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**The Effects of Pubertal Maturation and Sex on Biomechanics Associated  
with Risk of Anterior Cruciate Ligament Injury**

A thesis  
submitted in fulfilment  
of the requirements for the degree  
of  
**Doctor of Philosophy in Health, Sport and Human Performance**  
at  
**The University of Waikato**  
by  
**Anna Butcher**



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## Abstract

**Background:** Anterior cruciate ligament (ACL) injuries account for 45% of internal knee injuries and are burdensome to society due to prolonged recovery times, substantial costs of care, functional movement impairments, and an increased risk of early-onset posttraumatic osteoarthritis. Non-contact ACL injury occurrence rates are increasing in young athletes; however, post-pubertal females are more susceptible to non-contact ACL injuries than their male counterparts or pre-pubertal individuals. Considerable growth and development occur during pubertal maturation, including to the musculoskeletal and neuromuscular systems, which contribute to changes in movement patterns during dynamic manoeuvres. These changes in movement patterns may be linked to non-contact ACL injuries, however, there remain gaps in our understanding of the potential changes in biomechanics associated with ACL injury risk across maturational phases and between sexes. It is possible that the greater non-contact ACL injury risk in post-pubertal females is linked with their biomechanical movement patterns during dynamic tasks. Using injury risk screening tasks that reflect sport and ACL injury risk manoeuvres could assist in informing preventative strategies.

**Aim:** The main aim of this PhD thesis was to investigate the effect of sex and maturation on biomechanics associated with risk of ACL injury in a series of dynamic tasks suitable for clinical use.

**Methods:** This thesis comprises two parts: first, a systematic literature review and pilot study; and second, the main experimental study. The systematic review identified studies examining ACL-related biomechanics during defined maturational phases in dynamic tasks. The pilot study tested 26 court and field sport athletes using 2D video analysis completing a maximal and normalised land-cut task and informed the methods for the main experimental study. For the main experimental study, test-retest reliability and cross-sectional experiments were conducted that involved four different single-leg drop-landing tasks: single-leg drop-land, single-leg drop-land and cut, single-leg rotating drop and hop, and single-leg drop and vertical hop. The reliability portion establishes the test-retest reliability of the biomechanical measures collected using 3D motion capture and force plates from 15 young individuals, whereas the cross-sectional portion

compared the biomechanical and performance metrics of the four investigated single-leg tasks between males and females across three specific maturation stages from 69 individuals.

**Results:** The systematic review included 18 studies examining 400 males, 1377 females, and 315 participants of undefined sex across various maturation stages. The methodological quality of most studies ( $n = 16$ ) was considered good, and satisfactory for two. The most reported variables were knee abduction angle, knee abduction moment, knee flexion angle, and vertical ground reaction force (GRF). Knee abduction angles and moments and knee flexion angles were greater in late- and post-pubertal females than males and pre-pubertal females during both landing and cutting tasks. When normalised for body mass, ground reaction forces were generally greater in males compared to females overall and for less mature participants for both sexes. Overall quality of evidence was low or medium across the four biomechanical measures and findings were inconsistent between studies. Leap distances in the pilot study of the single-leg drop-land and cut task were significantly larger under a maximal than normalised to 150% of leg length condition ( $p < 0.001$ ,  $\eta_p^2 \geq 0.417$ ), with the maximal mean being  $154.5 \pm 24.7$  cm ( $175.1 \pm 18.6\%$  leg length) and the normalised mean being  $140.7 \pm 19.7$  cm ( $159.0 \pm 5.8\%$  of leg length). Regarding the reliability portion of the experimental study, all tasks demonstrated adequate [intraclass correlation coefficient (ICC) values  $> 0.50$ ] levels of reliability for kinematic angles and moments aside from the metrics of peak extension moment, moment ranges, anterior/posterior GRF, and medial/lateral GRF; however, large coefficient of variation values were commonly observed, likely due to the small magnitude of measures. In the cross-sectional experiment, few significant differences were found between males and females within the ages of 7 and 20 years when not accounting for maturation stage, including at the knee. Most of the observed significant differences were found between maturation stages. In general, the pre-pubertal participants demonstrated higher relative vertical GRFs, more extended knee positions, and greater variability in coronal and transverse plane knee angles and moments. Post-pubertal males also occasionally exhibited some mechanics typically associated with increased risk of ACL injury.

**Discussion:** The significant difference in single-leg drop-land and cut landing distances found in the pilot study between normalised and maximalised conditions imply that methods matter, whereby the normalised task may be better suited for heterogenous samples, but maximal for homogenous samples or pre-post study designs. Regarding the experimental study, it is possible that the movement pattern changes observed in the males were associated with improved performance or movement competence and not directly associated with an increased ACL injury risk. Additionally, although the results suggest that pre-pubertal participants exhibit biomechanics associated with ACL injury risk, it is relatively rare that ACL injuries occur in this population. A lack of exposure to more challenging sport and ACL injury specific manoeuvres, like the tasks used in the current research, likely contribute to their biomechanics differing from the more mature groups. Few differences in biomechanics were identified to indicate a decreased ACL injury risk with maturation, particularly in females. Hence, this lack of change combined with more frequent exposure to potentially injurious situations and greater sporting demand could contribute to the increased ACL injury occurrence in the late- to post-pubertal female population reported in the literature.

**Conclusion:** Overall, the lack of significant biomechanical differences found between sexes suggests there is no need to make screening tools or training interventions sex specific. As biomechanical factors associated with greater ACL injury risk were observed in the pre-pubertal groups, implementing screening and injury prevention in younger athletes (starting pre-puberty) could assist in development of safer landing strategies, proprioception, and neuromuscular control that significantly reduces the risk of ACL injuries as they mature.

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## List of abbreviations

3D – 3 dimensional

ACC – Accident compensation corporation

ACL – Anterior cruciate ligament

ANOVA – Analysis of variance

BMI – Body mass index

BW – Body weight

CAST – Calibrated anatomical system technique

CI – Confidence interval

CUT – Single-leg drop-land and cut task

CV – Coefficient of variation

*d* – Cohen's *d*

Dom – Dominant

DVJ – Drop vertical jump

ES – Effect size

*g* – Hedge's *g*

GRADE – Grading of recommendations, assessment, developments, and evaluation

GRF – Ground reaction force

HREC – Human research ethics committee

ICC – Intraclass correlation coefficient

LAND – Single-leg drop-land task

MD – Mean difference

Non-dom – Non-dominant

NOS – Newcastle ottawa scale

PHV – Peak height velocity

PKF – Peak knee flexion

PMOS – Pubertal maturation observation scale

PRISMA – Preferred reporting items for systematic reviews and meta-analysis

PROSPERO – International prospective register of systematic reviews

ROBINS-I – Risk of bias in non-randomised studies – of interventions

ROM – Range of motion

ROT – Single-leg drop rotate and land task

TE – Typical error

TRIPP – Translating research into injury prevention practice

SD – Standard deviation

SL – Single leg

VERT – Single-leg drop-land and vertical hop task

vGRF – Vertical ground reaction force

y – Years

## Research outputs arising from this doctoral thesis

### Published and submitted manuscripts

#### Published

##### Chapter 2

**Butcher, A. J.**, Ward, S., Clissold, T., Richards, J., & Hébert-Losier, K. (2024). Maturation and biomechanical risk factors associated with Anterior cruciate ligament injury: Is there a link? A systematic review. *Physical Therapy in Sport*. <https://doi.org/10.1016/j.ptsp.2024.06.002> (Appendix A)

##### Chapter 3

**Butcher, A. J.**, Clissold, T., Ward, S., Richards, J., & Hébert-Losier, K. (2025). Maximise or normalise? Examining single-leg drop-land-cut distances in young athletes. *Journal of Applied Biomechanics*. Advance online publication. <https://doi.org/10.1123/jab.2025-0061> (Appendix B)

#### Under review

**Butcher, A. J.**, Clissold, T., Ward, S., Richards, J., & Hébert-Losier, K. (2025). Biomechanical differences across pubertal maturation stages and sexes in a single-leg drop-land and a single-leg drop-land-and-cut task.

### Conference presentations arising from this thesis

**Butcher, A. J.**, Ward, S., Clissold, T., Richards, J., & Hébert-Losier, K. (2023). *Biomechanical Risk Factors Associated with Risk of ACL Injury and Their Link to Pubertal*

*Maturation: A Systematic Review*. Presented at the Sport and Exercise New Zealand Annual Conference, Wellington, New Zealand, 2023 (Appendix C)

**Butcher, A. J.**, Ward, S., Clissold, T., Richards, J., & Hébert-Losier, K. (2023). *Maximise or Normalise? Examining drop-land-cut distances in youth athletes*. Presented at the Sport and Exercise New Zealand Annual Conference, Wellington, New Zealand, 2023 (Appendix D)

**Butcher, A. J.**, Ward, S., Clissold, T., Richards, J., & Hébert-Losier, K. (2024). *Biomechanical Risk Factors Associated with Risk of ACL Injury and Their Link to Pubertal Maturation: A Systematic Review*. Presented at the Combined Scientific Meetings of the Australian and New Zealand Society of Biomechanics (ANZSB) & the Australian and New Zealand Orthopaedic Research Society (ANZORS), Melbourne, Australia, 2024 (Appendix E)

# **Part 1 – Building the base of current knowledge**

## **1.0 Chapter 1 – Introduction**

### **1.1 Prevalence and burden of ACL injuries**

ACL injuries are increasingly common, particularly in young athletes (Hosseinzadeh & Kiapour, 2021; Maniar et al., 2022). A study by Maniar et al. (2022) assessing knee injury occurrence across the lifespan in Australia reported a marked trend over a 20-year period of increased ACL injury frequency between ages 15 to 24 years. An Italian study demonstrated an increase of 14.81% from 2001 to 2015 in ACL reconstruction surgeries in individuals under 15 years, with 97.3% of these surgeries performed in the 10- to 14-year-old age group (Longo et al., 2021). Maniar et al. (2022) also showed a precipitous rise (10.4%) in the annual number of ACL injuries in younger Australians, particularly females aged 5 to 14 years old. Interestingly, there is a greater overall incidence of knee injuries in males than females, likely owing to their increased participation in higher ACL injury risk activities and sports (Maniar et al., 2022). However, when accounting for the difference in sporting participation between sexes, the rate of knee injuries in adult females is 3.4 times greater than males, and the rate of non-contact ACL injuries is up to 8 times greater in females compared to males (Joseph et al., 2013).

Accounting for 45% of all internal knee injuries across all populations (Majewski et al., 2006), ACL injuries are relatively common and devastating in nature. Patients often suffer prolonged recovery periods, a substantial cost of care (Janssen et al., 2012), functional movement impairments (Paterno et al., 2012), and an increased risk of early-onset posttraumatic osteoarthritis (Lohmander et al., 2004; Nebelung & Wuschech, 2005). In 2021 alone, ACL injuries cost New Zealand taxpayers over \$100 million, of which over 50% were claims from patients in the 15 to 29 year age group (ACC analytics and reporting, 2022). As a consequence of the injury's severity, increasing frequency, and impact on individuals and

society, there has been an increase in epidemiological and aetiological research regarding morphological and biomechanical factors associated with ACL injury occurrence.

## **1.2 Anatomy of the ACL**

It is well understood that the anterior cruciate ligament (ACL) is one of the four major ligaments stabilising the knee. The ACL attaches from the anterior intercondylar area of the tibia and ascends in the posterolateral direction in a slight twisting and fanning pattern to attach to the posteromedial area of the lateral femoral condyle (Markatos et al., 2013). According to Markatos et al. (2013), this arrangement makes the anterior portion of the ligament almost straight and the posterior portion slightly convex. Based on their tibial insertion sites, the anteromedial and posterolateral bundles have unique fibre orientation and tensioning patterns (Buoncristiani et al., 2006; Reider et al., 1981). The ACL has an average length of 38 mm and width of 11 mm in adults, receiving blood supply from branches of the middle and inferior genicular arteries (Woo et al., 2006) and contains many sensory nerve endings that assist in proprioceptive functions (Markatos et al., 2013). Importantly, the ACL acts to stabilise the knee joint by preventing anteroposterior translation of the tibia on the femur, resisting up to 86% of total anterior translation force (Markatos et al., 2013).

The two bundles of the ACL act to stabilise the knee joint at different points of knee motion, at 90 degrees of flexion the anteromedial bundle is under tension, and at full extension the posterolateral bundle is under tension. The ACL also partially contributes to resistance of internal and external rotation and valgus motions (Markatos et al., 2013) with a maximum tensile strength of  $1725 \pm 270$  N in adult ligament grafts (Noyes et al., 1984) and  $2160 \pm 157$  N in younger (22-35 years) cadaver knees (Woo et al., 1991). Force that occurs during sporting manoeuvres often exceeds this tensile strength; hence the surrounding muscles must act as dynamic stabilisers to support the stability of the knee joint. Mechanoreceptors and free nerve endings in the ACL and the posterior tibial nerve provide proprioceptive

feedback regarding the knee joint position to the muscles (Markatos et al., 2013; Woo et al., 2006), assisting in the appropriate timing of muscle actions.

### **1.3 Mechanism of ACL injuries**

Non-contact ACL injuries are more common than direct contact injury, accounting for roughly 70% of ACL tears (Boden et al., 2000). Non-contact ACL injuries are also considered more preventable with improvements in coaching that aim to reduce risky movement patterns, focussing on neuromuscular control and strength which may result in injury risk reduction (Boden & Sheehan, 2022). Up to 80% of non-contact ACL injuries are associated with biomechanics that increase ACL loading during single-leg landing or cutting manoeuvres (Koga et al., 2010). When the forces or moments at the knee exceed the loading capacity of the ACL and the supporting muscles, non-contact ACL injury can occur (Yu & Garrett, 2007). Although the aetiology of non-contact ACL injuries is multifactorial (Shultz et al., 2012), several risk factors are considered modifiable, including improving movement patterns that may reduce ACL loading. Specifically, movements identified as biomechanical risk factors of ACL injury include ACL loading through excessive knee abduction angles and moments, internal (or external) tibial rotation, anterior tibial translation, and decreased knee flexion (Holden et al., 2016; Quatman et al., 2009; Shimokochi & Shultz, 2008). In addition, multi-planar loading involving higher knee flexion moments, valgus angles and moments, and internal or external rotation moments with a more extended knee angle upon landing can cause combined knee loads that increase ACL strain (Acevedo et al., 2014; Quatman et al., 2010). However, there is a current lack of research reporting on multi-planar knee angles and moments in young athletes, as most studies focus on one or two planes only (Hass et al., 2005; Kim & Lim, 2014; Sigward, Pollard, Havens, et al., 2012; Sigward, Pollard, & Powers, 2012).

## **1.4 Sex and ACL injuries**

### **1.4.1 Sex versus gender**

The National Academies of Sciences and Medicine (2022) defined “sex” as the biological differences between males and females, which included components of anatomy, physiology, genetics, and hormones. Whereas “gender” has a broader definition that encompass socially constructed and enacted roles and behaviours, which occur in a historical and a social context (National Academies of Sciences & Medicine, 2022). According to these organisations, in health research, sex is considered as a biological variable, while gender is considered a social variable (National Academies of Sciences & Medicine, 2022). Although gender consideration in research is important for developing greater understanding of the societal influence of changes across the lifespan (Boerner et al., 2024), the scope of this thesis was primarily concerned with the influence of biological sex in relation to ACL injury risk. Differences in ACL injury occur between males and females, with females up to 8 times more likely to sustain an ACL injury compared to males (Mancino et al., 2023). However, these incidence discrepancies do not appear until after childhood (Andrish, 2001), suggesting that biological changes that occur during puberty may be influencing factors.

## **1.5 Maturation and ACL injuries**

### **1.5.1 Puberty and growth**

Pubertal maturation is the systemic physiological transition from childhood to adulthood, which is initiated by the central nervous system via the hypothalamic pituitary gonadal axis (Styne, 2003). This axis acts as a negative feedback loop and initiates the release of the sex hormones that drive pubertal development (Shirtcliff et al., 2009). One of the primary characteristics of pubertal development is peak height velocity (PHV) or the adolescent growth spurt (Tanner & Whitehouse, 1976). Driven by elongation of the long bones at the

epiphysis (growth plate), PHV is influenced by growth hormones that regulate bone formation and reabsorption (Saggese et al., 2002). As pubertal development comes to an end, oestrogen acts on bone cells to impede further bone elongation by inducing growth plate fusion in both sexes (Moshang, 2005). In females, PHV typically begins and subsequently ends at an earlier chronological age than in males, potentially due to the effects of higher oestrogen levels in females compared to males (Sato & Hasegawa, 2022). Bone growth is an important factor when considering the influence of maturation on biomechanical metrics and further highlights the importance of comparing individuals according to their maturation stage rather than chronological age. In addition, physical changes to genitalia, skeletal muscle, as well as breast tissue and menarche in females are commonly used as guides for determination of maturation stage. However, the age when pubertal changes occur varies considerably between sexes and individuals (Roemmich & Rogol, 1995). Typically, puberty begins between the ages of 8- and 13-years in females and 9- and 14-years in males (Breehl & Caban, 2018).

### **1.5.2 Maturation stage classification tools**

Several tools exist to classify maturation stage of individuals, the most common being PHV, pubertal maturation observation scale (PMOS), and Tanner stages. PHV, defined as when height “averages 10.5 cm a year in boys and 9 cm per year in girls” (Tanner, 1986), reflects the age at which maximum rate of growth occurs (Ford, Shapiro, et al., 2010; Mirwald et al., 2002; Sigward, Pollard, & Powers, 2012). PHV is typically calculated using standard equations by Mirwald et al. (2002) which categorises individuals as pre-pubertal, mid-pubertal, and post-pubertal when away from the PHV value by more than -1 year, from -1 to 1 year, and when 1 year or more from PHV, respectively (Rumpf et al., 2015). Due to limited information regarding its reliability and validity, use of PHV alone to determine maturation stage is not advised. In females, onset of menarche is another factor that can be used as an accompanying characteristic for determining maturation however has limitations when used as a standalone measure of maturation stage. Due to these limitations, both PHV and

onset of menarche are usually used alongside other scales, such as the PMOS (Davies & Rose, 2000) and Tanner stages (Tanner, 1986; Tanner & Whitehouse, 1976).

The PMOS is a validated tool to classify maturation stage based on a series of questions regarding observable physical characteristics, such as (McEachan et al., 2014). The PMOS classifies individuals into three maturational categories: pre-pubertal (equivalent to Tanner stage I), early-pubertal (equivalent to Tanner stages II and III), or post-pubertal (equivalent to Tanner stages IV and V) (Paszkevicz et al., 2013; Quatman et al., 2008). The Tanner stages method typically uses illustrations and descriptions to characterise five different pubertal stages from pre-pubertal to adult (Tanner & Whitehouse, 1976). The ‘gold standard’ of the Tanner stages assessment is clinical examination by a physician. However, such an assessment can be uncomfortable for many young people. Therefore, self-examination of the Tanner stages with assistance from parents, alongside the PMOS, PHV, and menarche tools, can provide sufficient information for appropriate maturation stage categorisation (Rasmussen et al., 2015). Strengths and weaknesses of each of these methods of pubertal maturation stage classification are presented in Table 1.

**Table 1** Strengths and weaknesses of different pubertal maturation stage classification tools.

<b>Classification tool</b>	<b>Strengths</b>	<b>Weaknesses</b>
<b>Peak Height Velocity</b>	<ul style="list-style-type: none"> <li>• Simple calculation</li> <li>• Non-invasive</li> <li>• Quick to perform</li> <li>• Scale based</li> </ul>	<ul style="list-style-type: none"> <li>• Does not account for pubertal changes aside from height</li> <li>• Limited validity and reliability information</li> </ul>
<b>Pubertal Maturation Observation Scale</b>	<ul style="list-style-type: none"> <li>• Accounts for many pubertal changes</li> <li>• Non-invasive</li> <li>• Validated pubertal classification tool</li> </ul>	<ul style="list-style-type: none"> <li>• Classified into a broader group, not scale based</li> <li>• Subjective data</li> </ul>
<b>Tanner stages</b>	<ul style="list-style-type: none"> <li>• Can be invasive (practitioner examination)</li> <li>• Validated pubertal classification tool</li> </ul>	<ul style="list-style-type: none"> <li>• Classified into a broader group, not scale based</li> <li>• Subjective data</li> </ul>

## 1.6 Sex, maturation, and ACL injuries

Prior to puberty, the occurrence of ACL injuries is relatively uncommon. This observation has been attributed to the lack of sex-specific disparities (Andrish, 2001) and no detectable differences in lower extremity biomechanics or neuromuscular function (Beunen & Malina, 1988; Hewett et al., 2004). Whereas, the greater non-contact ACL injury occurrence in females following pubertal onset has been attributed to sex-specific changes in structural alignment (Wild et al., 2012), hormones (Shultz & Fegley, 2023; Wild et al., 2012), and strength (Davidson & McLean, 2016). A recent systematic review assessed sex-specific physical characteristics associated with ACL injury risk by age and maturational stage

(Shultz et al., 2022). The authors reported that by the time females were 8 to 10 years (Tanner stage I), reductions in fat-free mass, leg strength, and power and increases in general joint laxity compared to males were observed. By 11 to 13 years (Tanner stage II), and during the pre-pubertal to pubertal transition, more evident sex differences were found in body composition, strength, power, general joint laxity, and balance. In ages 14 to 17 years (Tanner stage III), and during the pubertal to post-pubertal transitions, females had smaller ACL size and cross-sectional area, greater anterior knee laxity and tibiofemoral angle, and higher-risk biomechanics than males (Shultz et al., 2022). Anatomical considerations are non-modifiable risk factors that likely contribute to ACL injury risk, however, biomechanics and neuromuscular control are important risk factors that are modifiable with the use of effective intervention strategies or technique adjustments (Hewett, Myer, et al., 2016).

