean (standard deviation) for pre and post fatigue conditions. External knee flexion moment in figure 4.5 refers to the external torque generated by GRFs that typically bend or flex the knee joint (Trepczynski et al., 2025).

Table 4.2.1. Ankle kinematic data from drop jumps pre- and post-fatigue from all participants (n = 12).

	Biomechanical Parameters	Pre-fatigue Mean (Std)	Post-fatigue Mean (Std)	Two-sided *P*
IC	Plantarflexion angle (°)	6.38 (10.35)	6.92 (12.23)	.742
	Inversion angle (°)	6.84 (4.96)	7.55 (3.63)	.754
	External rotation (°)	6.38 (5.54)	6.90 (5.90)	.706
MS	Dorsiflexion angle (°)	32.64 (3.35)	30.78 (5.54)	.162
	Inversion angle (°)	2.67 (3.80)	2.69 (4.25)	.966
	External rotation angle (°)	16.90 (4.47)	17.00 (4.53)	.936

° degrees of rotation, *IC = initial contact, MS = mid-stance, Std = standard deviation.

Table 4.2.2 displays the pre- and post-fatigue mean values of ankle joint moments, presented as a % of body weight multiplied by height, in the frontal, sagittal, and transverse planes during the IC and MS.

Table 4.2.2. Ankle kinetic data from drop jumps pre- and post-fatigue from all participants (n = 12).

	Biomechanical Parameters	Pre-fatigue Mean (Std)	Post-fatigue Mean (Std)	Two-sided *P*
IC	External dorsiflexion moment (%BW.h)	1.01 (.45)	.99 (.58)	.347
	External inversion moment (%BW.h)	.003 (.09)	-.03 (.20)	.433
	Internal rotation moment (positive sign) (%BW.h)	-.01 (.12)	.01 (.09)	.488
MS	External dorsiflexion moment (%BW.h)	6.63 (2.32)	6.31 (2.06)	.356
	External inversion moment (%BW.h)	.80 (.48)	.70 (.37)	.202
	Internal rotation moment (%BW.h)	.58 (.48)	.51 (.51)	.362

*IC = initial contact, MS = mid-stance, Std = standard deviation.

Table 4.2.3 displays the pre- and post-fatigue mean values of knee joint angles in the frontal, sagittal, and transverse planes during the IC and MS.

Table 4.2.3. Knee kinematic data from drop jumps pre- and post-fatigue from all participants (n = 12).

	Biomechanical Parameters	Pre-fatigue Mean (Std)	Post-fatigue Mean (Std)	Two-sided P
IC	Flexion angle (°)	28.48 (5.48)	28.94 (6.20)	.663
	Adduction angle (°)	2.51 (3.80)	3.97 (3.56)	.218
	External angle (°)	8.67 (5.64)	9.64 (5.57)	.402
MS	Flexion angle (°)	87.43 (7.50)	85.16 (9.32)	.198
	Abduction angle (°)	2.06 (5.94)	.54 (7.04)	.304
	External angle (°)	2.58 (10.23)	1.64 (8.21)	.610

° degrees of rotation, *IC = initial contact, MS = mid-stance, Std = standard deviation.

Table 4.2.4 displays the pre- and post-fatigue mean values of knee joint moments in the frontal, sagittal, and transverse planes during the IC and MS.

Table 4.2.4. Knee kinetic data from drop jumps pre- and post-fatigue from all participants (n = 12).

	Biomechanical Parameters	Pre-fatigue Mean (Std)	Post-fatigue Mean (Std)	Two-sided *P*
IC	External flexion moment (%BW.h)	2.52 (1.84)	1.82 (1.37)	.160
	External abduction moment (%BW.h)	.63 (.49)	.57 (.30)	.555
	External external rotation moment (%BW.h)	.15 (.12)	.16 (.07)	.940
MS	External flexion moment (%BW.h)	9.26 (3.17)	8.93 (3.54)	.577
	External abduction moment (%BW.h)	.84 (1.67)	.68 (1.40)	.295
	External rotation external moment (%BW.h)	.76 (.61)	.75 (.65)	.934

*IC = initial contact, MS = mid-stance, Std = standard deviation.

Additional analysis.

As three participants did not demonstrate a decrease in single-legged CMJ height post fatigue, the same statistical tests were repeated with these participants excluded (n = 9) to assess whether their inclusion masked fatigue related biomechanical changes. No statistically significant differences were observed for ankle or knee angles or external joint moments between pre and post fatigue conditions (all P greater than .05). Full results for this sensitivity analysis are reported in Appendix J.

CHAPTER V

Discussion

This study examined whether an acute fatigue protocol altered ankle and knee landing biomechanics during drop jumps in female university football players. Joint angles and external joint moments were extracted at initial contact and mid stance of the first landing phase. The key finding was that no statistically significant pre- to post-fatigue differences were detected in ankle or knee kinematics or external joint moments in any plane at either event. Although fatigue was induced based on performance, as single leg countermovement jump height decreased from 11.91 (3.87) cm pre fatigue to 9.93 (2.76) cm post fatigue (16.6 per cent reduction, $P = .002$), there were no statistically significant pre to post fatigue differences in any of the 24 biomechanical variables (all P greater than .05). This pattern remained when sensitivity analyses excluded participants who did not demonstrate a reduction in countermovement jump height.

Importantly, the absence of statistically significant differences should not be interpreted as evidence that fatigue does not influence ankle or knee biomechanics. Given the small sample size and inter-individual variability in fatigue response, the study may be underpowered to detect small to moderate effects (an increased risk of Type II error). Therefore, the present findings are best interpreted as inconclusive regarding the true magnitude of fatigue related biomechanical changes, rather than demonstrating an absence of effect. These null biomechanical findings suggest that, within the constraints of the task and fatigue protocol used, female university football players maintained stable landing mechanics despite measurable reductions in jump

performance. This may indicate that the drop jump task is relatively robust to the type of fatigue induced in this study, or that fatigue affected performance capacity without materially altering the movement strategies captured at initial contact and mid stance.

Fatigue protocol and manipulation check.