Several factors have been linked to the increased ACL injury risk observed in females in late to post puberty, specifically between the ages of 15 to 19 years (Shea et al., 2004). Etzel et al. (2024) found strong predictors of an ACL injury among female participants including engaging in sports involving pivoting and early pubertal development. Among male participants, predictors of an ACL injury included being overweight or obese or participating in football or martial arts (Etzel et al., 2024). A review by Holden et al. (2016) also highlighted potential influencing factors, including increases in body mass and lever length; a shifted centre of mass position; limited adaptation of muscle strength in relation to body growth; a lack of a neuromuscular spurt concomitant with the adolescent growth spurt; hormonal adaptations including a sharp rise in oestrogen following menarcheal onset; and ongoing cyclical hormonal fluctuations. Pubertal development is commonly associated with sudden increases in height and mass increments, but altered movements and motor-control techniques are also apparent, which may contribute to the heightened injury risk (Atkins et al., 2016; Philippaerts et al., 2006; Van Der Sluis et al., 2014). Postural and anatomical adaptations concomitant with puberty, such as greater knee valgus and hip internal rotation (Nasser et al., 2021; Shultz et al., 2008), should be considered for their impact on biomechanics. Studies have shown increases in knee abduction moment with maturation in females (Ford, Shapiro, et al., 2010; Kim & Lim, 2014; Sigward, Pollard, & Powers, 2012),

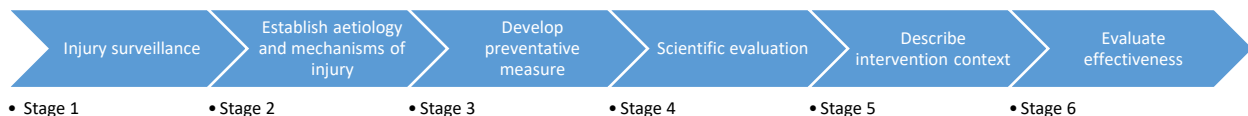
suggestive of greater knee valgus and increased ACL sprain (Hewett, Ford, et al., 2010; Hewett, Myer, & Ford, 2006). Additionally, the inconsistency in development of neuromuscular function across maturation may impact an individual's ability to effectively mitigate force to reduce ACL loading. This ability to mitigate force can vary considerably depending on maturation stage, sex, and training history (Hewett, Myer, Ford, et al., 2005; Quatman-Yates et al., 2012). Furthermore, Grinberg et al. (2024) have recently highlighted the importance of considering maturation stage rather than chronological age in the context of injury prevention, demonstrating changes in neuropsychological domains such as selective visual attention and information processing in girls across maturation stages.

Injury occurrence data is typically categorised according to chronological age without accounting for maturation stage. However, traumatic knee injuries, including ACL injuries, are reported to be four times more likely in ages aligning with typical early- to mid-puberty compared to typical pre-pubertal ages (Arendt et al., 1999; Powell & Barber-Foss, 2000; Shea et al., 2004). Previous studies have reported biomechanical differences between males and females beginning at 12 years old, when pubertal changes are occurring in many individuals, that are exacerbated with age (Lucarno et al., 2020; Sasaki et al., 2013; Yu et al., 2005). Given that the age when pubertal changes occur varies considerably between sexes and individuals (Roemmich & Rogol, 1995), categorising participants by age rather than maturational status severely limits interpretation of the effects of maturation on ACL injury risk. There currently is a paucity of literature describing how the risk of ACL injury changes across all stages of maturation. Furthermore, the methods used for determining maturation stage across studies are inconsistent (PHV, Tanner etc). This lack of standardisation is a further limitation in the understanding of ACL injury risk between the sexes and across maturational phases, warranting further investigation.

## 1.7 Prevention of ACL injuries

### 1.7.1 Injury prevention model

The alarming statistics for ACL injury in youth athletes justifies a public health priority focus for injury prevention. Whittaker et al. (2015) found that within 3 to 10 years after sustaining an intra-articular knee injury, adolescents had reduced function and quality of life and had an almost four times increased likelihood of being overweight or obese. Thus, preventing these injuries is vital for improving chances of continued sporting participation and minimising the potential impact on negative health outcomes. According to Finch (2006), development of an evidence base for injury prevention requires careful planning and study design. Finch (2006) proposed the six stage ‘Translating Research into Injury Prevention Practise (TRIPP) Model’ (Figure 1). Stage 1: *Injury surveillance* is where data needed to inform the following stages are collected through epidemiological monitoring and analysis of injury incidence rates and injury across specific groups. Stage 2: *Establishing aetiology and mechanisms of injury* identifies why injuries occur and potential risk factors. This thesis aims to inform Stage 2 of the TRIPP model, with the scope to further understand the biomechanical differences across sex specific maturation phases, which requires assessing the biomechanics associated with ACL injury in the context of sex and maturation. The contribution to research in this area will provide a better knowledge base for future research to undertake well informed steps towards Stage 3: *Develop preventative measures* where potential solutions for identification of injury risk mitigation can be developed appropriately for the target individuals. These solutions could lead to improved outcomes for the reduction of ACL injuries in youth athletes.



**Figure 1** Six stages of the translating research into injury prevention practice (TRIPP). Adapted from Finch (2006).

### **1.7.2 Assessing biomechanics associated with ACL injury**

Since it was first suggested as an ACL injury screening tool nearly 20 years ago (Hewett, Myer, Ford, et al., 2005), the double-leg drop jump task has been commonly used in biomechanical assessments of ACL injury risk (Ford, Shapiro, et al., 2010; Hewett et al., 2004; Otsuki et al., 2021; Pedley et al., 2020; Sigward, Pollard, & Powers, 2012). Assessment of 3 dimensional (3D) landing biomechanics using the double-leg drop vertical jump has demonstrated *good* to *excellent* reliability both within-sessions (ICC > 0.87) and between-sessions (ICC > 0.69) for most metrics (Mok et al., 2016). More recently, studies have criticised the double-leg drop jump task due to the mechanical simplicity, lack of reflection of typical injurious sporting manoeuvres, and poor ACL injury prediction ability (Fox et al., 2017; Hanzlíková & Hébert-Losier, 2020; Krosshaug et al., 2016). Field and court sports frequently involve unilateral stabilisation and propulsion during landing, running, kicking, or cutting manoeuvres, with up to 80% of non-contact ACL injuries occurring during single-leg landing, cutting or rotating (Koga et al., 2010). Therefore, movement tasks that involve frequent unilateral stabilisation, propulsion, rotational movements, and changes of direction may allow for more apparent and sport-specific high injury-risk pattern simulation compared to double-leg landings.

Less knee flexion at initial contact, less knee displacement in the sagittal plane, more knee displacement in the frontal plane, and greater knee abduction moments have been observed in single-leg compared to double-leg landing tasks (Yeow et al., 2011) likely owing to larger loads, a reduced base of support, and greater motor control requirement (Dingenen et al., 2015; Russell et al., 2006; Taylor et al., 2017). Additionally, the level of agreement between different jump-landing tests appears to be influenced by maturity status with high levels of variability observed between maturational groups (Lloyd et al., 2019). The use of single-leg landing tasks in maturing athletes may assist in identifying changes in biomechanics linked with ACL injury incidence, which could better inform development of preventative training programmes.

## 1.8 Summary

Given the increased incidence of ACL injuries in post-pubertal females, better understanding of the differences in biomechanics between males and females as they progress through puberty will provide novel information to guide future research and intervention. Categorisation of participants by age rather than maturational group provides limitations for the interpretation of the effects of maturation on ACL injury risk as pubertal changes vary considerably between sexes and individuals (Roemmich & Rogol, 1995). Therefore, this thesis aims to investigate the changes in biomechanical metrics associated with ACL injury risk during different movement tasks (single- and double-leg landing tasks), for court and field sport athletes across different maturational stages and sex.

The identification of high-risk biomechanical patterns associated with different landing tasks has the potential to reduce the societal and individual burden of this devastating injury. In addition, the identification of at-risk populations from a biomechanical perspective with respect to sex and/or maturational phase is crucial for implementation of effective prevention strategies specific to these metrics. The experimental studies within this thesis contribute to improved understanding of the changes in biomechanical movement patterns across sex-specific maturation. Furthermore, the relationships between observed biomechanical changes and increased incidence of ACL injury occurrence with maturation in females provides scope for implementation of targeted injury prevention programmes in these vulnerable populations. Based on the existing literature, it was hypothesised that: i) Biomechanical measures linked to higher ACL injury risk (such as increased knee extension angle, knee valgus angle and moment, and knee internal rotation moment) would be observed in female athletes compared to male athletes and; ii) Biomechanical metrics linked to higher ACL injury risk (such as increased knee extension angle, knee valgus angle and moment, and knee internal rotation moment) would be observed in late- to post-pubertal females compared with earlier maturational phases.

## 1.9 Thesis aims and outline

The primary aim of this thesis was to investigate the effect of sex and maturation on biomechanics associated with risk of ACL injury. The primary aim was addressed by the objectives outlined in Figure 2. This thesis is comprised of an introduction, a systematic literature review, a pilot study (which make up Part 1), and then followed by a methods, results, and discussion section incorporating reliability of the collected metrics and a cross-sectional exploration of the effect of sex and maturation on biomechanics of single-leg tasks, and finally a conclusion chapter (which make up Part 2).

Chapter 1 aimed to provide scope and background of the topic area. It also introduced the direction of the thesis.

The systematic literature review titled “Does maturation affect the biomechanical risk factors associated with ACL injury?” is presented in Chapter 2. The aim of this chapter was to systematically review all studies examining ACL-related biomechanics during defined maturational phases in dynamic tasks. This review sought to identify what exists in the literature, where gaps in knowledge may be, and to guide the methods of the experimental components of the thesis.

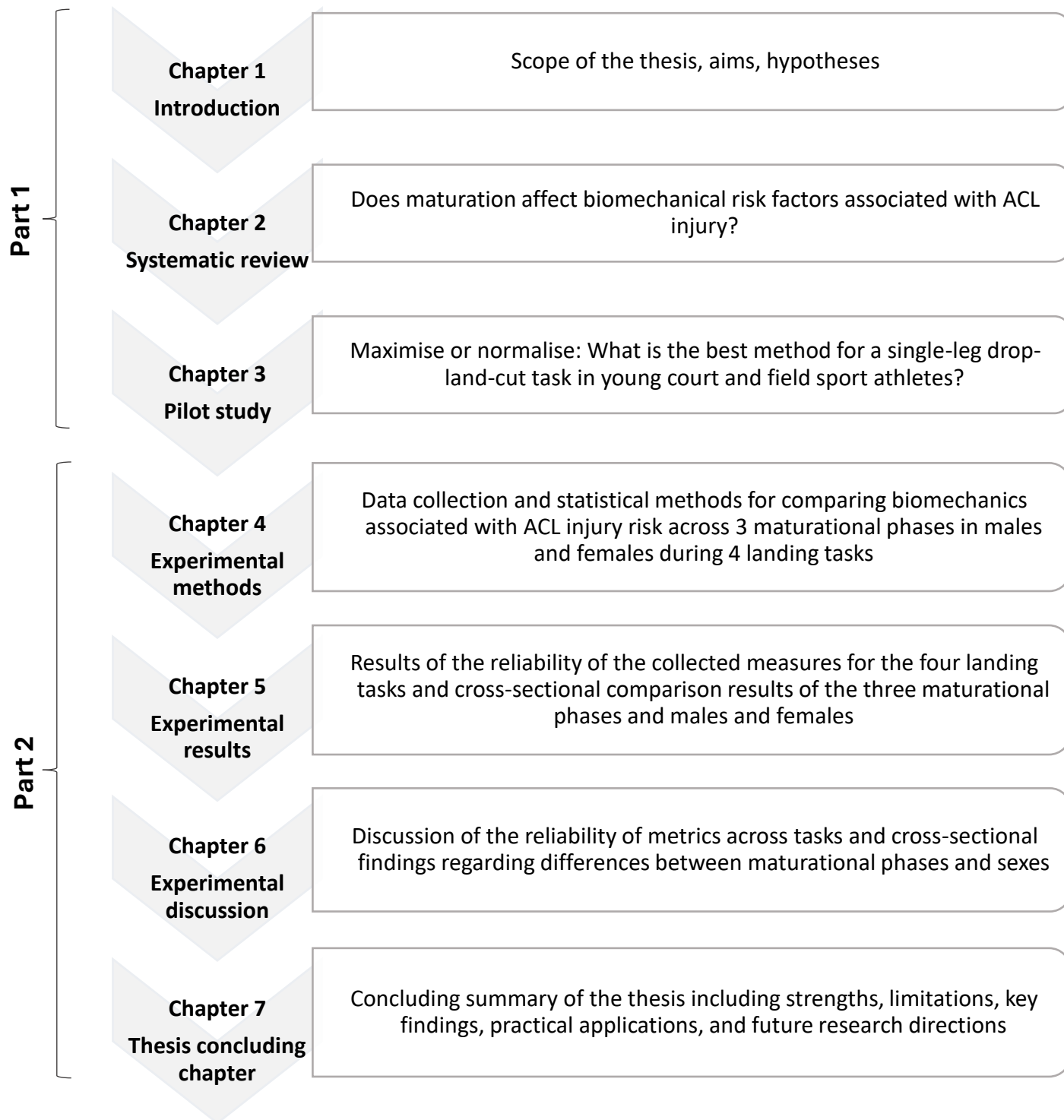
Following the systematic review, movement tasks deemed appropriate for assessing risk of ACL injury in young athletes were selected for experimentation. The land and cut task (CUT) has not been routinely used in research and the requirements of the task varied between studies. Chapter 3 is a pilot study which aimed to determine if differences in leap distance exist for the CUT task metrics based on using either a maximal or normalised (150% leg length) method in young court and field sport athletes. Secondly, this study explored whether the order of conditions or leg dominance would influence the distance achieved. This study was conducted to inform the most appropriate method for the CUT task in terms of participant requirements, which was then used for the experimental portion of the thesis. It was hypothesised that participants would leap to further distances using the maximal

method due to greater effort, on the maximal task when presented second, and when using the dominant leg.

Chapter 4 describes the methods used for the experimental portion of the thesis which included test-retest reliability and cross-sectional studies that involved four different single-leg drop-landing tasks. The reliability study aimed to establish the test-retest reliability of the metrics explored, anticipating that biomechanical metrics in the coronal and sagittal plane, and GRFs recorded from all the tasks would demonstrate high between-session reliability. The cross-sectional study aimed to address the gaps in the literature identified in the systematic review regarding maturation stage, sex, task, and relevant biomechanical variables by comparing the biomechanical and performance metrics of males and females across three specific maturation stages in four different sport specific landing tasks. It was hypothesised that increased knee extension angle, knee valgus angle and moment, and knee internal rotation moment would be observed in female athletes who are late- to post-pubertal in maturational stage compared to males and compared to females in earlier maturational phases. Chapter 5 presents the results for all four landing tasks, including the reliability of the metrics.

Chapter 6 discusses the results of the reliability and cross-sectional studies. The cross-sectional results are discussed systematically; firstly, in relation to the main metrics identified in the previously reported systematic review, followed by a deeper dive into the findings of each landing task separately, followed by the practical applications, limitations, recommendations for future research and conclusions specific to the experimental portion of the thesis.

Chapter 7 summarises the findings of the thesis overall, provides relevant practical applications and future research direction. It also addresses the strengths and limitations of the thesis and draws conclusions regarding the main findings.



**Figure 2** Thesis structure flow diagram. *Note:* ACL, anterior cruciate ligament.

## **2.0 Chapter 2 – Systematic review**

### **2.1 Prelude**

This thesis focuses on the use of dynamic movement tasks that reflect manoeuvres observed in sporting environment with a premise to compare biomechanics associated with ACL injury risk during these tasks across different stages of pubertal maturation and sex. Chapter 1 highlights the severity of ACL injuries and the potential influence of pubertal maturation on ACL injury risk. The increased occurrence of ACL injuries in late- to post-pubertal females in recent years (Maniar et al., 2022) has prompted a heightened interest in epidemiological, observational, and intervention research in this area. Different methods have been used in laboratory and field settings to explore the effects of maturation on biomechanics associated with ACL injury risk, which can challenge interpretation and ability to make meaningful inferences of findings. In addition to biomechanical metrics, understanding the factors that may influence outcomes of testing procedures, such as maturation stage identification or task demands, is necessary for the correct interpretation and subsequent implementation of results. Considered high on the hierarchy of evidence (Evans, 2003), systematic literature reviews use precise and thorough methods to summarise the current literature on a specific topic. To date, there has been no systematic review of the effects of maturation on biomechanics associated with risk of ACL injury that includes males and females. Considering the higher incidence of ACL injuries following puberty, summarising the observed differences in ACL injury related biomechanics between maturation stages in consideration of sex is vital to the implementation of injury mitigation strategies and the development of preventative training interventions that are population specific.

# Maturation and biomechanical risk factors associated with Anterior Cruciate Ligament injury: Is there a link? A systematic review

Butcher, A. J., Ward, S., Clissold, T., Richards, J., & Hébert-Losier, K. (2024). *Phys Ther Sport* 2024;68:31-50. doi: 10.1016/j.ptsp.2024.06.002 PMID: 38908221

## 2.2 Abstract

**Objective** To establish the potential link between sex-specific maturation and biomechanical factors associated with ACL injury during dynamic tasks.

**Design** Systematic review

**Literature search** Five databases (CINHAL®, Cochrane Library, PubMed®, Scopus®, and SPORTDiscus) were searched and monitored until 27 May 2024.

**Study selection criteria** Cross-sectional, cohort, case-control, or interventional studies reporting one or more biomechanical metric linked with ACL injury and which assessed participants across two or more maturation stages were considered eligible.

**Data synthesis** Studies were assessed for risk of bias using a modified version of the Newcastle Ottawa Scale and overall quality of evidence was rated using GRADE. Metrics and effect sizes were presented where available.

**Results** Eighteen included studies examined 400 males, 1377 females, and 315 participants of undefined sex across various maturation stages. The methodological quality of most studies (n = 16) was considered good, and satisfactory for two. Knee abduction angle, knee abduction moment, knee flexion angle, and ground reaction forces were most commonly reported. Knee abduction angles and moments and knee flexion angles were greater in late and post-pubertal females than males and pre-pubertal females during both landing and cutting tasks. When normalised for body mass, ground reaction forces were generally greater in males compared to females overall and for less mature participants for both sexes. Overall quality of evidence was low or medium across the four biomechanical metrics.

**Conclusion** Sex-specific maturation considerations are important in the targeted development and implementation of ACL injury risk identification and prevention strategies.

**Key words**

Biomechanics, ACL, injury risk, pubertal development

## 2.3 Background

Anterior cruciate ligament (ACL) injury is one of the most common and debilitating injuries among young athletes (Renstrom et al., 2008). Following the onset of puberty, ACL injury incidence rate in females appears to peak between the ages of 15 to 19 years (Maniar et al., 2022; Renstrom et al., 2008; Shea et al., 2004; Zbrojkiewicz et al., 2018). The annual incidence of ACL rupture in those under 25 years in Australia has increased by 74% over a 15-year period (Zbrojkiewicz et al., 2018). Annual rates of ACL injuries at an even younger age (5 to 14 years) has also increased over the last 20 years in Australia, rising 10.4% in females and 7.3% in males (Maniar et al., 2022). Although increases are apparent for both sexes, female athletes demonstrate a two-to-four times greater incidence of non-contact ACL injury and a younger average age of ACL injury than males across multiple sports and competition levels (Prodromos et al., 2007; Waldén et al., 2011).

Experts have suggested that prior to puberty, ACL injury rates are similar between sexes (Shea et al., 2004) and lower than post-puberty (Shea et al., 2004; Slauterbeck et al., 2006; Wild et al., 2012). Furthermore, pre-puberty, lower-extremity biomechanics (Wild et al., 2012), neuromuscular function (DiStefano et al., 2015), and ACL morphology [e.g., size, length, and cross-sectional area (Hosseinzadeh & Kiapour, 2021)] are similar between sexes. Rapid skeletal growth; changes in body mass, anatomy, and posture; and a lack of sufficient concomitant neuromuscular adaptations all likely contribute to the development of movement patterns associated with increased ACL injury risk with maturation (Hewett et al., 2004; Holden et al., 2016; Renstrom et al., 2008; Shultz et al., 2008). The development of neuromuscular function in maturing individuals often does not progress linearly (DiStefano et al., 2015), likely contributing to variance in ability to effectively mitigate forces to reduce ACL loading.

ACL injuries are more common from non-contact than contact mechanisms and often non-contact injury risk can be reduced with targeted interventions (Hewett, Lynch, et al., 2010; Webster & Hewett, 2018). Investigating potentially modifiable factors for reducing non-contact ACL injury risk, specifically in maturing individuals, is crucial for risk mitigation. Non-contact ACL injuries typically result from multiplanar loading during landing or cutting

manoeuvres, which can involve large knee abduction angles and moments, internal tibial rotation, anterior tibial translation, and reduced knee flexion (Hewett, Ford, et al., 2016; Kiapour et al., 2016; Koga et al., 2010; Levine et al., 2013; Olsen et al., 2004; Quatman et al., 2006). Dependent on maturation stage, sex, and training history (Hewett, Myer, & Ford, 2005; Quatman-Yates et al., 2012), these neuromuscular variations can result in altered proprioceptive acuity (Lee et al., 2015) and muscle activation patterns (Del Bel et al., 2018; Flaxman et al., 2014), which may be detrimental to sporting performance and safe landing and cutting biomechanics.

Research exploring the association between sex-specific maturation and lower-extremity biomechanics has highlighted deviations in movement mechanics and postural control across maturation (or between different maturational groups), typically during landing or cutting tasks (Chia et al., 2021; Ford, Myer, et al., 2010; Sigward, Pollard, Havens, et al., 2012; Sigward, Pollard, & Powers, 2012; Westbrook et al., 2020). Biomechanical metrics potentially associated with ACL injury include; increased knee abduction angle and moment, decreased knee flexion, and increased ground reaction forces (GRFs) (Hewett, Myer, & Ford, 2005; Paterno et al., 2010). A recent review highlighted changes in biomechanical risk factors associated with ACL injuries during jump-landing tasks in female athletes at various stages of maturity (Ramachandran et al., 2024). They reported strong evidence for higher peak knee abduction angle, external knee abduction moment and internal rotation moment, and lower relative peak vertical GRF (vGRF) in post-pubertal female individuals compared with pre-pubertal girls (Ramachandran et al., 2024). While this review indicates maturation in females can influence biomechanical risk factors related to ACL, it did not consider maturation in males and tasks other jump landing.

Confidence in the understanding of biomechanical differences associated with ACL injury across maturational phases requires a critical evaluation and synthesis of the research, which must also consider sex and task differences. Such an examination would aid in the development of athlete monitoring and injury risk reduction tools specific to maturation stage and sex. This systematic review aimed to establish the potential link between

maturation and biomechanical factors associated with ACL injury during dynamic tasks, while accounting for potential sex-specific differences.

## **2.4 Methods**

This systematic review was designed to meet the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (Page et al., 2021). Pre-registration was completed with the International Prospective Register of Systematic Reviews (PROSPERO; registration ID: CRD42022345627).

### **2.4.1 Searches**

The electronic databases CINHAL®, Cochrane Library, PubMed®, Scopus®, and SPORTDiscus were searched on 13 July 2022. These databases were also monitored for eligible studies up to 27 May 2024. The search included the following search terms: (ACL or anterior cruciate ligament) AND (matur\* OR pubert\*) AND (biomechanic\* or kinematic\* or kinetic\*) and were filtered for English language. The supplementary material contains a detailed description of the search syntax for each database (Supplement 1). References from identified papers were manually checked to ensure inclusion of all relevant articles.

### **2.4.2 Study inclusion and exclusion criteria**

Eligible studies included those published between journal inception and 27 May 2024. Inclusion criteria of individual studies was based on the PICOS framework: Participants, Interventions, Comparisons, Outcomes, and Study Type (Eriksen & Frandsen, 2018).

*2.4.2.1 Participants:* Studies that included uninjured adolescent/pre-pubertal/pubertal/post-pubertal males or females were included. No restriction was placed on participants' level of physical activity or performance.

*2.4.2.2 Interventions:* Studies using a dynamic task relevant to the assessment of ACL injury risk, such as landing or cutting, were eligible for inclusion.

*2.4.2.3 Comparisons:* The associations between sex-specific maturation and biomechanical risk factors for ACL injury were of interest. Therefore, studies needed to operationally define maturational groups and assessment methods; otherwise, studies were excluded. For an inclusive review, we did not set the operational definition for maturational status although, studies needed to assess at least two maturational phases either at two different points in time where the maturation stage of the participant changed (longitudinal) or at the same point in time but comparing different maturational groups (cross-sectional).

*2.4.2.4 Outcomes:* Studies needed to report one or more kinematic or kinetic metric linked with ACL injuries.

*2.4.2.5 Study type:* Peer-reviewed original research that were cross-sectional, cohort, case-control, or interventional studies published in English were eligible. These study designs reflect observational, analytical study designs according to the Centre for Evidence-Based Medicine (<https://www.cebm.ox.ac.uk/resources/ebm-tools/study-designs>). Only the baseline values from the interventional studies were included in the formal review process as these studies examined different maturational groups before and after an intervention aimed at altering their biomechanics. Qualitative studies, review articles,

commentaries, case reports, protocols, conference proceedings, and full-text articles in languages other than English were excluded.

All search results were imported into EndNote (EndNote 20.4.1, Clarivate™, Philadelphia, PA, USA) and duplicates were removed. The remaining studies were imported into Rayyan, an online eligibility screening and reviewer blinding tool (Ouzzani et al., 2016) (<http://rayyan.qcri.org>). Two reviewers (AB and SW) independently screened titles and abstracts in Rayyan. The same two reviewers independently screened the full-text articles. Studies that did not meet eligibility criteria at either step were excluded. At each step, the two independent reviewers met to resolve disagreements in the screening process. A third reviewer (KHL) was available when consensus was not reached, but not required.

#### 2.4.3 Study quality assessment

Two independent reviewers (AB and KHL) assessed the methodological quality and risk of bias of studies meeting inclusion using a modified version of the Newcastle Ottawa Scale (NOS) (Modesti et al., 2016), shown in the supplementary material (Supplement 2). A third reviewer (SW) was available if consensus was not established, but not required. The modified NOS tool was selected as most studies were observational (Modesti et al., 2016) and the NOS is deemed a suitable alternative to the ROBINS-I (Risk of Bias in Non-randomised Studies – of Interventions) (Sterne et al., 2019). The NOS uses a star system, with a maximum of five stars for selection. A star was awarded if the item was deemed low risk of bias and not awarded if deemed high risk of bias. The overall score is 10 stars, where a greater number indicates lower risk of bias and superior methodological quality. The overall quality of studies was qualitatively evaluated as very good, good, satisfactory, and unsatisfactory when correspondingly allocated 9-10, 7-8, 5-6, and 4 or less stars based on prior reviews (Naafs et al., 2020; Ortolan et al., 2021).

The semiquantitative synthesis (Huguet et al., 2013) undertaken involved evaluating and rating the certainty of evidence for differences in risk factors between maturation stages using a modified Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach (GRADE Working Group, 2004). All domain ratings were considered when assigning the overall GRADE rating. Where an equal number of studies were ranked as having no limitations and serious limitations for a specific domain, the overall GRADE rating was lowered. Risk of bias assessment, level of evidence, or study design ratings did not constitute study exclusion.

#### 2.4.4 Data extraction strategy

One reviewer (AB) extracted metrics of interest from the included studies using a standardised data extraction template. A second reviewer (SW) verified the accuracy and completeness of data extraction. The following data were extracted from studies: study characteristics, participant characteristics, participant maturation stages, maturational assessment method, dynamic task, relevant kinematic and kinetic metrics assessed, and key results. When not explicitly stated in text, the country of investigation was based on the institution granting ethical approval, followed by the affiliation of the first author. We attempted to contact the first authors of papers that appeared to involve the same participants for confirmation, as it could introduce bias in the findings of our review.

#### 2.4.5 Data synthesis and presentation

Data extracted were compiled and analysed using Microsoft Excel 2019 (Microsoft Corp., Redmond, WA, USA). Due to the variation in tasks used, maturation stages assessed, and biomechanical metrics reported, there was an insufficient amount of comparable data to perform a meta-analysis. Therefore, a systematic narrative synthesis of the included studies was conducted, organising the results based on tasks and narratively synthesising how maturation was associated with biomechanical variables when reported in at least two

studies. Double and single leg performances of the same type of task were not grouped together given the significant differences in biomechanics between double leg and single leg dynamic tasks (Taylor et al., 2016). Hedges *g* effect size differences were calculated to quantify between group differences when data were provided in sufficient detail using <https://effect-size-calculator.herokuapp.com/>. Paired effect size differences were used when data were longitudinal in nature. Effect size inferences were determined using the thresholds <0.2, 0.2, 0.5, and 0.8 for *trivial*, *small*, *medium*, and *large*, respectively (Cohen, 2013; Ellis, 2010).

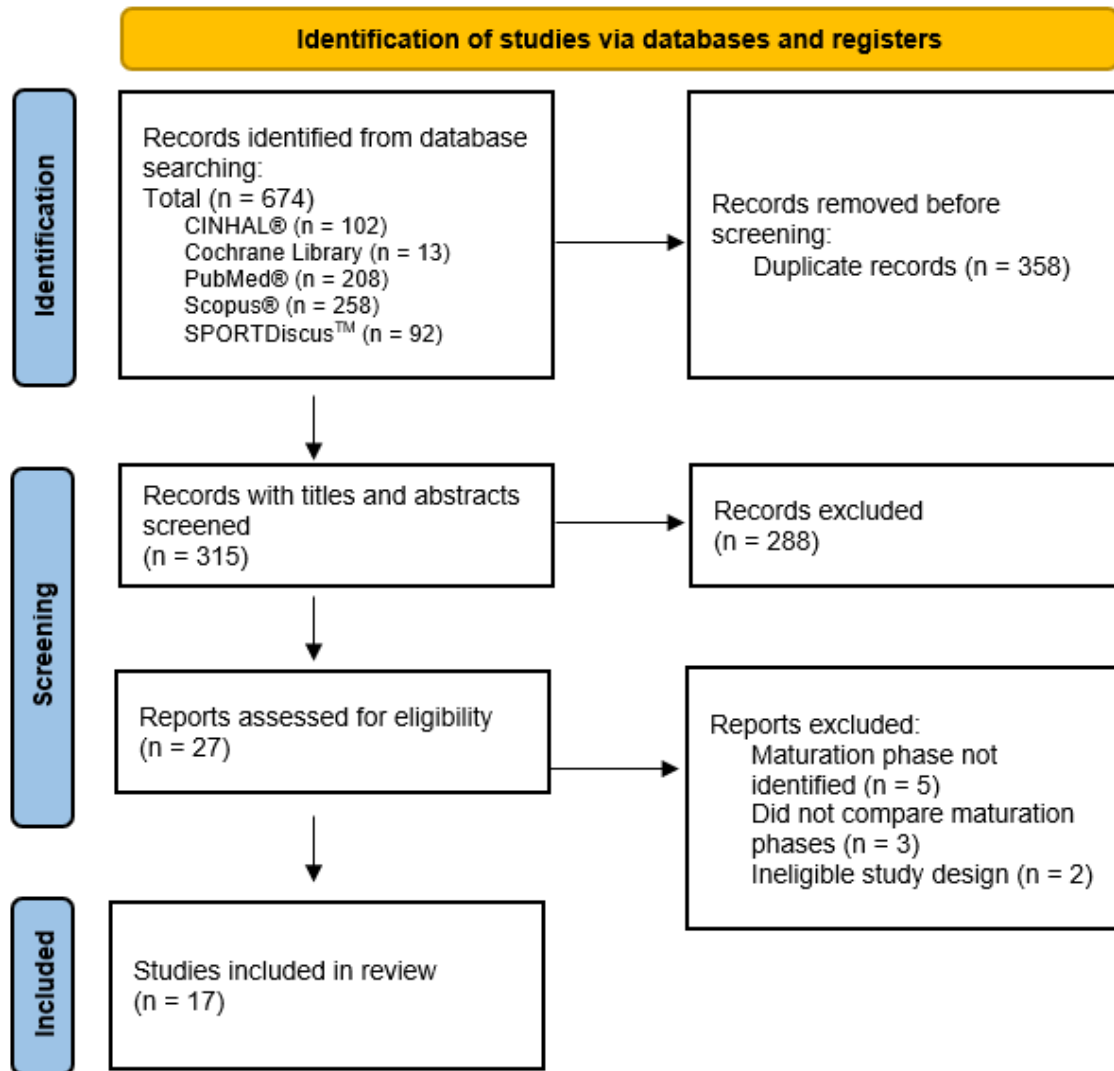
#### 2.4.6 Equity, diversity, and inclusion statement

The author group consists of four females and one male of whom are junior, early-career, and senior researchers from different disciplines, based in two countries. Our systematic review population included both males and females with no inclusion restrictions regarding marginalised groups. The influence of data availability regarding sexes and cultural diversity on maturation and biomechanics associated with ACL injury is considered in the discussion.

## 2.5 Results

### 2.5.1 Review statistics

The initial database search yielded 673 results, with 17 studies ultimately meeting inclusion. The search was monitored whilst the review was undertaken, and an additional study was included. The PRISMA flow diagram is presented in Figure 3. Many biomechanical metrics were examined across studies; however, a minimum of three studies reporting the same metric were required for inclusion in the narrative synthesis. Knee abduction angle, knee abduction moment, knee flexion, and GRFs were the four most common metrics and were reported across at least three studies; therefore, these metrics were included in the narrative synthesis.



**Figure 3** Preferred reporting items for systematic reviews and meta-analysis (PRISMA) flow diagram of the search strategy and study selection process.

**Table 2** Qualitative synthesis of studies (n = 18) reporting on changes in biomechanics associated with anterior cruciate ligament (ACL) injury during different maturational phases.

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturation stages and identification method	Biomechanical variables	Results	Effect sizes (Hedges's g)*
<b>Qualitative synthesis of studies (n = 9) reporting on biomechanics in DVJ tasks.</b>								
(Ford, Myer, et al., 2010)	United States of America	Longitudinal prospective cohort 8 stars: good	265 142 pubertal (age, 12.3 ± 0.8 y; height, 155.9 ± 6.8 cm; mass, 47.8 ± 10.2 kg), 120 post-pubertal (age, 14.4 ± 1.4 y; height, 164.4 ± 5.8 cm; mass, 59.0 ± 8.5 kg)	50 37 pubertal (age, 13.0 ± 1.1 y; height, 165.2 ± 10.2 cm; mass, 54.5 ± 10.2 kg) 13 post-pubertal (age, 15.1 ± 1.1 y; height, 180.8 ± 7.9	Pubertal, post-pubertal Modified PMOS	Ankle, knee and hip: Stiffness, flexion angle at initial contact, peak angle, and peak moment	All athletes ↑ active knee stiffness over a year (p < 0.05). Only M had ↑ ankle and hip active stiffness (p < 0.05). ↑ peak ankle (31.2 Nm MD) and hip (42.2 Nm MD) moments, but not knee moments, in post-pubertal M but not post-pubertal F (p < 0.05). F had a ↑ knee to hip moment ratio than M (p < 0.05).	<p><b>Females</b></p> <p>Knee flexion angle at initial contact (g - 0.127 <i>trivial</i>)</p> <p>Peak knee flexion angle (g -0.223 <i>small</i>)</p> <p>Peak knee flexion moment (g 0.842 <i>large</i>)</p> <p><b>Males</b></p> <p>Knee flexion angle at initial contact = 0.419 <i>small</i>)</p> <p>Peak knee flexion angle (g 0.021 <i>trivial</i>)</p>

								cm; mass, 70.1 ± 8.4 kg)	Peak knee flexion moment ( $g$ 1.362 <i>large</i> )
<b>(Ford, Shapiro, et al., 2010)</b>	United States of America	Longitudinal prospective cohort	315 total (female or male unspecified)  182 pubertal 133 post-pubertal	Pubertal, post-pubertal  Modified PMOS	Stature change, knee abduction angle, knee abduction moment	No sex differences in peak knee abduction angle or moment during DVJ between pubertal M and F ( $p > 0.05$ ). Pubertal F ↑ peak abduction angle from the first to second year (1.6° MD; $p = 0.001$ ), M had no change ( $p = 0.90$ ). Following puberty, peak abduction angle and moment ↑ in F relative to M (angle: F $-9.3 \pm 5.7^\circ$ , M $-3.6 \pm 4.6^\circ$ , $p = 0.001$ ; moment: F $-21.9$	<b>Females</b> Knee abduction moment ( $g$ -0.501 <i>medium</i> ) Knee abduction angle ( $g$ -0.271 <i>small</i> )		
		8 stars: good	Female: pubertal (age, 12.3 ± 0.8 y; height, 155.9 ± 6.8 cm; mass, 47.8 ± 10.2 kg), post-pubertal (age, 14.4 ± 1.4 y; height, 164.4 ± 5.8 cm; mass, 59.0 ± 8.5 kg) Male: pubertal (age, 13.0 ± 1.1 y; height, 165.2 ± 10.2 cm; mass, 54.5 ± 10.2 kg) post-pubertal (age, 15.1 ± 1.1 y; height, 180.8 ± 7.9 cm; mass, 70.1 ± 8.4 kg)				<b>Males</b> Knee abduction moment ( $g$ 0.621 <i>medium</i> ) Knee abduction angle ( $g$ 1.088 <i>large</i> )		

$\pm 13.5$  Nm, M -13.0 $\pm$   
12.0 Nm, p = 0.017).

<b>(Hass et al., 2005)</b>	United States of America	Cross-sectional 5 stars: satisfactory	32 16 pre-pubertal (age, 9.0 $\pm$ 1.0 y; height, 134.5 $\pm$ 9.1 cm; mass, 33.1 $\pm$ 9.2 kg), 16 post-pubertal (age, 20.2 $\pm$ 1.2 y; height, 162.6 $\pm$ 6.1 cm; mass, 58.5 $\pm$ 7.2 kg)	Pre-pubertal, post-pubertal Pre-onset of menarche, at least 6 y past menarche	Knee flexion angle at touchdown, landing phase duration, knee flexion and knee abduction ROM, peak magnitude of posterior GRF, magnitude and timing of peak vGRF, peak knee anterior-posterior and medial-lateral joint forces, and peak knee extensor and abduction-adduction moment	Significant maturation level x landing sequence interactions for post-pubertal who had $\downarrow$ knee flexion (4.5 $^{\circ}$ MD; p = 0.005) at initial contact, $\uparrow$ mediolateral knee joint forces [pre-pubertal: -0.63 + 0.21 N.(kg. $\sqrt$ LH) ; post-pubertal: 0.55 + 0.21 N-(kg $\sqrt$ LH)-f] 1.18 MD; p < 0.001), and $\downarrow$ knee extensor moments [pre-pubertal: -0.0124 + 0.001 Nm.(kg-BH. $\sqrt$ LH)- ; post-pubertal: -	<b>Females</b> Knee flexion angle at initial contact (g - 5.000 <i>large</i> ) Peak vGRF (g -5.348 <i>large</i> ) Peak knee abduction moment (g 0.200 <i>small</i> )
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0.0079 ± 0.001 N  
 m.(kg.BH.√LH)-1] (  
 0.0045 MD; p = 0.026)  
 compared to pre-  
 pubertal.  
 \*LH, landing height;  
 BH, body height

<b>(Hewett et al., 2004)</b>	United States of America	Cross-sectional 7 stars: good	100 14 pre-pubertal (age, 11.5 ± 0.7 y; height, 148.7 ± 5.9 cm; mass, 38.9 ± 5.9 kg), 28 early-pubertal (age, 12.6 ± 1.1 y; height, 158.5 ± 6.1cm; mass, 46.8 ± 5.5 kg),	81 27 pre-pubertal (age, 12.0 ± 0.6 y; height, 151.3 ± 6.7 cm; mass, 41.9 ± 8.3 kg), 24 early-pubertal (age, 14.2 ± 1.4 y; height, 169.7 ± 9.9	Pre-pubertal, early pubertal, late/ post-pubertal Modified PMOS, Tanner stages	Medial knee motion, valgus angle at initial contact and maximum angle, hamstring and quadriceps peak torque	F landed with ↑ total medial knee motion and (p < 0.01) ↑ maximum knee valgus angle (11° MD; p < 0.01) vs M following onset of maturation. F also had ↓ flexor moments (p < 0.01) vs M and significantly different maximum valgus angles between the dominant and non-dominant limbs after maturation.	<b>Females</b> Pre vs early pubertal Knee valgus angle at initial contact ( <i>g</i> 0.632 <i>medium</i> ) Peak knee valgus angle ( <i>g</i> 1.697 <i>large</i> ) Early vs late pubertal Knee valgus angle at initial contact ( <i>g</i> 4.000 <i>large</i> ) Peak knee valgus angle ( <i>g</i> 3.333 <i>large</i> ) Pre vs late pubertal

			58 late/post pubertal (age, 15.5 ± 1.5 y; height, 168.3 ± 6.5 cm; mass, 63.4 ± 10.9 kg)	cm; mass, 59.4 ± 11.8 kg), 30 late-post pubertal (age, 15.8 ± 1.7 y; height, 179.2 ± 8.4 cm; mass, 70.8 ± 10.9 kg)				Knee valgus angle at initial contact ( <i>g</i> 4.525 <i>large</i> ) Peak knee valgus angle ( <i>g</i> 1.897 <i>large</i> )
<b>(Hewett, Myer, Ford, et al., 2006)</b>	United States of America	Cross-sectional 6 stars: satisfactory	87 n for maturational groups and participant descriptives not reported	188 n for maturation al groups and participant descriptives not reported	Tanner stages 1, 2, 3, 4 and 5 Tanner stages	vGRF upon contact and take-off, vertical jump height	F had no change in vertical jump height whereas M ↑ 12.5% on average between pubertal stages ( <i>p</i> = 0.002). The ratios of drop landing force to drop take-off and maximum landing force to maximum take-off force ↓ in M as they matured ( <i>p</i> < 0.05) but	Data unavailable~
								<b>Males</b> Values were not provided.

did not change in F  
between pubertal  
stages.