The fatigue protocol was a modified version of the circuit used by Khazaee et al. (2021) and was designed to induce lower limb fatigue through repeated single leg squatting, jumping, and stepping actions. In this study, fatigue was standardised using a perceived exertion criterion of 9 on the Borg 0 to 10 scale alongside a performance-based manipulation check. The significant reduction in countermovement jumps height supports that participants were in a fatigued state at the point that post fatigue drop jumps were collected. However, two participants increased countermovement jump height post fatigue and one participant did not complete the countermovement jumps, which highlights inter individual variability in fatigue response and the limitations of using a single performance measure to reflect neuromuscular fatigue in all participants.

When compared with football specific protocols, the present circuit-based protocol likely induced a different fatigue profile. For example, match simulation protocols are more likely to include repeated accelerations, decelerations, and changes of direction that occur during competitive football and may alter landing strategies differently. Previous work comparing general and football specific fatigue protocols suggests that football specific protocols can lead to larger decrements in movement quality during high-risk manoeuvres, indicating that protocol selection may influence whether fatigue related biomechanical changes are observed. Therefore,

the absence of significant changes in landing mechanics in this study may reflect the nature of the fatigue induced, the task assessed, or both.

Landing error scoring system and sample risk profile.

LESS scores were used to describe baseline landing quality in this cohort. Using the cut point proposed by Padua et al. (2015), two participants were categorised as higher risk (LESS score of 5 or greater) and ten participants were categorised as lower risk (LESS score less than 5). This distribution suggests that most participants displayed relatively good landing technique during the screening task, which may have reduced the likelihood of observing fatigue related deterioration in landing mechanics. Although the original intention was to compare fatigue related biomechanical changes between higher and lower risk groups, the small number of higher risk participants meant subgroup analysis was not feasible within this project and should be considered in future research with larger cohorts.

Validity of the FP used.

The FP used in this study was a modified version of the FP used in Khazaee et al., (2021). The modifications made were as follows. For the single-legged squats, a box was used and individually adjusted (with the use of foam blocks) for each participant to ensure 90° knee flexion was achieved consistently. In the modified FP, the twenty single-legged maximum vertical jumps were replaced with ten repetitions, and a metronome was implemented to prevent the participant from resting between movements. Finally, instead of twenty repetitions of a step up and down a 31cm step, the modified version reduced the number of repetitions to ten to minimise recovery time, and a 12" (30.48cm) box was used instead due to equipment availability. The number of

single-legged maximum vertical jumps was reduced following pilot testing of the FP, during which volunteers were unable to complete multiple sets of twenty repetitions due to breathlessness. The number was halved, and it was anticipated that participants would be able to complete more sets of the circuit, engaging their dominant-leg muscles for a prolonged time. This change in methodology may be related to the lack of biomechanical differences in the knee and ankle pre- and post-fatigue.

This study introduced several modifications to the FP compared with Khazaee et al. (2021). Whereas Khazaee et al., (2021) terminated the protocol when participants reported an RPE of 10, the present study applied a slightly lower threshold of RPE 9, or termination following two consecutive failed repetitions within 30 seconds. Although both protocols avoided rest between sets, brief breaks for water were permitted here to maintain participant safety and compliance. Fatigue assessment methods also differed; Khazaee et al. (2021) employed a single-leg jump for distance, while the present study used three single-leg CMJs measured with an Output Sports device, with the mean value calculated. These adjustments may have influenced the fatigue profile induced and could partly explain the absence of significant changes in lower-limb biomechanics observed in this study, emphasising the importance of protocol design when investigating fatigue-related injury risk. Furthermore, the inclusion of both regularly training players and more recreational participants may have contributed to variability in fatigue responses, potentially attenuating observable biomechanical changes.

The modified FP presented multiple advantages, primarily the simplicity of it. The modified FP was used to attract participants, as there was a short testing window for this Master's by Research and Thesis, and it required minimal preparation time, making it practical for the

experimenter when only one was present, and it was easy for the participants to follow the instructions of the protocol. The FP used in this thesis was not soccer-specific; potentially limiting the external validity and not inducing fatigue that occurs in females when competing in a soccer match (Alimoradi et al., 2024).

Although the FP was not soccer-specific, it did unequivocally induce lower-limb fatigue, as evidenced by a statistically significant decrease of approximately 16% in single-leg countermovement jump performance post-FP compared with pre-FP (P = 0.002). Notably, two participants demonstrated increased post-FP jump heights; however, their drop jump trials were retained in the statistical analysis to preserve consistency in the dataset.

Lower limb biomechanics during DJs.

The kinetic chain describes how the body's segments, from the core to the limbs, work together through precise positioning, timing, and velocity. This process relies on muscular eccentric strength, joint flexibility, and elastic energy storage, as well as neuromuscular, sensorimotor, and neurocognitive control (Almansoof et al., 2023). Disruptions in the kinetic chain can produce compensatory movement patterns and increased strain on specific body segments, thereby elevating injury risk (Almansoof et al., 2023). (Xu *et al.* 2025) found that females with chronic ankle instability exhibited biomechanical trends associated with increased risk of non-contact knee injuries such as smaller knee flexion angles, greater knee abduction moments, and larger ankle inversion angles compared with healthy females during side-cutting tasks. These findings highlight the importance of assessing ankle joint biomechanics in this study, as impairments at

the ankle can disrupt the kinetic chain and alter knee mechanics, increasing the risk of non-contact knee injuries in female soccer players.

In addition, ankle mechanics can influence knee loading and frontal/transverse plane control, meaning that alterations at the ankle under fatigue could plausibly contribute to knee biomechanics relevant to ACL injury risk. As such, our null statistical findings should not be taken to contradict this established ankle-knee interaction, but rather to reflect that measurable changes were not detected under the current task and protocol in this sample.

Daoukas et al., (2019) assessed KVA and KFA between healthy and recently injured (within the last 12 months prior to testing) professional male soccer players during single-legged drop jumps and found that the group with history of lower limb injury displayed increased KVA and decreased KFA at IC, both are factors associated with non-contact injury risk in soccer (Belkhelladi et al., 2025). Yang et al., (2025) found similar trends occurred in soccer players, as KFA (P = .002) and trunk flexion angle (P = .04), both at IC, were significantly decreased post-mental fatigue. These findings show that fatigue regardless of the type affects lower limb biomechanics during different jumping and landing manoeuvres. Belkhelladi et al., (2025) highlights that significantly decreased KFAs can lead to increased ACL loading, which might increase risk of non-contact knee injury, which typically occurs at mid-stance of DJs (Mok et al., 2017).

As a result of the findings from past research, analysis of ankle and knee joint kinetics and kinematics in the frontal, sagittal, and transverse planes at IC and MS during the first landing of DJs were chosen as the primary focus for this study.

Ankle joint biomechanics.

In the present study, contrary to the thesis alternative hypotheses, fatigue did not induce significant changes in ankle angles or moments at IL or MS at any anatomical plane. Although APA at IL increased slightly post-fatigue, this difference was not statistically significant (pre-fatigue: -6.38°, Std = 10.35°; post-fatigue: -6.92°, Std = 12.23°; P = .742).

Malloy et al., (2014) assessed landing kinematics and kinetics and the association to ankle dorsiflexion flexibility during DVJs, in relation to increased risk of ACL injuries in female soccer and found that female soccer players with less ankle dorsiflexion flexibility had greater peak knee abduction moments, peak knee abduction angles, and lower peak KFAs during landing, than the female soccer players with increased ankle dorsiflexion flexibility. Although Malloy et al., (2014) measured ankle dorsiflexion flexibility and considered the ankle joint to be associated with ACL injuries in female soccer, the study did not assess any other ankle joint variables such as angles or moments during the DVJ tasks. This theme is common amongst research assessing knee injury risk such as Leppänen et al., (2017) , where peak external knee flexion moments and peak external hip flexion moments were assessed however peak external ankle plantarflexion moments (also primarily measured in the sagittal plane) were not. However, Leppänen et al., (2017) did measure ankle flexion angle range of motion and AMA at IC and found that they were not significantly associated with the risk of ACL injury. In the present study, ankle range of motion was not collected, as the measurement protocol focused on joint angles and moments during landing rather than on passive or active range of motion measures. This is a limitation that should be considered when comparing the findings from this present study with previous research. Lee & Shin (2021) compared the relationships between APA and biomechanical variables that have

previously been linked to non-contact ACL injuries, at IC of single-legged drops (with no jumps). The methods utilised in Lee & Shin (2021) differ from the current thesis as there was no fatiguing aspect within their study and it assessed single-leg landings, whereas this study analysed DJ landings. The height of which participants were jumping / dropping from were similar (0.3m, and 0.305m respectively). Lee & Shin (2021) did find significant negative correlation between APA and external knee valgus moment at IC (r = -0.50, P = 0.009), suggesting that greater APA at IC may be associated with biomechanical changes in the knee that cause increased risk of non-contact knee injuries.

The lack of significant changes in ankle angles or moments prompts two alternative interpretations. The first is that it is possible the FP did not sufficiently alter neuromuscular function to influence ankle biomechanics. Secondly, the lack of ankle biomechanical differences could reflect a genuine resistance of the joint to fatigue-related alterations when landing from a 30cm box.

From an applied perspective, these findings emphasise the need to reconsider the role of the ankle in relation to non-contact knee injuries in female soccer players. As mentioned in the literature review, the knee joint is consistently implicated in non-contact knee injury mechanisms and although the ankle may influence injury risk, the results from this present study suggest those risks do not change due to fatigue. Alternatively, the absence of observable changes in the ankle could reflect task specificity, as although DJs are widely used in laboratory studies, they may not reproduce the demands of the movements that occur during an actual soccer game and therefore lack external validity.

Overall, the results produced from this study suggests that fatigue does not significantly alter ankle joint angles or moments during DJs in female university soccer players.

Knee joint biomechanics.

The present study observed knee joint angles and moments across the frontal, sagittal, and transverse anatomical planes at IC and MS of the first phase of DJs, pre- and post-fatigue. Despite existing evidence linking fatigue to altered knee biomechanics (resulting in increased risk of non-contact knee injuries in soccer), the results of this study found no significant differences of any knee angle or joint moment assessed. This lack of statistically significant change is consistent even when removing the participant that did not complete the single-legged CMJs and the two participants that did not show decreases in jumping performance post-fatigue. Khazaee et al., (2021) is the study that used the original exercise circuit used as a FP and the results produced showed male soccer players had significant decreases in KFA on the fatigued leg at IC post-fatigue, however there were no other significant differences. In contrast to the previously mentioned study, Kamitani et al., (2023) used a high-intensity ergometer FP and found that elite female soccer players had no significant differences in KFA (pre-fatigue: 50.0° ± 5.9°; post-fatigue: 49.1° ± 6.1° [$P = .91$]) during DJs pre- and post-fatigue, these findings align with the results found in the present study. Cortes et al., (2014) used what they described as a "functional agility short-term fatigue protocol" which consisted of three 90% max-height CMJs, three squats to 90° knee flexion, a 5-10-5 agility drill, and step-ups on a 30cm box for 20 seconds (at a pace set by a metronome). Cortes et al., (2014) analysed knee kinematics whilst performing crossover manoeuvres instead of DJs and were tested before the first round of the FP and each round after, until maximum fatigue was reached. The results produced from Cortes et al., (2014) concluded significant

decreases in KFAs (pre-fatigue = -32 ± 9°, 100% fatigue = -29 ± 11°; P = <0.001) and knee adduction angles (pre-fatigue = 9 ± 5°, 100% fatigue = 6 ± 4°; P = 0.006) at IC of the crossover manoeuvres, which would suggest that fatigue causes changes in landing patterns associated with risk of non-contact knee injuries in soccer (Belkhelladi et al., 2025) . These differences in results can be for multiple reasons including different participant characteristics (such as sex and level of competition), use of different tasks when assessing the effects of fatigue, and different FPs used. Although Alimoradi et al., (2024) did not collect lower-limb kinetic or kinematic data, it did compare the effects of a general FP and a soccer-specific FP using a cutting motion assessment score tool during anticipated and unanticipated change of direction manoeuvres on female soccer players. Alimoradi et al., (2024) found that the group that underwent the soccer-specific FP demonstrated higher cutting motion assessment score changes, which suggests poorer movement quality, in comparison to the general FP group. Although the study assessed movement patterns during change of direction movements instead of DJs, the findings from Alimoradi et al., (2024) suggest that fatigue effects lower-limb biomechanics related to non-contact knee injuries in soccer however, the FP used is a key variable when determining if fatigue will have an effect or not. Future studies should aim to create methodologies that closely replicate the fatiguing elements present during soccer matches to enhance validity.

Potential reasons for null findings.