<b>(Otsuki et al., 2021)</b>	Japan	Intervention al  8 stars: good	154  17 (ctrl) and 18 (int) early- pubertal (age, 12.8 ± 0.7 y; height, 151.1 ± 5.4 cm; mass, 41.0 ± 4.6 kg), 22 (ctrl) and 28 (int) late- pubertal (age, 13.9 ± 1.0 y; height, 161.2 ± 5.8 cm; mass, 52.2 ± 6.2 kg),	Early pubertal, late pubertal, post-pubertal  Self- administered rating scale for pubertal development, Tanner stages	Medial knee displacement, knee flexion ROM, peak knee abduction moment	After six months of training, medial knee displacement significantly ↑ in early- pubertal control (p = 0.02) and did not change in early- pubertal training (p = 0.37). Knee flexion ROM significantly ↓ in early-pubertal control (p = 0.01) and did not change in early- pubertal training (p = 0.23). The probability of high knee abduction moment ↑ in early- pubertal control (p <	Data unavailable~
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			36 (ctrl) and 33 (int) post pubertal (age, 16.0 ± 0.7 y; height, 161.5 ± 5.7 cm; mass, 55.0 ± 5.3 kg)				0.001), but not in early- pubertal training (p = 0.13). The probability of high knee abduction moment also ↓ in post-pubertal training (p < 0.001) but did not change in post- pubertal control (p = 0.58).	
<b>(Quatman et al., 2006)</b>	United States of America	Longitudinal prospective cohort  7 stars: good	16  All pubertal first year (age, 12.6 ± 1.0 y; height, 162.0 ± 7.9 cm; mass, 47.5 ± 6.0 kg) and post- pubertal second year (age, 13.6 ± 1.0 y; height,	17  All pubertal first year (age, 13.8 ± 0.6 y; height, 173.0 ± 9.2 cm; mass, 62.6 ± 7.6 kg) and post- pubertal second year	Pubertal, post-pubertal  Modified PMOS,  Tanner stages	Vertical jump height, maximum GRF, GRF loading rate	M ↑ vertical jump height with maturation (3.2cm MD; p < .001); F did not. M significantly ↓ their maximal GRF (0.3BW MD; p = 0.005); F did not. Take-off force ↓ in females (0.1BW MD; p = 0.003), but not in M. Both M and F ↓ loading rates with maturation (p < 0.001). F had higher loading rates than M at both	<b>Females</b> Peak vertical ground reaction force ( <i>g</i> 0.509 <i>medium</i> )  <b>Males</b> Peak vertical ground reaction force ( <i>g</i> - 0.442 <i>small</i> )

			165.7 ± 8.4 cm; mass, 53.2 ± 6.2 kg)	(age, 14.8 ± 1.4 y; height, 177.0 ± 7.9 cm; mass, 67.9 ± 5.5 kg)				stages of maturation (p = 0.037).
<b>(Sigward, Pollard, &amp; Powers, 2012)</b>	United States of America	Cross-sectional 7 stars: good	60  15 pre-pubertal (age, 10.2 ± 0.8 y; height, 144.9 ± 7.2 cm; mass, 37.3 ± 6.4 kg)  15 pubertal (age, 12.5 ± 0.7 y; height, 156.9 ± 6.8 cm; mass, 47.8 ± 8.9 kg),  14 post-pubertal (age,	59  16 pre-pubertal (age, 11.4 ± 1.0 y; height, 146.9 ± 8.9 cm; mass, 37.9 ± 5.6 kg)  15 pubertal (age, 13.3 ± 1.2 y; height, 160.6 ± 9.7 cm; mass,	Pre-pubertal, pubertal, post-pubertal, young adult  Modified PMOS, Tanner stages	Internal knee adductor moment, sagittal plane knee/hip moment and energy absorption ratios	When averaged across maturation levels, F had ↑ internal knee adductor moments (0.06 ± 0.03 vs. 0.01 ± 0.02 Nm/kg*m; 0.05 Nm/kg MD; p < 0.005), knee/hip extensor moment ratios (2.0 ± 0.1 vs. 1.4 ± 0.1 Nm/kg*m; 0.6 Nm/kg MD; p < 0.001), and knee/hip energy absorption ratios (2.9 ± 0.1 vs. 1.96 ± 0.1 Nm/kg*m; 0.94 Nm/kg MD; p < 0.001) vs M.	Data unavailable ~

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15.7 ± 1.1 y; height, 166.3 ± 6.7 cm; mass, 59.7 ± 6.8 kg), 15 young adult (age, 19.3 ± 1.1 y; height, 166.1 ± 5.7 cm; mass, 64.9 ± 6.9 kg)	52.4 ± 7.8 kg), 14 post- pubertal (age, 15.6 ± 1.1 y; height, 176.4 ± 7.5 cm; mass, 69.7 ± 10.2 kg), 15 young adult (age, 19.8 ± 1.4 y; height, 181.5 ± 7.2 cm; mass, 78.0 ± 6.6 kg)
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<b>(Westbrook et al., 2020)</b>	United States of America	Cross-sectional 7 stars: good	138  17 pre-pubertal (age, 10.3 ± 0.6 y; height, 137.0 ± 6.8 cm; mass, 34.2 ± 4.5 kg), 32 pubertal (age, 11.9 ± 0.8 y; height, 151.1 ± 5.7 cm; mass, 43.3 ± 6.0 kg), 90 post-pubertal (age, 14.6 ± 1.6 y; height, 162.6 ± 5.6 cm; mass, 56.2 ± 8.8 kg)	Pre-pubertal, early pubertal, post-pubertal  Prediction of percentage of adult stature (Khamis-Roche method)	<b>DVJ</b> Knee abduction, knee flexion, normalised knee moments	Post-pubertal had significantly (p < 0.001) ↑ peak abduction angles and moments than pubertal and pre-pubertal (5.4° and 3.4°, 10.1 Nm and 14.2 Nm MD). Post-pubertal and pubertal had ↑ peak knee flexion moments vs pre-pubertal (54.2 Nm and 36.3 Nm MD), as did post-pubertal vs pubertal (17.9 Nm MD).	<b>Females</b> Peak knee abduction angle pre vs pub (g 0.322 <i>small</i> ) pre vs post (g 0.325 <i>small</i> ) pub vs post (g 0.679 <i>medium</i> ) Peak knee abduction moment normalised pre vs pub (g 0.277 <i>small</i> ) pre vs post (g -0.295 <i>small</i> ) pub vs post (g -0.448 <i>medium</i> )  Peak knee flexion angle pre vs pub (g 0.300 <i>small</i> )
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pre vs post (*g* 0.380  
*small*)  
pub vs post (*g* 0.054)

Peak knee flexion  
moment normalised  
pre vs pub (*g* 0.448  
*small*)  
pre vs post (*g* 0.636  
*medium*)  
pub vs post (*g* 0.257  
*small*)

**Qualitative synthesis of studies (n = 3) reporting on biomechanics in cutting tasks.**

<b>(Chia et al., 2021)</b>	United States of America	Longitudinal prospective cohort	172 69 pre-pubertal 8 stars: good	Pre-pubertal, mid-pubertal, post-pubertal Modified PMOS, Tanner stages	<u>45° unanticipated cutting task</u> Trunk: total ROM in all planes, peak trunk flexion, lateral flexion, rotation angles	With maturation, ↓ sagittal plane hip (1.8-2.6° MD, p < 0.03) and knee ROM (2.7-2.9° MD, p < 0.01). ↓ peak hip (2.9-3.2° MD, p < 0.02) and knee flexion angles (2.7-2.9° MD, p	Peak knee flexion pre vs pub ( <i>g</i> -0.492 <i>small</i> ) pre vs post ( <i>g</i> -0.395 <i>small</i> ) pub vs post ( <i>g</i> -0.061 <i>trivial</i> )
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<p>38.1 ± 5.8 kg), 164 mid-pubertal (age, 12.8 ± 0.9 y; height, 158.4 ± 5.8 cm; mass, 49.5 ± 8.2 kg), 131 post-pubertal (age, 14.6 ± 1.2 y; height, 163.4 ± 5.5 cm; mass, 57.5 ± 8.5 kg) (monitored across 2-3 phases)</p>	<p>Knee: total ROM in all planes, knee flexion angle at initial contact, peak knee flexion and abduction angles Hip: total ROM in all planes, hip flexion angle at initial contact, peak hip flexion and adduction angle</p>	<p>&lt; 0.01), indicating ↑ quadriceps dominance. Peak knee abduction angles ↑ (0.9-1.4° MD, p &lt; 0.02), suggesting ↑ ligament dominance. Trunk frontal (2.5-5.7° MD, p ≤ 0.03) and sagittal plane ROM ↓ (2.0° MD, p ≤ 0.01), but trunk transverse-plane ROM ↑ (2.8-3.6° MD, p ≤ 0.02). ↓ peak trunk flexion (3.8-7.8° MD, p ≤ 0.01), hip flexion (2.9-3.3° MD, p ≤ 0.02), and knee flexion angles (2.0-3.0° MD, p ≤ 0.03) at initial contact; more upright cutting posture.</p>	<p>Peak knee abduction Pre vs pub (<i>g</i> 0.116 <i>trivial</i>) pre vs post (<i>g</i> 0.364 <i>small</i>) pub vs post (<i>g</i> 0.219 <i>small</i>) Initial contact knee flexion Pre vs pub (<i>g</i> -0.245 <i>small</i>) pre vs post (<i>g</i> -0.387 <i>small</i>) pub vs post (<i>g</i> -0.127 <i>trivial</i>)</p>
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<b>(Chia et al., 2023)</b>	United States of America	Longitudinal prospective cohort	42	Pre-pubertal, mid-pubertal, post-pubertal	45° unanticipated cutting task	With maturation, hip sagittal-plane RoM ↓ (5.57° MD, p ≤ 0.027). ↓ hip flexion at IC and peak hip flexion from pre to mid (6.25° MD, p ≤ 0.018; 5.95° MD, p ≤ 0.046). ↑ trunk contralateral rotation from pre to post (7.58° MD, p ≤ 5 0.027). No sig diffs in knee variables.	Peak knee flexion pre vs mid (g 0.082 trivial)

				height, 178.3 ± 7.1 cm; mass, 68.4 ± 9.3 kg) (monitored across 2-3 phases)			
<b>(Colyer et al., 2021)</b>	United Kingdom	Cross-sectional  7 stars: good	35  (age, 15.0 ± 1.0 y; height, 166.1 ± 7.1 cm; mass, 58.0 ± 6.6 kg)	91.2% to 100% adult stature  Percentage of predicted adult stature	<u>90° unanticipated cutting task</u>  Peak external knee abduction moment, peak resultant GRF, knee abduction angle, knee internal rotation, hip internal rotation, and hip abduction angle at initial contact	Significant bilateral asymmetries observed with ↑ peak external knee abduction moments, ↑ GRF, and ↓ knee flexion (from 0-18% and 30-39% of contact) during the non-dominant vs dominant cuts (ES =0.36, 0.63 and 0.50, respectively).  Maturation did not affect asymmetries; however, ↓ hip abduction (e.g., 21-	Data unavailable ~

51% of contact for dominant cuts) with maturation.

<b>(Sigward, Pollard, Havens, et al., 2012)</b>	United States of America	Cross-sectional 8 stars: good	80 15 pre-pubertal (age, 10.2 ± 0.8 y; height, 144.9 ± 7.2 cm; mass, 37.3 ± 6.4 kg) 15 pubertal (age, 12.5 ± 0.7 y; height, 156.9 ± 6.8 cm; mass, 47.8 ± 8.9 kg), 14 post-pubertal	76 16 pre-pubertal (age, 11.4 ± 1.0 y; height, 146.9 ± 8.9 cm; mass, 37.9 ± 5.6 kg) 15 pubertal (age, 13.3 ± 1.2 y; height, 160.6 ± 9.7 cm; mass,	Pre-pubertal, pubertal, post-pubertal, young adult Modified PMOS, Tanner stages	<u>45° unanticipated cutting task</u> Peak knee valgus angle, knee adductor moments and GRFs in all planes	No sex × maturation interactions for any variable. On average, F had ↑ knee abduction and adductor moments than M. Pre-pubertal had ↑ knee adductor moments and GRFs than all other groups (p = 0.01).	Data unavailable~
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			(age, 15.7 ± 1.1 y; height, 166.3 ± 6.7 cm; mass, 59.7 ± 6.8 kg), 15 young adult (age, 19.3 ± 1.1 y; height, 166.1 ± 5.7 cm; mass, 64.9 ± 6.9 kg)	52.4 ± 7.8 kg), 14 post-pubertal (age, 15.6 ± 1.1 y; height, 176.4 ± 7.5 cm; mass, 69.7 ± 10.2 kg), 15 young adult (age, 19.8 ± 1.4 y; height, 181.5.1 ± 7.2 cm; mass, 78.0 ± 6.6 kg)			
<b>(Westbrook et al., 2020)</b>	United States of America	Cross-sectional 7 stars: good	138  17 pre-pubertal (age, 10.3 ±	Pre-pubertal, early pubertal, post-pubertal	<u>90° cutting task</u> Knee abduction, knee flexion, normalised knee moments	Post-pubertal had significantly (p < 0.001) ↑ peak abduction angles and moments than pubertal and pre-	Females Peak knee abduction angle pre vs pub (g 0.095 trivial)

0.6 y; height, 137.0 ± 6.8 cm; mass, 34.2 ± 4.5 kg), 32 pubertal (age, 11.9 ± 0.8 y; height, 151.1 ± 5.7 cm; mass, 43.3 ± 6.0 kg), 90 post- pubertal (age, 14.6 ± 1.6 y; height, 162.6 ± 5.6 cm; mass, 56.2 ± 8.8 kg)	Prediction of percentage of adult stature (Khamis- Roche method)	pubertal (3.1° and 2.6°, 12.3 Nm and 10.7 Nm MD). Post-pubertal and pubertal had ↑ peak knee flexion moments vs pre-pubertal (73.4 Nm and 33.1 MD), as did post-pubertal vs pubertal (40.3 Nm MD).	pre vs post ( <i>g</i> 0.482 <i>small</i> ) pub vs post ( <i>g</i> 0.597 <i>medium</i> ) Peak knee abduction moment normalised pre vs pub ( <i>g</i> 0.595 <i>medium</i> ) pre vs post ( <i>g</i> 0.249 <i>small</i> ) pub vs post ( <i>g</i> -0.413 <i>small</i> ) Peak knee flexion angle pre vs pub ( <i>g</i> -0.499 <i>small</i> ) pre vs post ( <i>g</i> -0.330 <i>small</i> ) pub vs post ( <i>g</i> 0.330 <i>small</i> )
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Peak knee flexion  
moment normalised  
pre vs pub (*g* 0.478  
*small*)  
pre vs post (*g* 0.552  
*medium*)  
pub vs post (*g* 0.201  
*small*)

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**Qualitative synthesis of studies (n = 5) reporting on biomechanics in other tasks.**

<b>(Kim &amp; Lim, 2014)</b>	Korea	Cross-sectional	22	Pre-pubertal,	<b>Single legged drop landing</b>	Post-menarche ↓ maximum knee flexion angle (5.56 MD, p = 0.019) and ↑ maximum knee abduction angle (3.26 MD, p = 0.039),	Peak knee flexion angle ( <i>g</i> -3.791 <i>large</i> )
		7 stars: good	11 pre-pubertal (age, 11.6 ± 2.2 y; height, 135.4 ± 9.0 cm; mass, 29.9 ± 5.8 kg), 11 post-pubertal (age, 19.1 ± 3.2 y; height, 153.4 ± 5.0 cm; mass, 47.3 ± 5.6 kg)	post-pubertal  Pre- or post-menarcheal onset	Max knee flexion angle, max knee abduction angle, max knee internal rotation angle, max knee abduction moment, and hamstring-quadriceps activation ratio	maximum knee abduction angle (3.26 MD, p = 0.039), maximum internal tibial rotation angle (5.73 MD, p = 0.043), maximum knee abduction moment (0.18 MD, p = 0.049), and hamstring-quadriceps muscle activity ratio (p = 0.033) compared to pre-menarche.	Peak knee abduction angle ( <i>g</i> 32.438 <i>large</i> )  Peak knee abduction moment ( <i>g</i> 1.791 <i>large</i> )
<b>(Nasseri et al., 2021)</b>	Australia	Cross-sectional	62	Pre-pubertal,	<b>Single legged drop landing</b>	Compared to pre- and early-/mid-pubertal,	ACL force pre vs early/mid ( <i>g</i> 3.994 <i>large</i> )
		8 stars: good	19 pre-pubertal (age, 9.8 ± 1.1 y;	early/ mid-pubertal,	ACL force (computationally modelled using	late-/post-pubertal had significantly ↑ ACL force with MDs of	early/mid vs post ( <i>g</i> 6.063 <i>large</i> )

<p>height, 140.1 ± 0.1 cm;  mass, 30.9 ± 4.5 kg),  19 early/mid-pubertal (age, 11.0 ± 1.3 y;  height, 150.0 ± 5.7 cm;  mass, 37.4 ± 5.6 kg),  24 late/post pubertal (age, 19.9 ± 4.1 y;  height, 160.0 ± 0.1 cm;  mass, 59.8 ± 9.3 kg)</p>	<p>late/post-pubertal   Tanner stages</p>	<p>external biomechanics, lower limb muscle forces, and knee contact forces), plane loading for all planes, stance percentage</p>	<p>471 and 356 N during the first 30% and 48% to 85% of stance, and 343 and 274 N during the first 24% and 59% to 81% of stance, respectively, which overlapped peaks in ACL force. At peak ACL force, contributions from sagittal and transverse plane loading mechanisms to ACL force were ↑ in late-/post-pubertal than pre- and early-/mid-pubertal (ES: 0.44 to 0.77). No differences between pre- and early-/mid-pubertal in ACL force or contributors.</p>	<p>pre vs post (<i>g</i> 11.905 <i>large</i>)</p>
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<b>(Sayer et al., 2019)</b>	Australia	Cross-sectional  8 stars: good	93  31 pre-pubertal (age, 9.4 ± 1.2 y; height, 1.4 ± 0.1 m; mass, 30.0 ± 5.7 kg), 31 early/mid-pubertal (age, 11.2 ± 1.4 y; height, 1.5 ± 0.1 m; mass, 38.4 ± 7.6 kg), 31 late/post-pubertal (age, 19.8 ± 4.0 y; height, 1.7 ± 0.1 m; mass, 60.8 ± 8.8 kg)	Pre-pubertal, early/ mid-pubertal, late/post-pubertal  Modified Tanner stages	<b>Single legged drop lateral jump</b>  Triplanar knee moments and hip moments at the time of peak knee moments	Late/post-pubertal had ↑ peak KFM (0.17 Nm/m and 0.45 Nm/m), KAbM (0.17 Nm/m and 0.45 Nm/m), and KIRM (3.53 Nm/m and 5.07 Nm/m) than the early/ mid and pre-pubertal group (p < 0.05).  *KFM, knee flexion moment; KAM, knee abduction moment; KabM, knee abduction moment.	Peak knee abduction moment  pre vs early/mid ( <i>g</i> 0.731 <i>medium</i> )  pre vs late/post ( <i>g</i> 1.541 <i>large</i> )  early/mid vs late/post ( <i>g</i> 0.926 <i>large</i> )
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<b>(Swartz et al., 2005)</b>	United States of America	Cross-sectional 7 stars: good	29 15 pre-pubertal (age, 9.2 ± 1.0 y; height, 136.6 ± 9.5 cm; mass, 32.9 ± 7.9 kg), 14 post-pubertal (age, 24.2 ± 2.3 y; height, 163.5 ± 6.2 cm; mass, 62.4 ± 9.1 kg)	29 15 pre-pubertal (age, 9.4 ± 1.1 y; height, 136.6 ± 12.2 cm; mass, 34.8 ± 7.9 kg), 14 post-pubertal (age, 23.6 ± 3.2 y; height, 178.3 ± 5.6 cm; mass, 83.3 ± 11.5 kg)	Pre-pubertal, post-pubertal Tanner stages	<b>Standing vertical jump</b> Knee flexion, hip flexion, knee valgus at initial contact and at peak vGRF, peak vGRF, time to peak vGRF, and impulse	Significant main effects for developmental stage. Both M and F had ↓ knee valgus (5.83 and 1.93 MD) and ↑ hip flexion (9.11 and 9.09 MD) at maximum vGRF, ↑ knee flexion at maximum vGRF (11.76 and 6.5 MD), ↓ maximum vertical force (3.67 and 2.93 MD) and impulse (0.4 and 0.3 MD), and a ↑ time to maximum vertical force (0.2 and 0.1 MD) with maturation. No sex differences among the biomechanical variables.	<b>Female</b> Knee flexion at initial contact pre vs post ( <i>g</i> 0.128) Knee flexion at peak vGRF pre vs post ( <i>g</i> 0.810 <i>large</i> ) Knee valgus at initial contact pre vs post ( <i>g</i> -0.528 <i>medium</i> ) Knee valgus at peak vGRF pre vs post ( <i>g</i> -0.445 <i>small</i> ) Peak vGRF Pre vs post ( <i>g</i> -1.571 <i>large</i> )
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**Male**

Knee flexion at initial  
contact

pre vs post (*g* 0.645  
*medium*)

Knee flexion at peak  
vGRF

pre vs post (*g* 0.708  
*medium*)

Knee valgus at initial  
contact

pre vs post (*g* -0.528  
*medium*)

Knee valgus at peak  
vGRF

pre vs post (*g* -1.209  
*large*)

Peak vGRF

pre vs post (*g* -1.581  
*large*)

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<b>(Wild et al., 2016)</b>	Australia	Longitudinal	33	Tanner stages 2, 3, and 4	<b>Horizontal leap task</b>	Throughout maturation, ↓ knee flexion moment (0.59 Nm/kg/m MD, p = 0.028), ↑ hip flexion (0.17 Nm/kg/m MD, p = 0.047), ↑ external knee abduction moments (0.23 Nm/kg/m MD, p = 0.008), and ↓ external hip adduction moments (0.6 Nm/kg/m MD, p = 0.003) during landing.	Knee flexion moment at peak anteroposterior GRF
		prospective cohort	Stage 1 (age, 11.4 ± 0.1 y; height, 149.7 ± 0.8 cm; mass, 40.1 ± 0.8 kg), Stage 2 (age, 11.8 ± 0.1 y; height, 152.7 ± 0.8 cm; mass, 42.2 ± 0.8 kg), Stage 3 (age, 12.1 ± 0.1 y; height, 155.2 ± 0.8 cm; mass, 44.2 ± 0.8 kg), Stage 4 (age, 12.5 ± 0.1 y; height, 157.9 ± 0.8 cm; mass, 46.7 ± 0.8 kg)	Tanner stages and estimated maturity offset calculation	Ankle plantar flexion/ dorsiflexion and inversion/ eversion, knee flexion/ extension and abduction/adduction and external/ internal rotation, and hip flexion/ extension and abduction/adduction and external/ internal rotation angles, ROM, and moments for ankle, knee and hip.	phase 1 vs phase 2 ( <i>g</i> - 1.809 <i>large</i> ) phase 1 vs phase 3 ( <i>g</i> - 2.869 <i>large</i> ) phase 1 vs phase 4 ( <i>g</i> - 3.001 <i>large</i> ) phase 2 vs phase 3 ( <i>g</i> - 1.133 <i>large</i> ) phase 2 vs phase 4 ( <i>g</i> - 1.593 <i>large</i> ) phase 3 vs phase 4 ( <i>g</i> - 0.690 <i>medium</i> )	
		7 stars: good					Knee abduction moment at peak anteroposterior GRF phase 1 vs phase 2 ( <i>g</i> - 3.802 <i>large</i> ) phase 1 vs phase 3 ( <i>g</i> - 8.229 <i>large</i> )

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Assessed	phase 1 vs phase 4 ( <i>g</i>
over all	5.023 <i>large</i> )
phases	phase 2 vs phase 3 ( <i>g</i>
	2.4 <i>large</i> )
	phase 2 vs phase 4 ( <i>g</i>
	4.197 <i>large</i> )
	phase 3 vs phase 4 ( <i>g</i>
	2.399, <i>large</i> )

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*Note:* ACL, anterior cruciate ligament; DVJ, drop vertical jump; CUT, cutting task; F, females; M, males; ROM, range of motion; GRF, ground reaction force; PMOS, pubertal maturation observational scale; MD, mean difference; *g*, Hedge's *g*, Data unavailable ~, data needed to calculate effect size were not provided in the manuscript.