There are a variety of potential reasons why this study failed to reject the null hypotheses in this study. The sample size was limited for multiple reasons such as time restrictions and difficulties with recruitment, raising questions of the study being under powered. The small sample size

made it difficult to assess biomechanical differences between sub-groups of participants that were categorised as high- or low-risk.

As comparisons between previous literature has shown, the FP used effects the way lower-limb biomechanics change because of fatigue. Although the participants of this study expressed high levels of perceived exertion and overall decreases in jumping ability post-fatigue, the lack of change found across all biomechanical variables suggest that either fatigue was not achieved or the muscular fatigue endured had minimal effect on landing mechanics which suggests that either the study was underpowered to detect changes, and/or the type of fatigue induced and the drop jump task did not elicit measurable alterations in the specific IC and MS variables analysed.

Academic and practical applications.

The null results suggest that, in this sample and under the specific fatigue protocol and drop jump task used, fatigue related changes in the measured ankle and knee variables were not detected. From an applied perspective, this should not be interpreted to mean fatigue is irrelevant to injury risk; rather, it indicates that drop-jump mechanics in this controlled setting may be less sensitive to the induced fatigue, or that larger samples and more sport-representative tasks are needed to detect meaningful changes.

Overall, these null findings emphasise the importance of a multifactorial approach to non-contact knee injury prevention in female university soccer players.

Limitations.

This study was not without limitations, most notably the small sample size (n = 12) and the use of a generic fatigue protocol. The limited sample size meant the study was underpowered, and the statistical findings may not accurately represent the wider population of university-level female soccer players. These limitations highlight the need for future research with larger cohorts and the use of sport-specific fatigue protocols to better capture the biomechanical responses associated with match play. Nevertheless, the findings provide valuable preliminary insight into the influence of fatigue on lower-limb biomechanics in female soccer players. A large cohort approach would be required before sub-group analyses could be performed, such as distinguishing between high- and low-risk players based on LESS score findings. Due to time constraints, a Cohen's D was not computed as a measure of effect size, to supplement inferential statistics but it is understood that by doing this would have provided a standardised index of magnitude and practical significance of the effect, enabling clearer interpretation and comparison across studies.

A further limitation is the ecological validity of the drop jump for football. Although DJs provide a controlled, repeatable assessment of landing mechanics, they differ from typical football jump landings, which often involve a run-up, aerial challenges/heading, unanticipated landings, cutting, external perturbations, and the use of boots on turf. Consequently, the findings should be interpreted as reflecting fatigue related changes in standardised laboratory landing mechanics, rather than directly representing biomechanical responses during match play scenarios.

With the removal of multiple motion capture cameras (for use in other research projects) during the data collection stage of this study, delays with recruitment and data collection occurred,

ultimately resulting in less time to dedicate towards the analysis of the results collected. This meant that only the first phase of DJs was analysed, a lack of vertical ground reaction force data was included in the study, and individual biomechanical analyses between low risk and high risk was not conducted. These areas of analysis would have enhanced the insight towards the effects of fatigue in relation to non-contact knee injuries in female soccer.

Although assessing lower-limb biomechanics via standard DJs has been a validated protocol (Cabarkapa et al., 2025), recent studies have used soccer-specific DJs (Mancini et al., 2022; Akbari et al., 2023) and single-legged DJs (Daoukas et al., 2019) to better evaluate lower-limb biomechanics when jumping and landing. This was not done in the present study however findings from Mancini et al., (2022) suggest that using a more soccer-specific DJ variation may produce different results.

The final key limitation this study faced is deciding on a FP that best fit the purpose of the study. Ultimately, with the significant differences in average single-leg CMJs pre- and post-fatigue, it can be assumed that fatigue was induced to some extent. However, the lack of biomechanical differences in ankle and knee data during DJs suggests that the FP used in this study may not have achieved the level or type of fatigue desired. Chia et al., (2021), found that non-contact ACL injuries occurred significantly more frequently during competition (0.53 per 1,000 player-hours, and 0.35 per 1,000 player-exposures) as opposed to during training (0.03 per 1,000 player-hours, and 0.02 per 1,000 player-exposures). This suggests that real game intensity and conditions increase the risk of non-contact knee injury and should be considered in future studies that assess the effects of fatigue in relation to non-contact knee injuries.

Directions for future research.

Building on the limitations of this study identified, there are several suggestions for future research surrounding the relationship between fatigue and non-contact knee injuries in female soccer, to further advance understanding in this area. Although it requires extensive recourses and time, future research that investigates fatigue in relation to non-contact knee injuries in female soccer should look to use a validated, soccer-specific protocol such as the SAFT90 protocol (Alimoradi et al., 2024) or should look to complete baseline testing when in a non-fatigued state pre-game, and test athletes during DJs, or other high-risk manoeuvres, post-game to see what biomechanical changes occur as a result of fatigue. This would come with logistical challenges when attempting to standardise time from the game finishing, to begin testing, and maybe issues with recruitment as it may be difficult to recruit participants that are interested in participating in research right after playing a 90-minute soccer match. However, it would provide an insight into how fatigue effects female soccer players in real-world scenarios and how those effects could potentially increase risk of non-contact knee injury.

Although the results produced in this study did not show any significant changes in ankle joint kinetic or kinematic data post-fatigue, future research should continue to evaluate the effects of surrounding limbs, joints, and muscles in primary use when performing manoeuvres associated with non-contact knee injuries in female soccer. This is because this study also found the same trends (or lack thereof) in knee joint kinetic and kinematic data and therefore, further research, with fewer limitations should be conducted to see if changes would occur under a more refined methodology. Evaluating lower limb biomechanics during alternative variations of DJs such as a soccer-specific vertical jump like in Mancini et al., (2022) or single-leg drop jump in Maestroni

et al., (2024) instead of a conventional DJ could provide data that more accurately represents the biomechanical demands and landing patterns associated with non-contact knee injuries commonly observed during female soccer matches.

Due to a limited sample size, the present study was unable to make statically valid comparisons between the female soccer players that were categorised as high-risk and those that were deemed as low risk of non-contact knee injury. Future studies with a larger sample size and with a substantial quantity of participants that fit into both groups, should aim to assess lower limb biomechanics between the two groups to evaluate if the high-risk group is affected by fatigue differently to the players in the low-risk group.