\*In the effect size column, a +ve number indicates an increase with maturation, a -ve indicates a decrease with maturation.

Effect size inferences were determined using the thresholds 0.2, 0.5, and 0.8 for *small*, *medium*, and *large* effects, respectively (Cohen, 2013; Ellis, 2010).

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### 2.5.2 Study quality assessment

The quality score and design for each study are reported in Table 2. The methodological quality of most studies was considered good (n = 16, 89 %), and satisfactory for the remaining (n = 2, 11 %) based on the NOS adapted for cross sectional studies (10-point scale: mean 7.2 ± 0.8 stars; range 5-8 stars). Reductions in study quality were commonly caused by lack of selecting a representative sample, no presentation of sample size calculations, poor description of non-respondents, and incomplete statistical reporting. The individual NOS item scores are detailed for individual studies in Table 3.

**Table 3** Newcastle-Ottawa scale (NOS) quality stars awarded for each study.

Study	Selection (max 5 stars)	Comparability (max 2 stars)	Outcome (max 3 stars)	Total (max 10 stars)
Chia et al. (2021)	3	2	3	8
Chia et al. (2023)	4	2	3	8
Colyer et al. (2021)	2	2	3	7
Ford, Myer, et al. (2010a)	3	2	3	8
Ford, Shapiro, et al. (2010b)	3	2	3	8
Hass et al. (2005)	1	2	2	5
Hewett et al. (2004b)	3	2	2	7
Hewett et al. (2006)	2	2	2	6
Kim et al. (2014)	3	2	2	7
Nasseri et al. (2021)	4	2	2	8
Otsuki et al. (2021)	4	2	2	8
Quatman et al. (2006)	3	2	2	7
Sayer et al. (2019)	3	2	3	8
Sigward et al. (2012a)	3	2	2	7
Sigward et al. (2012b)	4	2	2	8
Swartz et al. (2005)	4	1	2	7
Westbrook et al. (2020)	3	2	2	7
Wild et al. (2016)	3	2	2	7

Note: The number of stars reflect study quality: 9-10 stars = “very good”, 7-8 stars = “good”, 5-6 stars = “satisfactory”, and 0-4 stars = “unsatisfactory” quality. Max, maximum.

**Table 4** Summary of findings regarding risk factors associated with anterior cruciate ligament (ACL) injury (knee abduction angle, knee abduction moment, knee flexion angle, ground reaction force) from studies examining the drop vertical jump task.

Risk factor measured	Certainty assessment							Summary of findings		
	Studies (n)	Phase of investigation (study design)	Methodological weakness (risk of bias - from NOS)	Inconsistency	Indirectness	Imprecision	Publication bias	Participants (n)	Results (direction of relationship with maturation)	Overall certainty of evidence (GRADE)
Knee abduction angle	4 (Ford, Myer, et al., 2010; Hewett et al., 2004; Otsuki et al., 2021; Westbrook et al., 2020)	Phase 1 (1) Phase 2 (3)	✓	Unclear	✓(2) X(2)	X(4)	✓(4)	<b>Unspecified</b> 182 pub 133 post <b>Female</b> 31 pre 45 early 32 pub 196 late/post <b>Male</b> 27 pre 24 early 30 late/post	Knee abduction angle increases with maturation.	☑☑☐☐ low
Knee abduction moment	5 (Ford, Shapiro, et al., 2010; Hass et	Phase 2 (5)	✓	Present	✓(4) X(1)	X(5)	✓(5)	<b>Unspecified</b> 182 pub 133 post <b>Female</b> 53 pre	Knee abduction moment increases	☑☑☐☐ low

	al., 2005; Otsuki et al., 2021; Sigward, Pollard, & Powers, 2012; Westbroo k et al., 2020)								17 early 62 pub 22 late 185 post <b>Male</b> 32 pre 30 pub 43 post	with maturation.	
Knee flexion angle	4 (Ford, Shapiro, et al., 2010; Hass et al., 2005; Otsuki et al., 2021; Westbroo k et al., 2020)	Phase 2 (4)	✓	Absent	✓(2) X(2)	X(4)	✓(4)	<b>Female</b> 33 pre 17 early 190 pub 22 late 262 post <b>Male</b> 37 pub 13 post	Knee flexion angle increases with maturation.	<input checked="" type="checkbox"/> <input checked="" type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/>	moderate

Ground reaction force	3 (Hass et al., 2005; Hewett, Myer, Ford, et al., 2006; Quatman et al., 2006)	Phase 2 (3)	X	Absent	✓(1) X(2)	X(3)	✓(3)	<b>Female</b> 87 not specified 16 pre 16 pub 32 post <b>Male</b> 188 not specified 17 pub 17 post	Landing GRF (normalized to body mass) decrease with maturation in males. Take off GRF decrease with maturation in females.	<input checked="" type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> low
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Note: ACL; Anterior cruciate ligament, GRADE; Grading of Recommendations Assessment, Development and Evaluation, NOS; Newcastle-Ottawa Scale, GRF; Ground Reaction Force.

**Table 5** Summary of findings regarding risk factors associated with anterior cruciate ligament (ACL) injury (knee abduction angle, knee abduction moment, knee flexion angle, ground reaction force) from studies examining a cutting task.

Risk factor measured	Certainty assessment							Summary of findings		
	Studies (n)	Phase of investigation (study design)	Methodologic at weakness (risk of bias - from NOS)	Inconsistency	Indirectness	Imprecision	Publication bias	Participants (n)	Results (direction of relationship with maturation)	Overall certainty of evidence (GRADE)
Knee abduction angle	4 (Chia et al., 2021; Chia et al., 2023; Colyer et al., 2021; Sigward, Pollard, Havens, et al., 2012; Westbrook et al., 2020)	Phase 1 (2) Phase 2 (3)	✓	Present	✓(5)	✓(2) X(3)	✓(4) X(1)	<b>Female</b> 35 not specified 101 pre 212 pub 160 post <b>Male</b> 36 pre 53 pub 59 post	Knee abduction angle increases with maturation.	☑☑☐☐ low
Knee abduction moment	3 (Colyer et al., 2021; Sigward, Pollard, Havens, et	Phase 1 (1) Phase 2 (2)	✓	Absent	✓(3)	✓(1) X(3)	✓(2) X(1)	<b>Female</b> 35 not specified 32 pre 48 pub	Knee abduction moment increases	☑☑☑☐ moderate

	al., 2012; Westbrook et al., 2020)							29 post <b>Male</b> 16 pre 15 pub 29 post	with maturation.	
Knee flexion angle	3 (Chia et al., 2021; Chia et al., 2023; Colyer et al., 2021; Westbrook et al., 2020)	Phase 1 (2) Phase 2 (2)	✓	Present	✓(4)	X(4)	✓(2) X(2)	<b>Female</b> 35 not specified 86 pre 197 pub 131 post <b>Male</b> 20 pre 38 pub 30 post	Knee flexion angle decreases with maturation.	<input checked="" type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> low
Ground reaction force	2 (Colyer et al., 2021; Sigward, Pollard, Havens, et al., 2012)	Phase 1 (1) Phase 2 (1)	✓	Absent	✓(2)	✓(1) X(1)	✓(1) X(1)	<b>Female</b> 35 not specified 15 pre 15 pub 29 post <b>Male</b> 16 pre 15 pub 29 post	GRF (normalised to body mass) decrease with maturation.	<input checked="" type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> low

Note: ACL; Anterior cruciate ligament, GRADE; Grading of Recommendations Assessment, Development and Evaluation, NOS; Newcastle-Ottawa Scale, GRF; Ground Reaction Force.

**Table 6** Summary of findings regarding risk factors associated with anterior cruciate ligament (ACL) injury (knee abduction angle, knee abduction moment, knee flexion angle, ground reaction force) from studies examining other tasks.

Risk factor measured	Certainty assessment							Summary of findings		
	Studies (n)	Phase of investigation (study design)	Methodological weakness (risk of bias - from NOS)	Inconsistency	Indirectness	Imprecision	Publication bias	Participants (n)	Results (direction of relationship with maturation)	Overall certainty of evidence (GRADE)
Knee abduction angle	3 (Kim & Lim, 2014; Swartz et al., 2005; Wild et al., 2016)	Phase 2 (3)	✓	Present	✓(3)	✓(2) X(1)	✓(3)	<b>Female</b> 33 across 5 stages 26 pre 55 post	Knee abduction angle decreases with maturation in males and is unclear in females.	☑☑☑☐ moderate
Knee abduction moment	3 (Kim & Lim, 2014; Sayer et al., 2019; Wild et al., 2016)	Phase 2 (3)	✓	Unclear	✓(2) X(1)	✓(1) X(2)	✓(3)	<b>Female</b> 33 across 5 stages 42 pre 30 early 41 post	Knee abduction moment increases with maturation.	☑☑☐☐ low

Knee flexion angle	3 (Kim & Lim, 2014; Sayer et al., 2019; Swartz et al., 2005; Wild et al., 2016)	Phase 2 (3)	✓	Absent	✓(2) X(1)	✓(1) X(2)	✓(3)	<b>Female</b> 33 across 5 stages 57 pre 30 early 55 post	Knee flexion angle decreases with maturation.	<input checked="" type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>
Ground reaction force	2 (Swartz et al., 2005; Wild et al., 2016)	Phase 2 (2)	✓	Present	✓(2)	✓(2)	✓(1) x(1)	<b>Female</b> 34 pre 19 pub 38 post <b>Male</b> 15 pre 14 post	Ground reaction forces (normalised to body mass) decrease with maturation.	<input checked="" type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>

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Note: ACL; Anterior cruciate ligament, GRADE; Grading of Recommendations Assessment, Development and Evaluation, NOS; Newcastle-Ottawa Scale, GRF; Ground Reaction Force.

### 2.5.3 Semiquantitative analysis (evidence of effectiveness)

When considering phase of studies, sample sizes, risk of bias, precision levels, and consistency in findings, the GRADE ratings indicate low-to-moderate certainty of evidence regarding the link between maturation and potential ACL injury biomechanical risk factors during dynamic tasks, as summarised in Tables 4, 5, and 6, respectively. For drop vertical jump (DVJ) tasks, GRADE ratings indicate moderate certainty of evidence for knee flexion angle and low certainty of evidence for knee abduction angle, knee abduction moment, and GRF. For cutting tasks, certainty of evidence was moderate for knee abduction angle and low for the other three factors. For other dynamic tasks, certainty of evidence was moderate for knee abduction angles but low for knee flexion angles, knee abduction moment, and GRF. It should be considered that the participants involved in both of the studies by Sigward and colleagues (Sigward, Pollard, Havens, et al., 2012; Sigward, Pollard, & Powers, 2012) were the same (confirmed via personal communications), which may introduce bias, although the studies assessed different tasks. Similarly, it is fair to assume that the participants were the same in both studies by Ford and colleagues (Ford, Myer, et al., 2010; Ford, Shapiro, et al., 2010) given the reported sample size and participant demographics (unconfirmed), although the studies report different metrics for the same dynamic task.

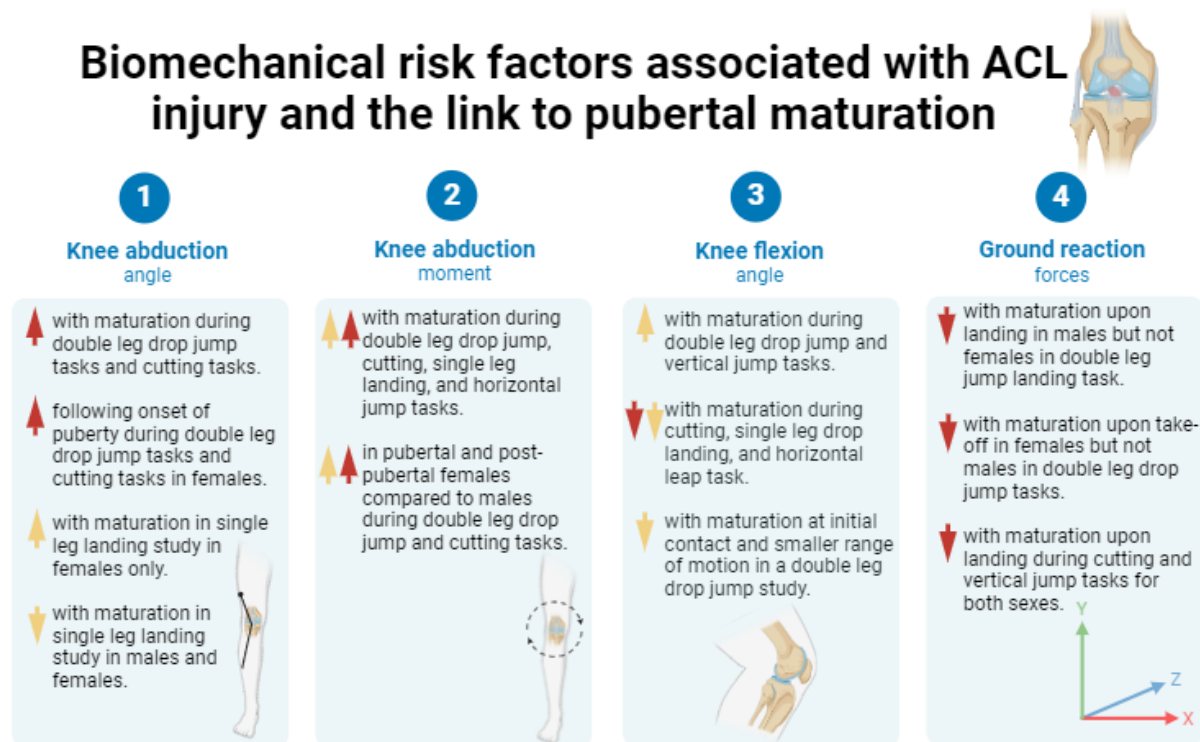
### 2.5.4 Study characteristics

Sample size ranged from 22 to 315 participants. A total of 2092 participants were represented across the 18 studies. Sex distribution was described across all studies except for one (Ford, Myer, et al., 2010) with a total of 400 males (19.1 %), 1377 females (65.8 %), and 315 participants of undefined sex (15.1 %). Nine of the 18 studies (50 %) used a DVJ task, four (22.2 %) used a cutting task (Chia et al., 2021; Chia et al., 2023; Colyer et al., 2021; Sigward, Pollard, Havens, et al., 2012), two (11.1 %) assessed a single-leg drop landing (Kim & Lim, 2014; Nasser et al., 2021), and one study each (5.5 %) examined a drop and cut (Sayer et al., 2019), standing vertical jump (Swartz et al., 2005), and horizontal leap (Wild et al., 2016) task. Most studies (61.1 %, n = 11) were cross-sectional (Colyer et al., 2021; Hass et al., 2005; Hewett et al., 2004; Hewett, Myer, Ford, et al., 2006; Kim & Lim, 2014; Nasser et al., 2021; Sigward, Pollard, & Powers, 2012;

Swartz et al., 2005; Westbrook et al., 2020), followed by longitudinal prospective cohort (33.3 %, n = 6) (Chia et al., 2021; Ford, Myer, et al., 2010; Ford, Shapiro, et al., 2010; Quatman et al., 2006; Sayer et al., 2019; Wild et al., 2016), and interventional (5.6 %, n = 1) (Otsuki et al., 2021).

### 2.5.5 Narrative synthesis

A summary of the proposed links between the commonly reported biomechanical metrics (knee abduction angle, knee abduction moment, knee flexion, and GRFs) and pubertal maturation is presented in Figure 4.



**Figure 4** Summary of the observed links between maturation and changes in biomechanics associated with anterior cruciate ligament (ACL) injury as reported in the literature. *Note:* Red arrows indicate low certainty of evidence, yellow arrows indicate moderate certainty of evidence (as determined by GRADE). Two arrows suggest different quality of evidence ratings for the different specified tasks, presented in order of mention.

#### 2.5.5.1 Knee abduction angle

Amongst the four DVJ studies regarding knee abduction angle, Hewett et al. (Hewett et al., 2004), Ford, Shapiro, et al. (2010), and Westbrook et al. (2020) reported significantly

greater peak knee abduction angles with maturation in females and significantly greater angles in females than males following the onset of puberty, with *large*, *small*, and *medium* effect sizes observed, respectively. Hass et al. (Hass et al., 2005), who had a lower methodological quality study, in contrast observed similar knee abduction ranges of motion between pre-pubertal and post-pubertal females.

Two studies incorporating a cutting task reported *small* but significantly greater maximum knee valgus angles with maturation in females (Chia et al., 2021; Westbrook et al., 2020), no significant differences were observed in males (Chia et al., 2023). Furthermore, a third study by Sigward, Pollard, Havens, et al. (2012) observed significantly greater peak knee valgus angles in females than males regardless of maturation stage; however, smaller angles were observed in the more mature participants regardless of sex.

During a single-leg landing task, Kim and Lim (2014) reported that pubertal females demonstrated an increased peak knee abduction angle compared to pre-pubertal participants with a *large* effect size. Conversely, Swartz et al. (2005) detected significantly lesser knee valgus angle at both initial contact (*medium* effect size) and at peak vGRF (*small* effect size) with maturation regardless of sex in a vertical jump task.

#### 2.5.5.2 Knee abduction moment

When completing a DVJ task, four studies found that pubertal and post-pubertal females generally demonstrated greater knee abduction moments than pre-pubertal females and males (Ford, Shapiro, et al., 2010; Otsuki et al., 2021; Sigward, Pollard, & Powers, 2012; Westbrook et al., 2020), although the effect sizes were *small* and *medium*. Otsuki et al. (2021) reported increases in peak knee abduction moments over a six-month period in early pubertal females. Similarly, Ford, Shapiro, et al. (2010) observed larger knee abduction moments during DVJ tasks in pubertal females with maturation with *medium* effect sizes. Ford, Shapiro, et al. (2010) also found greater knee abduction moments in females than males post-puberty, but no sex differences were observed pre-puberty.

Similar changes in knee abduction moments to those observed in the DVJ tasks were observed in three studies during cutting or horizontal jump tasks (Kim & Lim, 2014; Westbrook et al., 2020; Wild et al., 2016) with *small* effect sizes. Females post-puberty demonstrated greater peak abduction moments than females during pre- and mid-puberty (Westbrook et al., 2020). Pubertal females demonstrated greater peak knee abduction moments than pre-pubertal females during single-leg landings (Nasseri et al., 2021). Knee abduction moment in an all-female cohort was also significantly greater in late/ post-pubertal and early/ mid-pubertal groups compared to the pre-pubertal group during a drop-land and cut task (Sayer et al., 2019).

#### 2.5.5.3 Knee flexion angle

During a DVJ task, peak knee flexion angle was generally greater with maturation regardless of sex, and females landed with larger knee flexion angles than males (Ford, Myer, et al., 2010), although the effect sizes were *trivial*. Swartz et al. (2005) also detected significantly greater knee flexion angles at peak vGRF with maturation regardless of sex during a vertical jump task. Despite having similar magnitudes and timing of knee flexion, post-pubertal females landed with lesser knee flexion at initial contact than pre-pubertal females with a *small* effect size, but the post-pubertal females demonstrated a larger knee flexion range of motion in a DVJ with a *large* effect size (Hass et al., 2005). Westbrook et al. (2020) found no differences in knee flexion between maturational groups in both DVJ and cutting tasks (*small* effect sizes), similarly Chia (Chia et al., 2023) found no significant differences in males. Data from three studies indicated reduced knee flexion range of motion and peak angles during cutting (*small* effect size) (Sigward, Pollard, & Powers, 2012), double-leg drop landing (Otsuki et al., 2021), and horizontal leap (Wild et al., 2016) tasks in females with maturation.