CHAPTER VI

Conclusion

This thesis set out to investigate the ankle and knee joint biomechanics of female university soccer players across the three anatomical planes during the first phase of DJs pre- and post-fatigue, which has not been previously done in relation to non-contact knee injuries in soccer. The findings of this study indicate that no statistically significant pre- to post-fatigue differences were detected in ankle or knee angles or external joint moments at initial contact or mid stance during drop jumps in this sample. However, given the small sample size and associated limited statistical power, these results should be interpreted cautiously and do not rule out fatigue related biomechanical changes. Moreover, because DJs are a simplified laboratory task, future research should evaluate fatigue effects using larger, adequately powered cohorts and soccer representative jump/landing tasks and fatigue protocols to better reflect match play demands and ACL injury scenarios.

Despite these findings, there are limitations that warrant consideration. These include a lack of a soccer-specific FP, a limited sample size, and the use of a standard DJ instead of a soccer-specific DJ variation. Addressing these limitations can improve the strength of future research and provide further insights into the effects fatigue have on non-contact knee injuries. Based on the findings and observed gaps, potential areas for future research include assessment with soccer-specific task and a soccer-specific FP. Continued exploration of lower-limb biomechanics with

those adjustments will be valuable in understanding on how fatigue effects female soccer players, and if it increases risk of non-contact knee injury.

In conclusion, this thesis provides valuable insights into the effects of fatigue in relation to non-contact knee injuries in female soccer players and offers a foundation for future research and practical application.

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Appendices

Appendix A. *Participant information Sheet.*

Participant Information Sheet

University of Kent

Study Title – Differences in Knee Joint Loading Pre- and Post-Fatigue During Drop Jumps in Female Collegiate Athletes.

You are invited to take part in this research study. Before you decide, we want you to understand why the research is being done, and what we will ask you to do and give you the opportunity to ask any questions.

What is the purpose of the research?

To establish whether knee mechanics differ when performing drop jumps in a pre-fatigued compared to a fatigued state.

Who can take part?

If you are injury free, play for a University Women's intermittent sports team (trains a minimum of twice a week), generally fit and well, have no cardiovascular or respiratory disease, no history of lower limb surgery, and no lower limb injury within the last 8 weeks you are invited to participate

Unfortunately, you are unable to take part in this study if you have or have had a lower limb injury within the last 6 months, lower limb surgery, you are pregnant, you have been told you have high blood pressure (>140/90), cardiovascular disease, metabolic disease, uncontrolled respiratory disease (exacerbation in past 3 months), joint problems that would impair full functional movement, viral infections/illness within the past 2 weeks, or are unable to understand instructions to take part in the study assessments.

How long am I expected to be part of the study?

Participants will report to the School of Sport and Exercise Sciences Biomechanics Laboratory based in the University of Kent, Canterbury Campus Sports' Centre, for a single visit which will last up to 2 hours.

Do I have to take part in the study?

No, taking part is voluntary. It is completely up to you whether you want to join the study. If you agree to take part, we will ask you to sign a consent form and will give you a copy of this form. However, you are free to withdraw from the study at any time without giving a reason.

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There will be absolutely no penalty if you do not want to take part in the research, or if you withdraw.

What will I be asked to do if I agree?

On the day of assessment, you will report to the School of Sport and Exercise Sciences, Biomechanics Laboratory (located in the University of Kent's Sport Centre) for a single 2-hour visit. Please attend this session with skin-tight shorts/undershorts/cycling shorts, a tight-fitting t-shirt or sports bra with no reflective features, and comfortable shoes. During the jumping tasks, we will ask you to remove your shoes and socks so we can place markers onto the feet. If you do not have the above, we can provide you with the appropriate clothing when you visit the lab but please do email to inform me.

After filling out the necessary consent sheet and health questionnaire, you will be guided by the experimenter through the following steps:
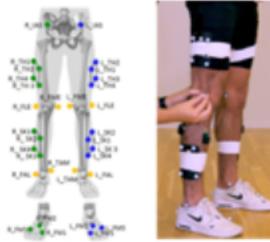
Figure 1: Passive retroreflective markers (white markers) placed on the lower limbs. Image retrieved from https://docs.qualisys.com/getting-started/content/getting_started/getting_started_in_biomechanics/placing_motion_capture_markers.htm

1. Generic data collection (e.g. height, weight, age, menstrual cycle phase, etc)
2. Warm-up
3. Basic jumping assessments (landing error procedure and maximum vertical jump test)
4. Application of reflective markers (example shown in Figure 1)
5. Drop jump procedure (pre-fatigue)
6. Removal of reflective markers as they are likely to fall off during the following exercise circuit
7. Exercise circuit to exhaustion to induce fatigue
8. A second maximum vertical jump test to compare with the pre-fatigue results
9. Application of reflective markers

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10. Drop jump procedure (post-fatigue)
11. Removal of reflective markers
12. Cool-down

What are the possible side effects of taking part?

You will be required to participate in jumping and landing manoeuvres as well as single-legged squats and step-up and downs until fatigue. Therefore, there are associated fatiguing aspects of jumping and squatting which may occur. This is typical with exercising and can result is post-exercise muscle fatigue and soreness (up to 48 hours post-exercise). This experience of both muscle fatigue and soreness should be considerably mild in regularly training athletes who have been provided a pre-exercise warm-up. Nonetheless, these risks will be minimised through a full health screening by the completion of a general health questionnaire to ensure that you are healthy and suitable to participate.

What are the possible benefits of taking part?

This is a fun and unique chance to take part in a study using cutting-edge motion capture equipment whilst at University. The data collected for the study will be used to see how athletes like yourself may be at greater risk of non-contact knee injuries once fatigue is induced.

Will my taking part be confidential?

Yes. The consent form you sign will be kept within a locked filing cabinet that is only accessible by the research team named below. The consent form includes space for an anonymous code that will be written against your test scores and the questionnaires you complete. As a result, no one will be able to see what your test scores and questionnaire answers are except the research team who have the consent form with both your code and your name. The consent forms are kept for up to 12 months after testing so that we can show our ethics committee that you gave written informed consent and are then securely destroyed. Anonymous data such as your test scores and questionnaires will be stored for up to 5 years after the study.

What will happen to the results of the research?

The anonymous data will be analysed and used in a postgraduate thesis project and will be presented as PowerPoint presentations and in the form of a published written document. If appropriate, the findings of the project will also be submitted to a Journal for publication and

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to conferences. If wanted, participants would have access to the final postgraduate thesis findings.

Who is organising and funding the study?