#### 2.5.5.4 Ground reaction force

Using a DVJ task, three studies examined GRF (Hass et al., 2005; Hewett, Myer, Ford, et al., 2006; Quatman et al., 2006). Quatman et al. (2006) and Hewett, Myer, Ford, et al.

(2006) (satisfactory quality study) found that maturation was linked with significantly smaller landing GRFs in males, but not females, and smaller take-off forces in females, but not males when normalised to body mass (*small to medium* effect sizes). Partially aligning with these findings, females showed higher loading rates than males across all maturational stages, but both sexes decreased DVJ landing loading rates with maturation (Quatman et al., 2006). Hewett, Myer, Ford, et al. (2006) also found fluctuations in DVJ landing GRF across maturation, with females showing slight decreases in GRF pre-puberty, slight increases during puberty, and larger decreases again post-puberty. Similarly, a satisfactory quality study by Hass et al. (2005) indicated smaller GRFs, joint forces, and peak forces in post-pubertal than pre-pubertal females during a DVJ task with a *large* effect size. Significantly larger ACL forces were observed in late-pubertal compared to pre- and early-/mid-pubertal females in a single-leg drop jump task, although the estimation method using computational modelling limits the comparability of this study to the other studies included in this review (Nasseri et al., 2021). Colyer et al. (2021) observed no differences in GRFs with maturation during a non-dominant versus dominant limb cutting task. Regardless of sex, lesser peak vGRF was observed with maturation during cutting (Sigward, Pollard, Havens, et al., 2012) and DVJ (Quatman et al., 2006) tasks.

## **2.6 Discussion**

Understanding the association between maturational development and biomechanical risk factors associated with ACL injury is important for addressing the increasing ACL injury incidence rates in adolescent athletes (Maniar et al., 2022). The purpose of this systematic review was to establish potential associations between maturation and biomechanical factors associated with ACL injury in males and females. Generally, the studies included were of moderate quality. The only biomechanical factors commonly reported in the included studies (reported across at least three studies) were knee abduction angle, knee abduction moment, knee flexion, and vGRF, which are factors identified as potentially linked to ACL injury incidence (Hewett, Ford, et al., 2016; Myer et al., 2011; Pappas et al., 2016). These factors had either low or moderate overall quality of evidence ratings as assessed by the modified GRADE regarding their association with

maturation. For these metrics, both males and females tended to exhibit biomechanics suggestive of an increased risk of ACL injury during various landing and cutting tasks with maturation. Moreover, greater knee abduction angles, knee abduction moments, and vGRF, and lesser knee flexion angles were observed in females compared to males in the later maturation stages. These findings support that females in the late and post-pubertal maturational development stages tend to portray biomechanics associated with increased risk of ACL injury, which aligns with the rise in ACL injury occurrence observed in this demographic (Maniar et al., 2022).

The increases in knee abduction angle and moment with maturation in females may contribute towards their increased ACL injury susceptibility in the late and post-pubertal maturational stages (Ford, Myer, et al., 2010; Ford, Shapiro, et al., 2010; Hewett et al., 2004; Maniar et al., 2022; Otsuki et al., 2021; Renstrom et al., 2008; Sayer et al., 2019; Shea et al., 2004; Sigward, Pollard, & Powers, 2012; Westbrook et al., 2020; Zbrojkiewicz et al., 2018). Although it should be noted that the effect sizes of these differences varied from *small* to *large* across studies. Larger knee abduction angles and moments during landing, particularly when paired with higher vGRF, have been suggested as contributing mechanistic factors for non-contact ACL injury (Della Villa et al., 2020; Hewett et al., 2009; Sigurðsson et al., 2021) due to the increased anterior tibial translation and consequent increased ACL load (Fukuda et al., 2003). The reported association between knee abduction moment during landing and tibia and femur length during the growth spurt (Hewett et al., 2015) highlights the potential influence of rapid limb growth on increasing knee abduction moments (Wild et al., 2013), substantiating this review's findings of increased moments with maturation. Knee abduction moment is commonly used as a predictor of ACL injury risk during jump landing injury screening tasks with reports of 73% sensitivity and 78% specificity for ACL injury forecasting in females (Hewett, Myer, & Ford, 2005; Hewett, Myer, Ford, et al., 2005); although, it has recently been argued that knee abduction moment in isolation may not be a standalone ACL injury risk factor as other biomechanical metrics may contribute to injury risk (Cronström et al., 2020).

There is conflicting evidence for changes in knee flexion biomechanics with maturation during dynamic tasks. As females matured, knee flexion range of motion and knee flexion

angles decreased (Della Villa et al., 2020; Hewett et al., 2009; Sigurðsson et al., 2021), although, the effect sizes ranged from *trivial* to *large*. In contrast, two studies showed that knee flexion angle upon initial contact and at peak GRF increased (Ford, Myer, et al., 2010; Swartz et al., 2005). The varied outcomes and effect sizes identified between studies may be partially due to the different movement requirements of the tasks assessed. Decreases in knee flexion angle with maturation were generally observed in studies where tasks incorporated a horizontal component whereas those which reported knee flexion angle increases generally assessed tasks which were more vertical in nature. Landing with a more extended knee or ‘stiff knee strategy’ suggests a greater tendency for using the quadriceps to stabilise the knee joint (Chia et al., 2021; Hewett, Ford, et al., 2010; Pappas et al., 2016). Knee flexion angles less than 22° upon landing may increase the potential for quadricep dominance and place excess demands on the ACL, increasing the potential for injury (Colby et al., 2000; Larwa et al., 2021; Leppänen, Pasanen, Kujala, et al., 2017; McNair et al., 1990). Adopting a more flexed knee position during landing or cutting can improve force absorption and consequently protect internal knee structures (Boden et al., 2009; Hass et al., 2005).

Furthermore, stiff landings cause tibiofemoral compression, which loads the ACL (Meyer & Haut, 2008). During a DVJ task, stiff landings have been associated with increased risk of ACL injury in young females (Hewett, Myer, Ford, et al., 2005; Leppänen, Pasanen, Kujala, et al., 2017). Specifically, athletes who went on to sustain ACL injuries displayed lower peak knee flexion angle and higher peak GRF (Hewett, Myer, Ford, et al., 2005; Leppänen, Pasanen, Kujala, et al., 2017). As females mature, GRF during dynamic tasks generally remains the same (Colyer et al., 2021; Hewett, Myer, Ford, et al., 2006; Quatman et al., 2006), or may slightly decrease (Hass et al., 2005; Sigward, Pollard, Havens, et al., 2012; Swartz et al., 2005). GRF tends to decrease with maturation in males (Colyer et al., 2021; Hewett, Myer, Ford, et al., 2006; Quatman et al., 2006), suggesting greater improvements than females in force attenuation with maturation. During a DVJ task, the spring-like behaviour observed via the force-time data profile (referred to as stretch-shortening cycle ability) generally improved with maturation, but remained relatively poor in post-pubertal females (Pedley et al., 2021). Stretch-shortening cycle ability is also impacted by an individual’s neuromuscular development rate, which is not

consistent across maturation (Hewett, Myer, Ford, et al., 2005; Quatman-Yates et al., 2012). Inconsistent development in neuromuscular control may explain individual differences or lack of improvement in force attenuation ability, which is often observed in pubertal females.

The differences in tasks, including the use of double or single limb landing, likely contributed to the conflicting results regarding the link between maturation and biomechanics (Taylor et al., 2017). Over half of the included studies used the DVJ task for identifying potential biomechanical risk factors. Although commonly used as a screening tool for ACL injury risk, biomechanics during a DVJ correlate poorly with cutting biomechanics (Hanzlíková et al., 2021), which limits comparability and pertinence of results (Kristianslund et al., 2014). Regardless of the link between the task's biomechanical variables and ACL injury risk, observed changes in dynamic tasks across maturation can be viewed more holistically due to previous identification of the higher risk of ACL injuries in post-pubertal females (Prodromos et al., 2007; Waldén et al., 2011). Tasks such as the DVJ involve deceleration and force attenuation, primarily in the sagittal plane. Single-leg tasks increase the load and task difficulty. Cutting tasks impose a more frontal plane demand and are more sport specific. Implementing both a single-leg landing and incorporating movements that reflect cutting or rotating manoeuvres for assessment of high-risk biomechanics should be considered to improve specificity for ACL injury risk screening (Koga et al., 2010; Westbrook et al., 2020).

Definitions of maturation stages and phases examined also varied between studies, impacting the ability for cross-study inferences and strength of evidence on specific variables. Comprehensive and consistent reporting standards for maturation stage identification and grouping would enhance cross-study inferences (Koopman-Verhoeff et al., 2020). Tanner stages, as identified using the self-administered pubertal maturation observational scale, were used most often across the included studies. Tanner stages via physical examination from a medical professional are deemed 'gold standard' for maturational phase identification (Rasmussen et al., 2015); however, self-reported Tanner stages are valid for determining maturational status and less intrusive than other validated methods (Leone & Comtois, 2007; Schmitz et al., 2004). Nonetheless, further

investigation into the reliability and validity of the pubertal maturation observational scale in different demographics is warranted.

Reporting or controlling for menstrual cycle phase was rarely reported. Given the domination of female participants (65.8 %), future research should attempt to control for or report menstrual cycle phase and contraceptive usage status to better understand potential hormonal influence on biomechanics (Balachandar et al., 2017; Herzberg et al., 2017). Although more common in females (Joseph et al., 2013), non-contact ACL injury is relatively common in adolescent males (Maniar et al., 2022). The risk of ACL injury throughout maturation in males is relatively unknown and only one of the included studies examined the biomechanics of males alone (Chia et al., 2023). The small amount of data available suggests significantly different biomechanical movement patterns in males compared to females. Hence, further research into ACL injury risk factors specific to males should be considered.

This review specifically examined biomechanical risk factors associated with ACL injury; however, it should be noted that ACL injuries are multifactorial in nature and factors such as the demands of the sport or an athlete's position (Bram et al., 2021), individual anatomy and morphology (Bayer et al., 2020), cognitive ability (Bertozi et al., 2023), and the gendered differences regarding coaching, training, and physical activity participation (Parsons et al., 2021) will contribute to overall risk of injury.

## **2.7 Limitations**

This systematic review is not without limitations. Firstly, few studies assessed the same metric, used the same task, or considered the same maturation stages, thereby restricting the ability for a meta-analysis to be performed. Studies that did examine the same variables often reported large standard deviations, presented limited or only statistically significant findings, or had small sample sizes; all factors likely to distort the results of a meta-analysis if one had been undertaken. Most studies were of good quality and two were of satisfactory quality in accordance with the NOS, but the strength of the evidence was low-to-moderate based on GRADE ratings. The small quantity of studies assessed for each domain and the variations in effect sizes should be considered when

interpreting these results. We chose to include studies of varied study designs (cross-sectional, longitudinal, and interventional) to enhance the breadth of the review and data available for review, despite longitudinal study designs potentially yielding more robust data to establish the potential link between maturation and biomechanical factors associated with ACL injury. Additionally, many of the studies included researchers from the same group based in the USA, which may influence the generalisability of the results of the current review as well as introduce bias through homogeneity of study findings. This overt representation of these researchers and country may mean that many of the participants were from the same or a similar group (as was confirmed or assumed in studies of the same author and year (Ford, Myer, et al., 2010; Ford, Shapiro, et al., 2010; Sigward, Pollard, Havens, et al., 2012; Sigward, Pollard, & Powers, 2012)), consequently limiting the cultural diversity and global applicability of findings.

## **2.8 Conclusion**

Late and post-pubertal females demonstrate lower-extremity biomechanics associated with increased ACL injury risk. Although the evidence was of low-to-moderate quality and varied between studies, this review demonstrates modified landing and cutting biomechanics occur in response to maturational development, particularly in females. As females mature, there is a tendency for increased knee abduction angles and moments, decreased knee flexion angles and range of motion, and increased GRF during dynamic tasks; variables linked with increased ACL injury risk. Potential changes throughout maturation in males and females in other biomechanical factors require further investigation during multi-planar movement tasks more specific to sport and injury risk, as the DVJ is overtly represented. Future research should explore movement mechanics across maturation, specific to sex, using sport-specific assessment tools and standardised maturation stage identification methods. Despite some contention in the evidence, differences in biomechanics linked with ACL injury risk are evident when comparing sexes and maturation stages. Hence, considering sex and maturation is needed when selecting tasks in injury risk identification processes and developing strategies for ACL injury prevention.

### **Key points**

- ACL injuries are increasingly common in late- to post-pubertal individuals, particularly females.
- As females mature, knee abduction angles and moments typically increase whereas knee flexion angles generally decrease during dynamic tasks.
- Maturation can influence biomechanics associated with ACL injury during landing and cutting tasks, indicating that late- to post-pubertal females may be at increased risk of ACL injury.
- Few studies examined the same variables and those that did reported large standard deviations, presented limited or only statistically significant findings, or had small sample sizes. The small quantity of studies assessed for each domain, the generally low-to-moderate levels of evidence, and the variations in effect sizes should be considered when interpreting the results.

## **3.0 Chapter 3 – Pilot study**

### **3.1 Prelude**

The previous chapter summarised the differences in biomechanics associated with ACL injury between maturation stages, identifying inconsistent findings between studies underpinned by a lack of injury and sport specificity of the tasks used. A double-leg landing task was commonly used in the reviewed studies, but is not injury specific due to most non-contact ACL injuries occurring as a result of a single-leg landing or change of direction manoeuvre (Hewett, Ford, et al., 2010). Therefore, implementing tasks that reflect movements that frequently occur in sporting situations and have been linked to ACL injury occurrence may be important in identifying differences between maturation groups. The aim of this study was to compare methods that have been used previously for a single-leg drop-land and cut (CUT) task in young populations, a maximal condition and a normalised condition (targeting 150% leg length). Previous research has used both a maximal effort lateral cut condition (Hass et al., 2005) and condition targeting a lateral cut to 150% leg length (Nasseri et al., 2021). No studies have directly compared the outcomes from these two tasks, leading to uncertainty regarding which one is optimal for use in a heterogeneous group of maturing individuals. Thus, the purpose of this study was to inform the use of either the maximal or normalised condition for the single-leg drop-land and cut task for the main experimental study.

## **Maximise or normalise? Examining single-leg drop-land-cut distances in young athletes. A pilot study.**

### **3.2 Abstract**

This study investigated differences in cut distance performance for a single-leg drop-land-cut (CUT) task based on using either a maximal or normalised (150% leg length) method and the influence of condition order and leg dominance. Twenty-six young court and field sport athletes (61.5% female) completed the CUT task on the dominant and non-dominant leg under maximal and normalised conditions in a randomised order. Multivariate repeated measures ANOVA tests with post-hoc pairwise comparisons were used to determine the effect of condition (maximal, normalised), leg dominance (dominant, non-dominant), and interaction effect on leaping distance. Potential order effects were explored as a Between Subjects Factor within the ANOVA. The findings showed significantly larger leap distances under the maximal condition ( $p < 0.001$ ,  $\eta_p^2 \geq 0.417$ ) with the maximal mean being  $154.5 \pm 24.7$  cm ( $175.1 \pm 18.6\%$  leg length) and the normalised mean being  $140.7 \pm 19.7$  cm ( $159.0 \pm 5.8\%$  of leg length). Furthermore, greater distances were achieved during the maximal task when performed following the normalised task ( $p < 0.001$ , 24.5% further). Practically, the normalised task may be better suited for heterogeneous samples, yet the maximal task may be more suitable for homogeneous samples or pre-post study designs.

### 3.3 Introduction

Anterior cruciate ligament (ACL) injuries are becoming increasingly common in youth athletes (Hosseinzadeh & Kiapour, 2021; Maniar et al., 2022). The annual number of ACL injuries reported in young people has risen exponentially. In particular, females aged 5-14 years have demonstrated an 10.4% annual growth rate in ACL injury incidence from 1998 to 2018 in Australia (Maniar et al., 2022). In New Zealand, claims from male and female individuals aged 15-29 years contributed to over 50% of the \$100 million cost of ACL injuries to taxpayers in 2021 alone (ACC analytics and reporting, 2022). Representing 45% of all internal knee injuries (Majewski et al., 2006), ACL injuries are associated with prolonged recovery periods (e.g., return to play at least 9 months post-surgery (Kaplan & Witvrouw, 2019)), a substantial financial cost of care (Janssen et al., 2012), impaired functional sporting performance (Paterno et al., 2012), and an increased risk of early-onset posttraumatic osteoarthritis (Lohmander et al., 2004; Nebelung & Wuschech, 2005).

The demands of court and field sports require frequent accelerations, decelerations, changes of direction, rotations, and single-leg landings, all of which are movements associated with ACL injury incidence (Boden et al., 2009; Koga et al., 2010). Additionally, side-cutting manoeuvres are responsible for most non-contact ACL injuries in sports such as football and handball (Faude et al., 2005; Olsen et al., 2004), likely due to the multi-planar nature of the movement that exposes the knee joint to high loads (Kristianslund et al., 2014). In response, screening for biomechanical injury risk factors is becoming common practice in team sports, particularly in high injury risk populations such as young female court and field sport athletes (Krosshaug et al., 2016). However, for widespread adoption, the task needs to be suitable for implementation in clinical settings and on the field. A task that involves a single-leg landing followed by an immediate and explosive side-cut may suit these requirements and may better resemble manoeuvres associated with ACL injury than what is typically used (Butcher et al., 2024), such as double-leg drop vertical jumps (Petushek et al., 2021), single-leg squats (Petushek et al., 2021), and tuck jumps (Fox et al., 2016). Double-leg drop vertical jump tasks have been frequently used to assess ACL injury risk factors in team sport athletes (Hanzlíková & Hébert-Losier, 2020; Petushek et al., 2021) despite generally being

determined as unsuitable for predicting ACL injury risk (Kristianslund & Krosshaug, 2013; Krosshaug et al., 2016). Although run and cut manoeuvres might be better in the context of screening for potential risk of ACL injury and commonly assessed in laboratory settings (Kristianslund & Krosshaug, 2013), they are often not practical in clinical environments and can be difficult to standardise in terms of approach speed and angle of cut.

The design of the single-leg drop-land-cut (CUT) task should consider variations in the perception of maximal effort (Lamb et al., 2017) with respect to subjective and anthropometrical factors. Previous research has observed differences in performance and biomechanics between individuals of different maturational groups using both a maximal effort method (Hass et al., 2005) and a normalised cutting distance to 150% of leg length (Nasseri et al., 2021). Although rationales for each of these methods are justifiable, their suitability may depend on the circumstance and purpose of implementation. For example, the maximal condition may be appropriate in a more homogenous sample of athletes of similar body sizes, however, a normalised condition may be better to compare a more heterogeneous sample as the task is relative to body size. It is currently difficult to select one method over the other as there is a lack of studies directly comparing the two methods. Such information would allow practitioners to make an informed decision on test parameters for this task and enable a more appropriate comparison of performance between groups or individuals. This study focused on exploring the differences in performance of two conditions of the same task that have previously been used with participants in different pubertal maturation stages to inform development and implementation of injury risk screening tasks in this population. Additionally, if performance from both tasks are assessed, the order of condition of tasks may impact performance as it has been suggested that, in younger populations, some participants can believe they are performing maximally, but once given a target, may achieve further distances (Lamb et al., 2017). The raw values in cm and these values expressed as a percentage of leg length are included to provide perspective of the absolute and relative values. Furthermore, leg dominance can influence biomechanical risk factors (Wang & Fu, 2019) and performance (McGrath et al., 2016) during sport-specific tasks that warrant consideration in establishing test

parameters, interpreting outcomes, and comparing between groups or individuals. The potential effect of limb dominance on functional performance could impact clinical outcomes for injury risk or recovery screening, particularly considering the influence of perceived task difficulty (Virgile & Bishop, 2021).

The current study sought to a) determine if differences in leap distance (i.e., performance outcome) exist for the CUT task based on using either a maximal or normalised (150% leg length) method in young court and field sport athletes and b) determine whether the order of conditions or c) leg dominance would influence the distance achieved. It was hypothesised that participants would leap further when a) using the maximal method due to greater effort, b) on the maximal task when presented second, and c) using the dominant leg.

### **3.4 Methods**

Given the exploratory nature of the pilot study and the overall lack of data on the examined tasks in the target population, no formal sample size was conducted a priori. To account for drop-out or data-loss, a sample size between 20-30 participants was targeted based on previous pilot studies stating 12 participants to be appropriate (Julious, 2005; Kunselman, 2024). Ultimately, 26 healthy young court or field sport male and female athletes aged between 7 and 20 years volunteered to participate (Table 7), providing 80% power to detect an effect size  $f$  of 0.24 at a 5% significance level based on the ANOVA: repeated measures, within-between interaction setting of G\*Power 3.1.9.7 (Faul et al., 2007). The calculation considered the collection of four measurements (dominant and non-dominant for maximal and normalised conditions) and two groups to account for a potential order effect on leap distances. All participants were right leg dominant determined by the leg used to kick a ball (van Melick et al., 2017). The participants had no history of serious back or leg injuries within the 12 months prior to testing. All participants and their parents/legal guardians (if under 16 years) provided informed consent prior to participating in this study, which was approved by the University of Waikato Human Research Ethics Committee (HREC (Health) 2022#53) and adhered to the Code of Ethics of the World Medical Association (Declaration of Helsinki Ethical Principles for Medical Research Involving Human Subjects) and the Health

Research Council’s guidelines relating to research involving children and UNICEF’s principles guiding ethical research involving children (Graham et al., 2013).