This is a self-funded Masters by Research project. The research has been organised by the researchers named at the end of this Participant Information Sheet with permission from the University of Kent School of Sport and Exercise Sciences.

Who has reviewed the study?

The School of Sport and Exercise Sciences (SESS) Research Ethics and Advisory Group (REAG) at the University of Kent approved this study.

Who can I contact if I need to ask more questions about the study?

If you are interested in participating in this study, would like additional information, or have any general questions about the study not answered by this Participant Information Sheet, please contact the research team on one of the follow emails: Dr Jake Bowd – Supervisor (J.Bowd@kent.ac.uk), Alastair Thrush – Supervisor (A.Thrush@kent.ac.uk), or Danel Yesim – Postgraduate Researcher (Dy63@kent.ac.uk).

Who can I contact if I want to complain about the study?

If you wish to complain about the way that the study was conducted you can contact the Head of the School of Sport and Exercise Sciences, Professor Glen Davison (G.Davison@kent.ac.uk or by phone (01227 806927).

What do I do now?

If you are happy to participate in the research, then please either contact the research team via email and we can get the familiarisation / preliminary testing session booked.

Research Team:

Project supervisors:

Dr Jake Bowd   J.Bowd@kent.ac.uk   01227 816942

Alastair Thrush   A.Thrush@kent.ac.uk

Postgraduate Researcher:

Danel Yesim   Dy63@kent.ac.uk

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Postal address for all researchers: Chipperfield Building, School of Sport and Exercises, University of Kent, Canterbury, CT2 7NH

Website: https://www.kent.ac.uk/sport-sciences/people

Thank you for showing interest in this study and taking time to read this information sheet. If you wish to participate in this study, please sign the informed consent form for confirmation.

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Appendix B. *Informed consent form.*

CONSENT FORM

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Title of project: Differences In Knee Joint Loading Pre- And Post-Fatigue During Drop Jumps In Female Collegiate Athletes.

Name of researchers: Supervisor Dr Jake Bowd. Supervisor Alastair Thrush. Postgraduate researcher Danel Yesim.

Participant Identification Number for this project:

Please initial box

1. I confirm I have read and understand the Participant Information Sheet dated 21/10/2024 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

2. I understand that my participation is completely voluntary and that I am free to withdraw at any time without giving any reason. If I wish to withdraw, I will contact the project researcher (DY63@kent.ac.uk).

3. I understand that my test results will be anonymised before analysis. I give permission for members of the research team to have access to my anonymised data.

4. I understand that the information collected about me will be used to support other research in the future and may be shared anonymously with other collaborators.

5. I understand that I must read the health questionnaire (PAR-Q) carefully and answer all the questions to the best of my ability. And that the researchers will use my answers to this questionnaire to assess my suitability for participation.

6. I agree to take part in the above research project.

Name of participant:	Date	Signature
Name of person seeking consent:	Date	Signature

To be signed and dated in presence of the participant

Copies: When completed: 1 for participant; 1 for researcher site file; 1 (original) to be kept in main file

Draft version 2.0: 07/11/2024

Appendix C. *Pre-Activity Readiness Questionnaire (PAR-Q).*

Pre Activity Readiness Questionnaire Form (PAR-Q-Form)

Personal Details

Title	Forename		Surname	
Date of Birth	DD MM YYYY	Age	Male/Female	*delete as appropriate
Address				
Town		County	Postcode	
Email				
Tel Home		Tel Mobile		
Emergency Contact		Tel		

Medical Questions

*Answer the following questions as honestly as you can and provide as much relevant additional information. Answer the following questions by placing a tick in either the **Yes** or **No** boxes (if you should answer **Yes** to any of the questions please provide further information in the space provided)*

Do you currently or have you ever suffered from any of the following conditions?

1) Heart problems?	Yes ☐ No ☐	If **yes**, please provide details below
2) Circulatory problems?	Yes ☐ No ☐	
3) Blood pressure problems?	Yes ☐ No ☐	
4) Joint, movement problems?	Yes ☐ No ☐	
5) Feel dizzy or imbalance during exercise?	Yes ☐ No ☐	
6) Currently pregnant or recently given birth?	Yes ☐ No ☐	

Health History
Do you currently receive medical care or do any of the following affect you?

7) Back/spinal pain?	Yes ☐ No ☐	If **yes**, please provide details below
8) Headaches or migraines?	Yes ☐ No ☐	
9) Have you recently had surgery?	Yes ☐ No ☐	
10) Currently being prescribed medication?	Yes ☐ No ☐	
11) Recently finished a course of medication?	Yes ☐ No ☐	
12) Diabetes?	Yes ☐ No ☐	
13) Asthma or breathing problems?	Yes ☐ No ☐	

Is there is any other reason that you believe may prevent you from taking part in any regular activity?

Declaration		
I have answered all question in this form honestly and I am aware that if I have answered **yes** to any of the questions I will need to consult my GP before commencing an exercise program if I am affected by any of the questions mentioned in this form or at a later date I agree to inform my personal trainer or instructor on any changes in health or fitness.		
Signed:	Print Name:	Date: __ __ / __ __ /20 __ __
Instructor:	Print Name:	Date: __ __ / __ __ /20 __ __

Pre Activity Readiness Questionnaire & Health History
Action Required for YES Responses

What is the PARQ and why do I need to complete it?

The PARQ (Pre Activity Readiness Questionnaire) is an industry-standard for fitness professionals and fitness faculties to use when screening clients for exercise.
The reason for doing this is to ensure you (the client) is healthy and will not be put at risk from taking part in a fitness programme or regular exercise.
Fitness professionals are not medical professionals and cannot commence a fitness programme with a client who has provided positive responses to a PARQ. In this case, the client will be referred to their local GP to ensure they are ready for exercise.

A yes to the first 6 questions on the PARQ form overleaf will normally result in a referral to your GP however a YES response to questions 7 to 13 depending on the circumstances of each question will not normally require GP consent.

The guide below is our policy and we must enforce on all occasions with no exceptions.

Action Required for YES Responses to PAR-Q Questions
1) *Heart problems?* **Refer to GP**
2) *Circulatory problems?* **Refer to GP**
3) *Blood pressure problems?* **Check blood pressure**
   - o If blood pressure is lower than 160/95 mmHg no referral is necessary
   - o If blood pressure is between 140/90 and 160/95 induct on CV only (Advice to see Doctor)
   - o If blood pressure is between 160/95 and 180/100 accept on GP referral only
   - o If blood pressure is 180/100 or higher will not be accepted
4) *Joint, movement problems?* **Refer to GP**
5) *Feel dizzy or imbalance during exercise?* **Refer to GP**
6) *Currently pregnant or recently given birth?* **Ask more questions about pregnancy/birth:**
   - o If pregnant and after the first three months, no referral is necessary
   - o If pregnant, within the first three months and was exercising regularly before became pregnant, no referral is necessary
   - o If pregnant within the first three months and not already exercising regularly, refer to GP
   - o If had a natural birth less than 6 weeks ago refer to GP
   - o If had caesarean section less than 10 weeks ago refer to GP

Action Required for YES Responses to Health History Questions

7) *Back/spinal pain?* Find out limiting factors, i.e. movement and pain. If in doubt refer to GP
8) *Headaches or migraines?* Be aware that people who suffer from headaches on a regular basis may develop a headache caused by exercise while exercising.
9) *Have you recently had surgery?* Find out how recent surgery was and what it was if very recent refer to GP.
10) *Currently being prescribed medication?* Find out more information about the medicine and possible side effects, if in doubt refer to GP
11) *Recently finished a course of medication?* Find out about medication that was taken, if in doubt refer to GP
12) *Diabetes?* Not a limiting factor but will need to be aware of the condition, encourage them to carry a snack and ideally, they should take their blood sugar level before and after exercise. Best not to exercise if their level is too low or too high immediately before exercising. Ensure the client drinks plenty of water before, during and after exercise. If in doubt, refer to GP.
13) *Asthma or breathing problems?* If the inhaler is required, ensure they have it with them and re-schedule induction if they don't.

Appendix D. *List of Qualisys camera models used for 3D-motion capture data collection.*

Original 11-camera configuration	Modified 8-camera configuration
Oqus 300	Oqus 300
Oqus 300+ (x7)	Oqus 300+ (x5)
Oqus 301	-
Oqus 310	Oqus 310
Oqus 310+	Oqus 310+

Appendix E. *Drop jump trial tracking spreadsheet.*

Spreadsheet Key:

Colour	Meaning
	100% marker tracking
	< 100% marker tracking but still within range to use
	Invalid trial
	Trial not used for other reasons

Top table:

Participant	Pre_Fatigue_Static	Post_Fatigue_Static	Pre_Jump_1	Pre_Jump_2	Pre_Jump_	Pre_Jump_	Pre_Jump_	Pre_Jump_	Pre_Jump_	Pre_Jump_	Pre_Jump_	Pre_Jump_	Post_Jump	Post_Jump	Post_Jump	Post_Jump	Post_Jump	Post_Jump	Post_Jump	Post_Jump	Post_Jump	Post_Jump	Issues /
P_001	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	Pre_F_7	Pre_F_8	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	n/a	n/a	n/a	n/a	Knee m
P_002	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	n/a	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	n/a	n/a	n/a	n/a	R_FM1 f
P_003	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	n/a	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	n/a	n/a	n/a	n/a	Static1
P_004	Static4	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	Pre_F_7	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	Post_F_7	n/a	n/a	n/a	Pre_F_1
P_005	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	n/a	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	n/a	n/a	n/a	n/a	R_FM2 f
P_006	Static3	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	n/a	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	Post_F_7	n/a	n/a	n/a	Static3
P_007	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	Pre_F_7	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	Post_F_7	n/a	n/a	n/a	R_FCC l
P_008	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	n/a	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	n/a	n/a	n/a	n/a	For Post
P_009	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	n/a	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	n/a	n/a	n/a	n/a	Right thi
P_010	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	n/a	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	Post_F_7	Post_F_8	n/a	n/a	Left thig
P_011	Static2	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	Pre_F_7	Pre_F_8	Pre_F_9	Pre_F_10	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	Post_F_7	Post_F_8	Post_F_9	n/a	Use FM1
P_012	Static1	Post_F_Static	Pre_F_1	Pre_F_2	Pre_F_3	Pre_F_4	Pre_F_5	Pre_F_6	n/a	n/a	n/a	n/a	Post_F_1	Post_F_2	Post_F_3	Post_F_4	Post_F_5	Post_F_6	Post_F_7	n/a	n/a	n/a	R_TAM 8

Bottom table:

Participant	Pre_F_First_Jump (	Post_F_First_Jump (	Pre_F_First_Jump (Full)	Post_F_First_Jump (Full)	Notes
P_001	Pre_F_Work P_001	Post_F_Work P_001	Pre_F_Workspac P_001	Post_F_Workspac	
P_002	Pre_F_Work P_002	Post_F_Work P_002	Pre_F_Workspac P_002	Post_F_Workspac	Pre_F_2 sh
P_003	Pre_F_Work P_003	Post_F_Work P_003	Pre_F_Workspac P_003	Post_F_Workspac	Post_F_1 fe
P_004	Pre_F_Work P_004	Post_F_Work P_004	Pre_F_Workspac P_004	Post_F_Workspac	Pre_F trial
P_005	Pre_F_Work P_005	Post_F_Work P_005	Pre_F_Workspac P_005	Post_F_Workspac	Pre_F trialt
P_006	Pre_F_Work P_006	Post_F_Work P_006	Pre_F_Workspac P_006	Post_F_Workspac	
P_007	Pre_F_Work P_007	Post_F_Work P_007	Pre_F_Workspac P_007	Post_F_Workspac	
P_008	Pre_F_Work P_008	Post_F_Work P_008	Pre_F_Workspac P_008	Post_F_Workspac	I inserted t
P_009	Pre_F_Work P_009	Post_F_Work P_009	Pre_F_Workspac P_009	Post_F_Workspac	Pre_F_3 an
P_010	Pre_F_Work P_010	Post_F_Work P_010	Pre_F_Workspac P_010	Post_F_Workspac	Pre and pc
P_011	Pre_F_Work P_011	Post_F_Work P_011	Pre_F_Workspac P_011	Post_F_Workspac	Pre and pc
P_012	Pre_F_Work P_012	Post_F_Work P_012	Pre_F_Workspac P_012	Post_F_Workspac	Pre and pc

100

Appendix F. *Raw data exported from Visual3D.*

Appendix G. *Number of sets of the fatigue protocol circuit completed by each participant.*

Participant ID	FP Sets
P_001	6
P_002	4
P_003	6
P_004	9
P_005	5
P_006	6
P_007	10
P_008	7
P_009	44
P_010	10
P_011	8
P_012	9

Appendix H. Testing for normality using the Shapiro-Wilk test for all dependent variables during the stance phase of the first land of the drop jump.