**Table 7** Baseline characteristics of the participants, mean  $\pm$  standard deviation.

<b>Characteristic</b>	<b>Males (<i>n</i> = 10)</b>	<b>Females (<i>n</i> = 16)</b>	<b>Total (<i>n</i> = 26)</b>
<b>Age (y)</b>	13.9 $\pm$ 3.6	13.0 $\pm$ 4.4	13.5 $\pm$ 4.1
<b>Height (cm)</b>	154.5 $\pm$ 33.6	145.0 $\pm$ 30.0	155.4 $\pm$ 19.1
<b>Body mass (kg)</b>	49.4 $\pm$ 17.1	47.1 $\pm$ 16.3	48.5 $\pm$ 16.2
<b>BMI (kg/m<sup>2</sup>)</b>	18.9 $\pm$ 2.8	20.1 $\pm$ 5.2	19.6 $\pm$ 4.0
<b>Leg length (cm)</b>	88.4 $\pm$ 19.4	85.7 $\pm$ 18.4	88.6 $\pm$ 12.8

Note: BMI, body mass index.

### 3.4.1 Equipment

A high-speed Sony RX10 II video camera (Sony Corporation, Tokyo, Japan) with a focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm) captured the CUT trials at 120 frames per second. The camera was placed 3.5 m in front of the landing area on a tripod with a 1.3 m lens-to-ground distance.

### 3.4.2 Procedures

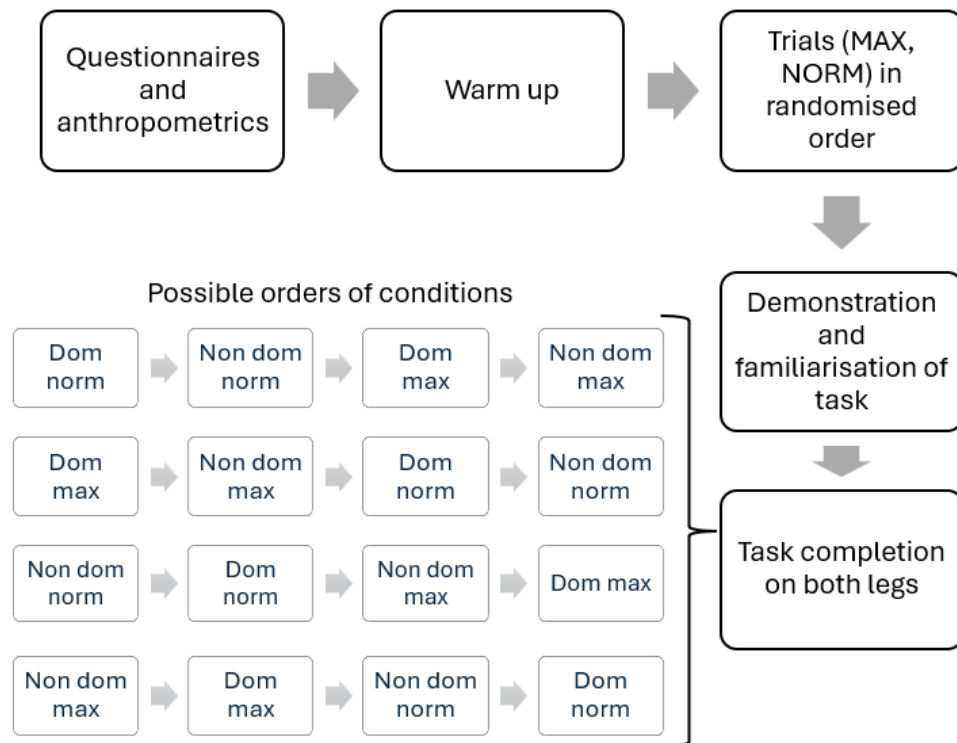
The participants attended a single testing session where they first had their leg length measured until two identical measurements were recorded using a tape measure to record the distance from the anterior superior iliac spine (ASIS) to the medial malleoli on the right (dominant) leg in a supine position (Neelly et al., 2013). Participants then completed a standardised 5 minute warm up involving jogging at a self-selected pace on a turf surface for two minutes, dynamic stretching (8 reps of each per leg; leg swings, walkouts, lunges, and lateral reaches), and jump-landing drills (15 reps per leg of submaximal vertical hopping, 5 reps of double-leg landing, and 5 reps per leg of single-leg landing).

For the CUT task, participants were required to stand on one foot, drop down from a 30 cm box, land on the same foot to a marked distance placed 30 cm in front of the box, and to immediately leap 90° laterally to land on the opposite foot (Nasseri, 2021) along a marked line on the floor (Figure 5). For instance, participants dropping down and landing on their right foot would leap towards the left to land on their left foot. This task was novel to all the participants. Participants completed the task in the two experimental conditions: 1) normalised distance to 150% of leg length, and 2) maximal distance. For the normalised CUT condition, the leg length normalised distance was indicated on the floor using a line of tape. For the maximal distance CUT condition, participants were asked to leap as far as possible, aiming to maximise distance, with no leap distance marker indicated on the floor (i.e. the 150% marker was not present). In both conditions, participants were required to maintain balance upon landing and were encouraged to keep their body facing forwards. The participants were allowed 2-3 practice trials of each condition directly before the test of that same condition for familiarisation, following a standardised explanation and demonstration from the primary researcher (AB).

Condition order was randomised, as was the use of the dominant or non-dominant leg within the condition. For each leg and condition, three successful efforts were performed. The individual efforts were separated by 20 seconds of rest for both legs and between legs, whereas individuals rested for 2 minutes between tasks. Participants wore their own footwear that they would usually wear during sporting participation (Hébert-Losier et al., 2023). A pictorial representation of the CUT phases is presented in Figure 5, and a flow chart of the data collection procedure is presented in Figure 6 along with the possible orders of conditions.



**Figure 5** Image of single-leg drop-land-cut task, cutting to reach 150% of leg length as indicated by a marker on the floor. For the maximal condition, task sequence was similar, but participants leapt as far as possible with only the initial landing marker present.



**Figure 6** Flow chart of data collection procedure and possible orders of conditions.

### 3.4.3 Data processing

Leap distances were extracted from frontal videos using Silicon Coach (Silicon Coach Pro, version 8, Dunedin, NZ) and displacement calibration was performed to a marked 1 m distance along the line where the participants leapt. SiliconCoach Pro has been commonly used to provide accurate data for coaching (Ajithkumar & Kumar, 2025), and has been assessed for displacement agreement against VICON in pelvis measures ( $r^2 = 0.92$ ) (McDonald et al., 2011) and against 3D measures in golf kinematic parameters (ICC = 0.929) (Hunter et al., 2022). A marker was placed in the middle of the toe box (proximal

point of the 2<sup>nd</sup> phalange) of participants' shoes and leap distance was calculated from the marker on the initial landing foot upon ground contact to the marker on the opposite foot upon the second ground contact. Ground contact was measured from the first frame where any part of the foot articulated with the ground. For each participant, the mean leap distance of three trials per leg for each condition were used in further analysis. The normalised to leg length units were calculated using the equation (distance leapt (cm)/ leg length (cm)) x 100.

#### 3.4.4 Statistical analysis

Using IBM SPSS Statistics (version 29.0.0.0 (241)), descriptive statistics were calculated and reported as means, standard deviations, and ranges. Multivariate repeated measures ANOVA tests with post-hoc pairwise comparisons were used to determine the within-subject effect of condition (maximal, normalised to leg length), leg dominance (dominant, non-dominant), and interaction effect on leaping distance outcomes, both in raw (cm) and normalised to leg length (%) units. Mean differences (MD) are reported alongside their *p* values and 95% confidence intervals (CI's). Potential order effects between completing the maximal or normalised condition or the dominant or non-dominant leg first were explored as between-subject factors within the ANOVA. Assumption checks for normality of distribution, sphericity of data, and outliers were completed in SPSS using the Shapiro-Wilk test, Mauchly's test of sphericity, and visual inspection of studentised residuals for values  $\pm 3$  standard deviations, respectively. Partial eta squared ( $\eta_p^2$ ) effect sizes were used to express the magnitude of differences between conditions using the following interpretations: 0.01 as a small effect, 0.06 as a medium effect, and 0.14 as a large effect (Cohen, 2013). Variances were compared using the modified Levene's test by calculating the absolute deviations of each value from the group mean ( $d_{i1}=|x_{i1}-\bar{x}_1|$ ,  $d_{i2}=|x_{i2}-\bar{x}_2|$ ) and the deviations across conditions were compared using paired *t*-tests. Statistical significance was set to  $p < 0.05$ . Individual measures were plotted on a scatter plot for the two conditions to visualize individual performance for the dominant and non-dominant legs separately (Figures 7 and 8, respectively).

### 3.5 Results

Repeated measures ANOVA assumptions were met for distance leapt expressed in raw units and normalised to leg length, and no outliers were detected. The results for the repeated measures ANOVA are reported in Table 8. For both measures, there were no significant interaction effects between side and condition ( $p = 0.429$ ,  $p = 0.547$ , raw and normalised respectively) or main effects for leg dominance ( $p = 0.247$ ,  $p = 0.282$ , raw and normalised respectively). The main effect of condition was statistically significant for distance leapt expressed in both raw and normalised units ( $p < 0.001$ , for both) with large effect size differences ( $\eta_p^2 = 0.417$ ,  $\eta_p^2 = 0.432$ , respectively). The distance leapt was 13.9 [7.1, 20.6] cm and 16.1 [8.5, 23.7] % of leg length greater in the maximal than normalised to leg length CUT condition, with all participants leaping further in the maximal than normalised conditions. Participants leapt an average of  $154.5 \pm 24.7$  cm ( $175.1 \pm 18.6\%$  of leg length) during the maximal task and  $140.7 \pm 19.7$  cm ( $159.0 \pm 5.8\%$  of leg length) during the normalised task. All but two participants leapt greater than or equal to the 150% of leg length distance during the maximal trials.

There was no interaction effect between (order and dominance) ( $p = 0.644$ ) and no main effect of order ( $p = 0.197$ ). There was an interaction effect between order and condition for both the raw ( $F_{(1,25)} = 5.767$ ,  $p = 0.024$ ,  $\eta_p^2 = 0.194$ ) and normalised units ( $F_{(1,25)} = 6.195$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.205$ ). Results from the order of conditions are presented in Table 9. For the raw values, pairwise comparisons revealed no statistically significant differences when considering order within conditions ( $p = 0.062$ ); however, when considering condition within order, the maximal trial was significantly further than the normalised trial when the normalised task was completed first (MD = 21.1 cm,  $p < 0.001$ , 95% CI [12.3, 29.8]), but the maximal trial was not significantly further than the normalised trial if the maximal trial was completed first (MD = 6.7 cm,  $p = 0.130$ , 95% CI [-2.1, 15.4]). For the normalised values, pairwise comparisons revealed statistically significant differences when considering order within condition suggesting that within the maximal condition, if normalised was completed first then the maximal trial was further than if the maximal trial was completed first (MD = 14.0%,  $p = 0.042$ , 95% CI [0.5, 27.5]). Furthermore, when considering condition within order, the maximal trial was significantly further than the

normalised trial when the normalised task was completed first (MD = 24.5%,  $p < 0.001$ , 95% CI [14.7, 34.3]). However, the maximal trial was not significantly further than the normalised trial if the maximal trial was first (MD = 7.7%,  $p = 0.117$ , 95% CI [-2.1, 17.5]).

The modified Levene's test revealed a significant difference in variances between the absolute deviations of the maximal and normalised conditions for the raw data (maximal mean residual = 20.3 cm, normalised mean residual = 16.4 cm, MD = 4.0 cm,  $p = 0.048$ , 95% CI [0.6, 7.3]) and for the normalised to leg length data (maximal mean residual = 14.1%, normalised mean residual = 4.6%, MD = 9.5%,  $p < 0.001$ , 95% CI [6.4, 12.5]). No significant differences in variance were observed between order of condition for raw ( $p = 0.755$ ) or normalised data ( $p = 0.694$ ).

Regarding the individual measures on the scatter plot, one participant for the dominant leg and non-dominant leg and one participant for the non-dominant leg did not achieve a cut distance of 150% leg length during the maximal trial but did during the normalised trial. Also, one participant for the dominant leg and the non-dominant leg did not achieve a cut distance of 150% leg length during the normalised trial but did during the maximal trial. These observations suggest that for both legs, all participants were able to achieve the 150% leg length target during either or both conditions.

**Table 8** Raw and percentage of leg length leap distances for maximal and normalised to 150% of leg length conditions for the single-leg drop-land-cut task. Data are mean  $\pm$  standard deviation, range (minimum, maximum), and 95% confidence interval [lower, upper].

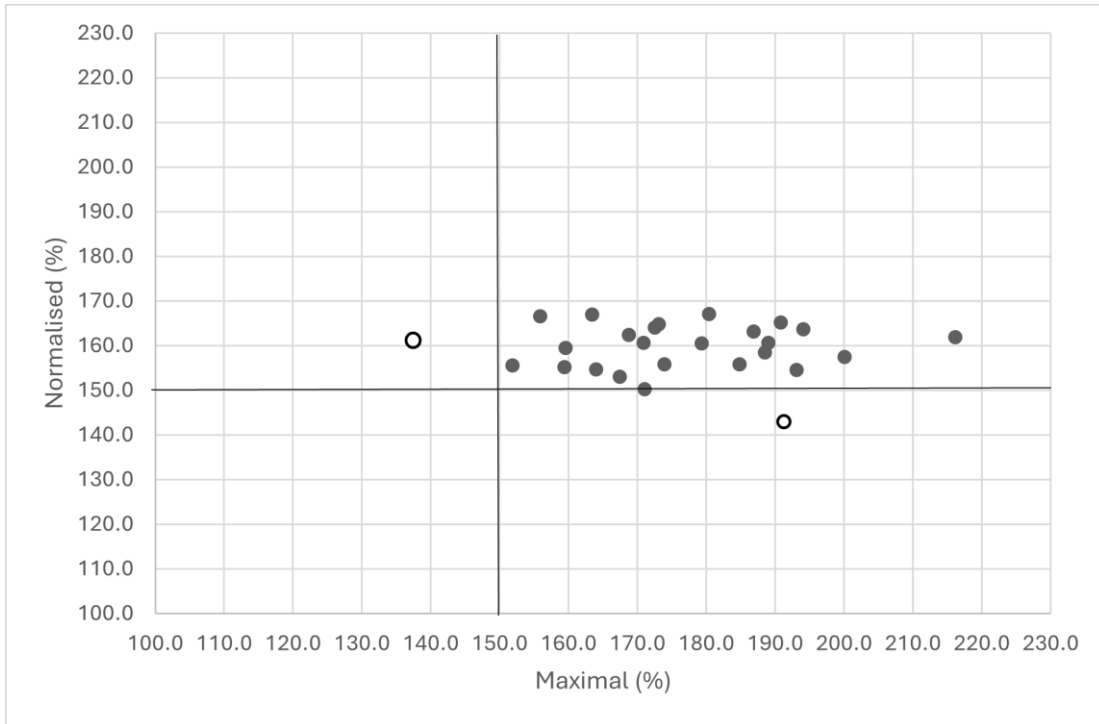
CUT task	Maximal		Normalised		Effects $p$ value, $\eta_p^2$		
	Non-dom	Dom	Non-dom	Dom	Condition	Dominance	Interaction
<b>Raw (cm)</b>	153.5 $\pm$ 24.9 (115, 197)	155.5 $\pm$ 24.5 (123, 206)	140.4 $\pm$ 20.4 (105, 181)	140.9 $\pm$ 19.0 (104, 170)	$p < 0.001^*$ $\eta_p^2$ 0.417 [0.161, 0.580]	$p = 0.282$ $\eta_p^2$ 0.046 [0.000, 0.219]	$p = 0.429$ $\eta_p^2$ 0.025 [0.000, 0.181]
<b>Normalised (%)</b>	174.0 $\pm$ 20.2 (122, 219)	176.2 $\pm$ 17.0 (138, 216)	158.5 $\pm$ 5.8 (147, 172)	159.5 $\pm$ 5.7 (143, 167)	$p < 0.001^*$ $\eta_p^2$ 0.432 [0.175, 0.591]	$p = 0.247$ $\eta_p^2$ 0.053 [0.000, 0.230]	$p = 0.547$ $\eta_p^2$ 0.015 [0.000, 0.156]

Note: Dom = dominant, \* indicates statistical significance ( $p \leq 0.05$ ), negative values indicate larger right value. Effect size: *small* (0.01), *medium* (0.06), *large* (0.14) (Cohen, 2013).

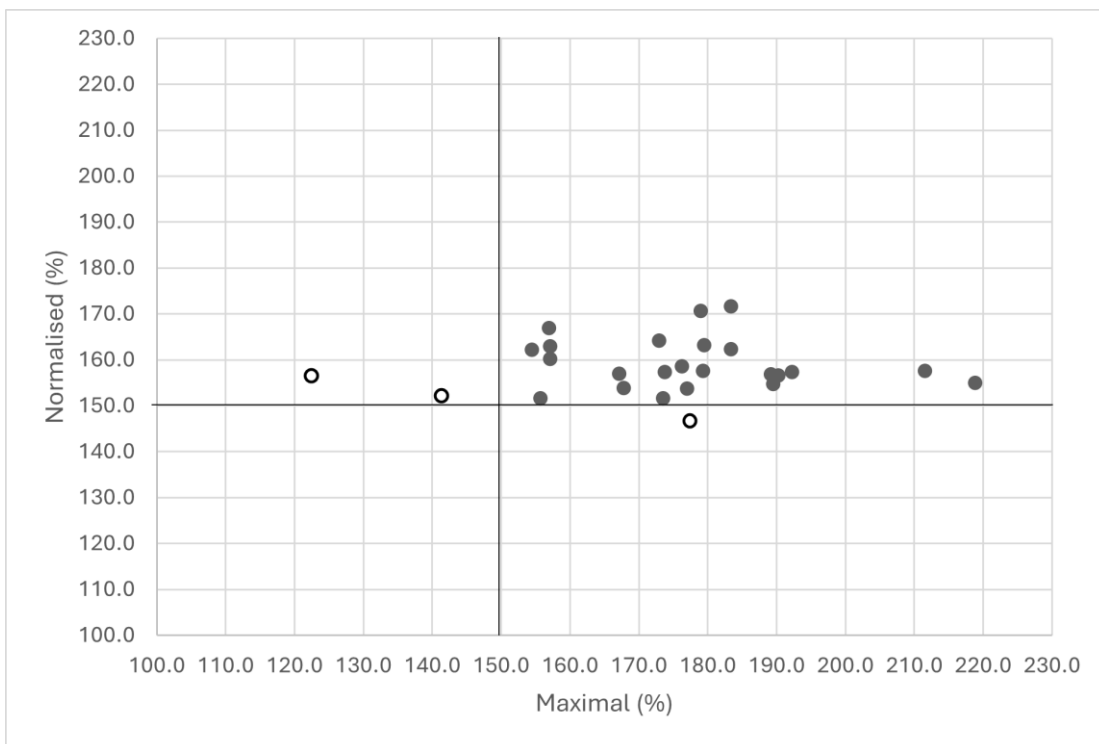
**Table 9** Leap distances by condition and order. Data are mean  $\pm$  standard deviation, range (minimum, maximum), and mean difference with 95% confidence interval [lower, upper].

	Maximal				Normalised			
	First	Second	MD [95% CI]	<i>p</i> value, $\eta_p^2$	First	Second	MD [95% CI]	<i>p</i> value, $\eta_p^2$
<b>Raw (cm)</b>	145.7 $\pm$ 23.8 (115, 206)	163.3 $\pm$ 22.1 (130, 201)	17.7 [-1.0, 36.3]	<i>p</i> = 0.062, $\eta_p^2$ 0.138 [0.000, 0.338]	142.2 $\pm$ 20.6 (104, 181)	138.9 $\pm$ 18.6 (111, 169)	3.2 [-12.8, 19.3]	<i>p</i> < 0.681, $\eta_p^2$ 0.007 [0.000, 0.131]
<b>Normalised (%)</b>	168.2 $\pm$ 16.5 (122, 200)	182.1 $\pm$ 18.1 (141, 219)	14.0 [0.5, 27.5]	<i>p</i> = 0.042*, $\eta_p^2$ 0.161 [0.003, 0.363]	157.6 $\pm$ 4.8 (150, 171)	160.3 $\pm$ 6.3 (143, 172)	2.7 [-1.2, 6.6]	<i>p</i> = 0.171, $\eta_p^2$ 0.076 [0.000, 0.267]

Note: Dom = dominant, \* indicates statistical significance ( $p \leq 0.05$ ), negative values indicate larger right value. Effect size: *small* (0.01), *medium* (0.06), *large* (0.14) (Cohen, 2013).



**Figure 7** Scatter plot of the dominant leg cut distance on the of maximal compared to normalised (target of 150% leg length) conditions. Dark grey lines indicate 150% of leg length. Markers without fill indicate participants who did not achieve 150% leg length.



**Figure 8** Scatter plot of the non-dominant leg cut distance on the of maximal compared to normalised (target of 150% leg length) conditions. Dark grey lines indicate 150% of leg length. Markers without fill indicate participants who did not achieve 150% leg length.