		Biomechanical Parameters	Significance (P <.05)
IC	Ankle	Dorsiflexion / plantarflexion angle	.307
		Inversion / eversion angle	**.011***
		Abduction / adduction angle	.899
		Dorsiflexion / plantarflexion moment	**.005***
		Inversion / eversion moment	**<.001***
		Abduction / adduction moment	.055
	Knee	Flexion / extension angle	.739
		Abduction / adduction angle	.703
		Internal / external angle	.521
		Flexion / extension moment	.987
		Abduction / adduction moment	.699
		Internal / external moment	.548
MS	Ankle	Dorsiflexion / plantarflexion angle	.264
		Inversion / eversion angle	.868
		Abduction / adduction angle	.118
		Dorsiflexion / plantarflexion moment	.313
		Inversion / eversion moment	.814

	Abduction / adduction moment	.130
Knee	Flexion / extension angle	.139
	Abduction / adduction angle	.969
	Internal / external angle	.710
	Flexion / extension moment	.988
	Abduction / adduction moment	.423
	Internal / external moment	.638

*IC = initial contact; MS = mid-stance; ***** = significant difference.

Appendix I. *Second round of testing for normality using the Shapiro-Wilk test for all dependent variables during the stance phase of the first land of the drop jump, with the exclusion of participants that did not demonstrate a decrease in maximum single-leg CMJ post-fatigue.*

		Biomechanical Parameters	Significance (P <.05)
IC	Ankle	Dorsiflexion / plantarflexion angle	.326
		Inversion / eversion angle	.296
		Abduction / adduction angle	.058
		Dorsiflexion / plantarflexion moment	**.032***
		Inversion / eversion moment	**<.001***
		Abduction / adduction moment	.114
	Knee	Flexion / extension angle	.733
		Abduction / adduction angle	.431
		Internal / external angle	.500
		Flexion / extension moment	.518
		Abduction / adduction moment	.640
		Internal / external moment	.981
MS	Ankle	Dorsiflexion / plantarflexion angle	.272
		Inversion / eversion angle	.918
		Abduction / adduction angle	.661

	Dorsiflexion / plantarflexion moment	.571
	Inversion / eversion moment	.990
	Abduction / adduction moment	.242
Knee	Flexion / extension angle	.394
	Abduction / adduction angle	.936
	Internal / external angle	.855
	Flexion / extension moment	.958
	Abduction / adduction moment	.548
	Internal / external moment	.544

*IC = initial contact; MS = mid-stance; * = significant difference.

***Appendix J.** Statistical analysis results from DJ data pre- and post-fatigue with the exclusion of participants that did not show signs of fatigue after completing the fatigue protocol (n = 9).*

Appendix J.1. Ankle kinematic data from drop jumps pre- and post-fatigue with the exclusion of participants that did not show signs of fatigue after completing the fatigue protocol (n = 9).

	Biomechanical Parameters	Pre-fatigue Mean (Std)	Post-fatigue Mean (Std)	Two-sided p
IC	Plantarflexion angle (°)	6.53 (11.96)	6.84 (14.32)	.886
	Inversion angle (°)	8.29 (3.84)	7.67 (3.73)	.478
	External rotation (°)	5.93 (3.23)	6.61 (6.10)	.619
MS	Dorsiflexion angle (°)	32.68 (3.78)	30.16 (6.29)	.222
	Inversion angle (°)	3.84 (2.90)	4.11 (2.89)	.654
	External rotation angle (°)	17.18 (3.97)	16.79 (4.69)	.744

AppendiX J.2. Ankle kinetic data from drop jumps pre- and post-fatigue with the exclusion of participants that did not show signs of fatigue after completing the fatigue protocol (n = 9).

	Biomechanical Parameters	Pre-fatigue Mean (Std)	Post-fatigue Mean (Std)	Two-sided p
IC	External dorsiflexion moment (%BW.h)	.97 (.52)	1.05 (.66)	.767
	External inversion moment (%BW.h)	.01 (.11)	-.04 (.66)	.214
	Internal rotation moment (%BW.h)	.02 (.08)	.02 (.10)	.998
MS	External dorsiflexion moment (%BW.h)	6.86 (2.58)	6.41 (2.37)	.310
	External inversion moment (%BW.h)	.90 (.48)	.73 (.37)	.056
	Internal rotation moment (%BW.h)	.62 (.52)	.56 (.52)	.560

Appendix J.3. Knee kinematic data from drop jumps pre- and post-fatigue with the exclusion of participants that did not show signs of fatigue after completing the fatigue protocol (n = 9).

	Biomechanical Parameters	Pre-fatigue Mean (Std)	Post-fatigue Mean (Std)	Two-sided p
IC	Flexion angle (°)	28.99 (5.96)	28.51 (6.36)	.683
	Adduction angle (°)	2.43 (4.13)	2.90 (3.43)	.725
	External angle (°)	10.42 (4.67)	11.26 (5.41)	.561
MS	Flexion angle (°)	86.36 (5.66)	82.85 (6.03)	.116
	Abduction angle (°)	1.71 (6.21)	1.06 (8.01)	.716
	External angle (°)	2.43 (8.01)	2.50 (7.36)	.968

Appendix J.4. Knee kinetic data from drop jumps pre- and post-fatigue with the exclusion of participants that did not show signs of fatigue after completing the fatigue protocol (n = 9).

	Biomechanical Parameters	Pre-fatigue Mean (Std)	Post-fatigue Mean (Std)	Two-sided p
IC	External knee flexion moment (%BW.h)	2.80 (2.21)	1.83 (1.53)	.096
	External knee abduction moment (%BW.h)	.68 (.37)	.61 (.17)	.465
	External knee external rotation moment (%BW.h)	.16 (.11)	.15 (.07)	.897
MS	External knee flexion moment (%BW.h)	9.61 (3.61)	8.73 (4.12)	.200
	External knee abduction moment (%BW.h)	.88 (1.33)	.75 (1.12)	.479
	External knee external rotation moment (%BW.h)	.83 (.64)	.75 (.64)	.587