### 3.6 Discussion

There is currently a lack of standardisation of the CUT task. Given the incidence of ACL injury in young athletes (Maniar et al., 2022), it is important to understand the differences that exist for these tasks when used to explore potential injury risk factors linked to single-leg landings. Our aim was to compare the distances leapt during a CUT task under maximal and normalised conditions (set to 150% leg length) in young court and field sport athletes, and to determine the effect of leg dominance and order of tests on outcomes. In agreement with our hypotheses, the distance leapt was significantly further with the maximal condition compared to the normalised condition (mean difference: 13.9 cm or 16.1% of leg length), however, contrary to our hypothesis, no significant differences were observed between dominant and non-dominant legs. The significantly large differences in effect size observed between the normalised and maximal conditions values emphasises that, although both conditions have their benefits and limitations, the condition selected for assessment warrants consideration as they are fundamentally different.

Additionally, when examining the significant interaction effect between condition and order ( $p = 0.024$ ), it was observed that if participants completed the normalised condition first, they then leapt significantly further during the respective maximal condition compared to those who completed the maximal condition first ( $p < 0.001$ ). As the normative value was set, it was not influenced by the maximal condition being performed first. These results highlight the potential variation in perceptions of effort in this population of young athletes as they were able to achieve a further distance once they had jumped to the set distance previously. It is possible that the participants were able to hop further when performing the maximal condition second as they would have practiced the task more times, albeit sub-maximally, by performing the normalised condition first. In a clinical or research setting, employing a normalised trial prior to a maximal effort trial could lead to a 'truer' result for the maximal effort trial. Furthermore, no significant differences were observed between variances of the order of condition which suggests similarities in this outcome between participants ( $p = 0.755$  and  $p = 0.694$ ) for raw and normalised distances respectively. Perception of maximal effort and consistency in motor control during the maximal effort trials may be more varied in

younger populations. As demonstrated by Lamb et al. (2017), some participants can believe that they are performing maximally, but once given a target, may achieve further distances. The maximal condition may be better suited when observing pre-test post-test performance differences within a given individual or when the group has similar physical abilities, perceptions of effort, and anthropometric characteristics. The normalised method may be better when seeking to compare groups with a wider range of abilities, varied perceptions of effort, and differences in anthropometric characteristics. Furthermore, selecting the normalised task may be better if the task goal is completion oriented rather than performance oriented.

The range of individual ability for the maximal condition and how different the distance was from the standardised condition are also noteworthy. Landing distance was more variable under the maximal condition, as demonstrated by the large standard deviations and significant differences in variance between the maximal and normalised conditions ( $p = 0.048$  for raw and  $p < 0.001$  for normalised). These results demonstrate that there were variations in ability and/or effort applied between participants, which should be considered in task selection and result interpretation. It is possible that the presence of a floor tape marker in the normalised condition served as a visual target which introduces a potential confound when comparing the normalised condition to the maximal condition. A visual target may reduce movement variability by providing participants with an external reference point, which may influence motor planning and execution (Cowin et al., 2022). Contrastingly, the lack of a target in the maximal effort condition could inherently allow for more variability. This discrepancy could have contributed to observed differences in movement consistency between conditions. Researchers have suggested that children often adopt different movement patterns from trial-to-trial, possibly in attempt to learn how their bodies produce more force and therefore achieve a better performance outcome, but nonetheless, altering their biomechanics each time (Raffalt et al., 2016). Raffalt et al. (2016) found higher intra-subject variability in the movement patterns of children compared to adults when assessing reaction force components and joint angles during maximal effort jumping tasks. Previous research has suggested greater variability in jump length in a pre-peak height velocity group during a broad jump task (Meylan et al., 2012) and greater jump height variability during a vertical

jump task in younger participants, which diminishes with maturation and growth (Gerodimos et al., 2008; Harrison & Gaffney, 2001; Viitasalo, 1988). Selection of the normalised condition in our target population of young field and court sport athletes may encourage more consistency in performance and movement patterns leading to a more natural demonstration of how the participant would typically perform the task in a sporting situation. However, the variation in physical ability that exists in youth populations, demonstrated by the variance under the maximal condition, may influence the level of challenge provided by the normalised test condition.

All participants except for two leapt to the 150% of leg length distance during the maximal trials, which seems like an appropriate distance based on the lower end of the maximal distance values (122% non-dominant and 138% dominant, Table 9). When set to 150%, all participants were close to the set target (lower end 147% non-dominant and 143% dominant). Research has previously suggested that normalising tasks can be considered good practice in research as it allows standardisation in an individualised sense (Jaric et al., 2005). Practically, setting the same absolute distance or requiring a maximal landing distance may be unsuitable for comparing individuals of different heights, ages, maturation, sexes, and abilities. In a heterogeneous sample, using a CUT task normalised to leg length allows greater standardisation and facilitates valid comparisons between individuals. Whether 150% of leg length is the most appropriate has not been established, but it appears reasonable and achievable based on our dataset. Setting the distance to 175% might be more reflective of a maximal effort, but it is unlikely that all participants could reach this threshold based on the performance of participants in the current study.

The CUT task has not been used extensively in previous research to explore movement performances based on maturation phases (Butcher et al., 2024), hence further research is required as there are no tools unequivocally agreed to be linked with ACL injury incidence. It has been suggested that a larger lateral step distance in a cutting task increases hip and knee extension, and ankle plantar flexion moments (Inaba et al., 2013). Additionally, Havens and Sigward (2015) noted greater knee abduction moments during cutting with wider lateral foot plants. Therefore, the distance of the cutting task could be an important factor to consider in rendering a task more sensitive and specific for

assessing risk of ACL injury. A normalised method for setting distance during a CUT is yet to be explored, however, previous research has used maximal effort methods. Hass et al. (2005) used a maximal effort CUT task alongside a landing task and a vertical jump task for assessing lower extremity injury risk in pre-pubertal and post-pubertal females. Their study found significant interactions between maturation phase and landing sequence for post-pubertal compared to pre-pubertal participants who demonstrated biomechanics linked with ACL injury incidence including reduced knee flexion at initial contact, increased mediolateral knee joint forces, and reduced knee extensor moments. The researchers suggested these results to be a consequence of differences in motor and neuromuscular control strategies (such as reflex and voluntary muscle activation) at different maturational phases and they emphasised the need to study multiple landing strategies. It is logical to assume that instructing participants to perform a task using a maximal effort would create a relatively consistent challenge level between participants; however, differences in effort perception and neuromuscular ability may influence their ability to produce a maximal or close to maximal effort repeatedly. It is also currently unknown whether performing the maximal version of this or any jump-landing task is injury-risk specific. It is possible that a threshold exists where a normalised distance is challenging enough to elicit biomechanical patterns similar to a maximal effort, but determining this threshold would require further biomechanical research. Typically, athletes are not required to leap laterally as far as possible in a sporting situation as they are usually only required to leap far enough to evade a player or to make a play, indicating that a normalised distance may suffice for assessment of movement competency in the context of ACL injury risk.

This study is not without limitations. Although the order of tests (normalised or maximal) was randomised, an order effect was observed. Therefore, it is possible that the participants gave different levels of effort across the trials, but not necessarily produced a true maximal effort owing to factors such as fatigue, familiarisation, perception of effort, or attention. Perceived difficulty was not collected in this study, limiting our ability to quantify the participants' perceptions of the task demands. Furthermore, the CUT task was anticipated (i.e., participants knew which leg to land on and perform the task with), limiting generalisation to unanticipated tasks that are more reflective of ACL injury

mechanisms (Weinhandl et al., 2013). It has been suggested that individuals use different strategies to execute planned versus unplanned movements, specifically, greater implications of overuse injuries are apparent in planned compared to unplanned movements. Future research should examine whether biomechanics are affected based on whether the task is set or involves a reactive component, as well as how biomechanics change with increase in leaping distance. A further limitation is the sample size ( $n = 26$ ), which represented a cross-section of the maturation stages for both sexes. With a larger sample size than 26 participants based on detecting differences between CUT tasks, it would have been possible to further explore additional factors, such as the effect of maturation on outcomes or between sex differences. Furthermore, the mean hop distance of the normalised condition was 159% of leg length, exceeding the 150% target. There are several potential underlying factors to this overshooting: the landing distance was too easy; participants had difficulty seeing the target in their peripheral vision while facing forwards; the Hawthorne effect (Sedgwick & Greenwood, 2015) and the testing environment incited participants to perform better than the requirement; or the decision to measure the distance based on a marker placed on the toes rather than the midfoot or heel. It is generally common in sports and jump tests involving horizontal components for individuals to be instructed to “reach” a set landing distance (Padua et al., 2009), inferring they must get to or exceed the set target. Reinforcing the importance of landing on the target or re-doing trials which were too far off the target would likely bring the mean value closer to the target.

Further research is required to determine whether the normalised condition of 150% leg length currently used is appropriate, or if our mean maximal values of 175% would be more suitable and achievable. Furthermore, it would be beneficial to determine if an ideal percentage of leg length exists for the normalised CUT which best represents that of a high ACL injury risk sporting situation, particularly in different maturational groups or in groups with different abilities. Assessing what the average cutting distance is across the course of a game, considering fatigue, within different sports and quantifying this in relation to percentage of leg length may inform the development of screening tools which are more specific to the demands of the sport.

To conclude, on average, participants leapt significantly further during the CUT task when requiring a maximal effort compared to when normalising the distance to 150% of leg length, suggesting significantly different performance demands of the conditions. However, a more variable landing distance was observed during the maximal condition, as indicated by larger standard deviations and significant variance in absolute deviations. We recommend that normalising leaping distance to leg length allows for standardisation of the CUT task and facilitates comparisons between individuals deriving from a heterogeneous sample. However, the normalised condition may not elicit a maximal response or sufficiently represent an injury-risk specific situation. Hence, selection of a protocol specific to the study goals is important. A normalised distance based on a percentage of leg length may be better suited when examining individuals presenting with a wide range of heights, maturation stages, sexes, or physical abilities, yet a maximal may be more suitable for a more homogeneous sample or pre-post study designs. Future research should investigate whether lower-extremity kinematics and kinetics differ between normalised and maximised CUT tasks and explore the specificity of these manoeuvres to biomechanics related to ACL injury risk.

## **Part 2 – Stepping into the unknown: Experimental research**

### **Prelude**

Part 1 systematically appraised and summarised the literature concerning the differences in biomechanics associated with ACL injury between maturation stages and piloted the methods of a sport and injury specific drop-land and cut task. The systematic review highlighted differences between studies in the methods used to identify and group maturation stages. The use of different methods for maturation stage identification and grouping highlighted the need for standardisation of these definitions to improve scientific inference. We used validated and reliable tools to determine and confirm each participant's maturation stage and categorised them into a pre-pubertal, early-/ mid-pubertal, or late-/ post-pubertal group accordingly. This approach allowed the examination of differences in biomechanics between groups that have experienced no pubertal influence, a small to moderate level of pubertal influence, and almost complete or complete pubertal influence based on subjective and objective validated tools.

Another limitation identified in the systematic review was the lack of research in males across maturational phases, and research comparing males and females across different maturational phases. Consequently, equal numbers of males and females across all three maturation stages were targeted to allow comparisons in biomechanics between males and females across maturation, underpinning the differences in injury rates between sexes observed with biological maturation (Maniar et al., 2022).

Non-contact ACL injuries typically occur during the deceleration phase of single-leg landing or change of direction tasks (Boden et al., 2000; Yu & Garrett, 2007). From a biomechanical perspective, reduced knee flexion angles, larger knee abduction angles and moments, and greater peak vertical ground reaction force (vGRF) upon landing have been associated with an increased ACL injury risk (Hewett, Myer, Ford, et al., 2005). Furthermore, although the metrics examined between studies included in our

systematic review varied, four key metrics (knee flexion angle, knee abduction angle, knee abduction moment, and vGRF) were the most commonly observed metrics.

The systematic review identified the use of the double-leg drop jump task in many studies as a limitation due to their lack of sport or ACL injury specificity, hence, the transferability of the results to real life interpretation and application were limited. Different single-leg landing tasks were selected for investigation in these experimental studies. Single-leg landing tasks have a similar perceived challenge to cutting, are more biomechanically challenging for the knee joint, and more commonly observed during ACL injury situations than double-leg tasks (Boden et al., 2000; Hanzlíková et al., 2021). Single-leg landings generally involve greater lower limb loading, a smaller base of support, and greater stability challenges (Russell et al., 2006). The single -leg landing tasks utilised in the experimental studies are described in terms of their relevance to sporting movements and biomechanical challenge. The single-leg drop-land task (LAND) challenges force absorption, balance, and stability slightly more than the other tasks. The single-leg drop-land and vertical hop task (VERT) requires an absorption and then reapplication of force, which adds a sagittal plane challenge. The single-leg drop-land and cut (CUT) task incorporates a frontal plane change of momentum, simulating the sporting demands of a commonly used running change of direction task but being appropriate for a laboratory setting. The single-leg drop rotate land and vertical hop task (ROT) includes a transverse plane dynamic component where the participant needs to decelerate their downwards and rotational momentum upon landing to then perform a vertical hop. Furthermore, the ROT task as been suggested as more appropriate than a double-leg drop-jump for revealing risky movement patterns for non-contact ACL injury with higher levels of challenge and sport specificity (Hanzlíková et al., 2021). The tasks were chosen to cover a range of difficulty levels and biomechanical challenge, but all reflect movement patterns observed in sporting situations and associated with ACL injury risk profiles.

Establishing the reliability of the biomechanical metrics of tasks used to assess injury risk factors supports their suitability for identifying potentially high injury-risk movement patterns (Yeow et al., 2011). Reproducible and reliable screening methods are paramount for ascertaining accurate changes both within individuals (for identifying changes to risk of injury over time) and between individuals (for identifying level of risk or

movement pattern trends within groups). Due to the paucity of literature describing the use of the single-leg landing tasks used in the experimental studies and the differences in their movement demands, it was important to determine the importance and reliability of the key biomechanical metrics with respect to each task. Therefore, a secondary focus of the experimental research was to establish the test-retest reliability of biomechanical metrics associated with ACL injury risk within the study population to determine their suitability for identifying differences in movement patterns between maturational groups (Yeow et al., 2011).

Therefore, the overall aim of Part 2 is to explore potential differences in biomechanics associated with ACL injury in males and females of different specified maturation stages using four different sport and injury risk specific single-leg landing tasks. The identification of differences in biomechanics associated with ACL injury risk is crucial for informing the development of effective risk mitigating strategies and preventative training programmes specific to maturation stage and sex.

## 4.0 Chapter 4 – Methods

### 4.1 Participants

#### 4.1.1 Sample size estimation

For the cross-sectional study, sample size calculations were performed in G\*Power 3.1.9.7 using the “ANOVA: Fixed effects, special, main effects and interactions” setting. Kim and Lim (2014) detected a *large* effect size difference in knee abduction moment ( $f = 0.5$ ) between pre-menarcheal and post-menarcheal female athletes during a single-leg drop-land task. Hence, sample size calculations were based on detecting a *large* effect size difference in knee abduction moment ( $f = 0.4$ ), resulting in a requirement of 64 participants given an alpha of 0.05 (5% significance) and beta of 0.20 (80% power) when accounting for the main effect of sex (2 levels), maturational group (3 levels), and their interactions (i.e., 6 groups and 2 degrees of freedom). Twelve participants per maturational group and sex were targeted to account for 10% of missing data (i.e.,  $n = 72$ ) however, 69 participants were recruited. For the reliability study, 15 young court or field sport athletes volunteered to return for a second testing session.

**Table 10** Demographic data of all participants included in the reliability study grouped by sex.

	Females	Males
<b>Sample (<i>n</i>)</b>	8	7
<b>Age (y)</b>	14.2 ± 4.7	16.3 ± 4.6
<b>Height (cm)</b>	153.4 ± 18.5	169.0 ± 38.2
<b>Mass (kg)</b>	53.4 ± 19.5	73.4 ± 26.8
<b>BMI (kg/m<sup>2</sup>)</b>	21.9 ± 5.0	24.6 ± 6.9

#### 4.1.2 Inclusion and exclusion criteria

Participants were included if they were: aged 7 to 21 years, had a body mass index < 30 kg/m<sup>2</sup>, were currently participating in a court or field sport at least twice per week

involving jump-landing or change of direction, and were classified as recreationally active (i.e., at least 30 minutes of moderate or vigorous daily physical activity on four days per week). The modified Children's Leisure Activity Study Survey (Telford et al., 2004) (Appendix N) self-reported physical activity questionnaire was used to determine habitual physical activity levels. Exclusion criteria included the use of hormonal contraceptive treatment/medication (excluding the monophasic contraceptive pill) as previous research has demonstrated biomechanical differences and potential for ligamentous laxity effects in those using some contraceptive treatments (Samuelson et al., 2017). Other exclusion criteria included: individuals who identified as a gender different to their sex at birth or were transitioning to a sex different from that at birth, a history of significant orthopaedic lower limb trauma in the six months prior to testing requiring surgery or more than three months of physiotherapy, a previous ACL or meniscal injury or surgery, a medical condition affecting performance of sporting tasks, or a recent (less than three months) or current knee pain (specifically patellofemoral pain and patella tendinopathy).

#### 4.1.3 Maturation stage classification

Participants were categorized into three pubertal maturation stages using a modified Pubertal Maturation Observational Scale (PMOS) (Appendix O) and the peak height velocity (PHV) calculation. The PMOS was used to classify participants as pre-pubertal (Tanner stage I), early-/mid-pubertal (Tanner stages II and III with growth spurt or menarche for females), and late-/post-pubertal (Tanner stages IV and V with growth spurt and menarche for females). These maturation stages were based on self- or parent/guardian-rated Tanner staging for breast development, growth spurt (i.e., 7.5-9.0 cm of growth in the past six months), menarche status, body hair development, sweating, and muscular definition (Tanner, 1986; Tanner & Davies, 1985) (see Appendix P). The PHV was calculated using reported date of birth and measured standing height, seated height, measured leg length, body mass, and body mass index (BMI) (Mirwald et al., 2002), and was used to confirm the 'growth spurt' criteria within the PMOS. Male and female participants were defined based on their biological sex at birth.

## **4.2 Procedures**

Ethical approval was obtained prior to collecting any data: HREC(Health)2022#53 and adhered to the Code of Ethics of the World Medical Association (Declaration of Helsinki Ethical Principles for Medical Research Involving Human Subjects) and the Health Research Council's guidelines relating to research involving children and UNICEF's principles guiding ethical research involving children (Graham et al., 2013).

Participants in the reliability study attended two testing sessions after the principal investigator had screened their eligibility to ensure they meet the inclusion/exclusion criteria. Menstruating female participants attended the one testing session during the first five days of their follicular phase of their menstrual cycle as identified by the onset of menstruation as this phase was simplest to identify and has the lowest sex hormone levels (Reilly, 2000). If these participants were in the reliability portion, their second session was 48-72 hours later but also within the first five days of their menstrual cycle.

### **4.2.1 Questionnaires**

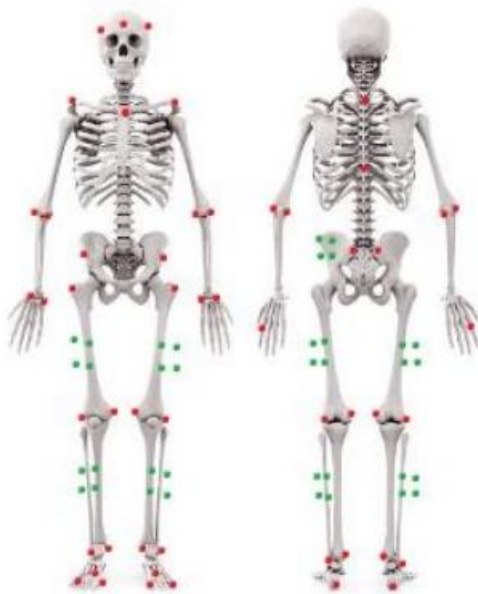
The first stage of data collection involved completion of consent and assent forms, a baseline questionnaire composed of demographic characteristics (age, sex, leg dominance, training history, and injury history), a physical activity questionnaire, and the PMOS. Females also completed a menstrual cycle tracking app (with at least one month of prior tracking), and a menstrual cycle questionnaire composed of regularity and timing characteristics of menses (see Appendix Q).

### **4.2.2 Descriptive data collection**

Participant standing and seated height was measured using a stadiometer (Seca model, 0123), mass was taken from the Kistler 9260AA6 multicomponent force plate (Kistler Group, Winterthur, Switzerland), and leg length was measured on the right leg using a tape measure, the same measurement recorded twice with the participant lying supine, from the anterior superior iliac spine (ASIS) to the medial malleoli (Neelly et al., 2013).

#### 4.2.3 Set-up of participant for 3D motion capture

Prior to data collection, 42 retroreflective markers and five 4-marker clusters were positioned on the skin surface at select anatomical locations according to the Calibrated Anatomical System Technique (CAST) (Cappozzo et al., 1995). The clusters were positioned on the lateral aspects of the mid-shank and thigh on the line connecting the proximal and distal joints of the respective segments projected to the sagittal plane (Kim & Lim, 2014; Nasser et al., 2021; Orishimo et al., 2009; Schache & Baker, 2007); Figure 9). The CAST approach is beneficial as it models each body segment in six degrees of freedom, which enables full representation of function and interaction of different body segments and joints in comparison to simpler anatomical models (Richards, 2018). The markers were attached using hypoallergenic double-sided tape and topical skin adhesive and the cluster sets secured using elastic bandages. When the markers and clusters were placed on the body segments, a 1-second static trial was recorded for the purposes of model calibration.



**Figure 9** 3D motion capture marker set based on the Calibrated Anatomical System Technique (CAST) model.

#### 4.2.4 Tasks

Four different landing tasks were assessed: 1) single-leg drop-land (LAND) (Figure 10), 2) single-leg drop-land and cut (CUT) (Figure 11), 3) single-leg rotating drop-land and hop (ROT) (Figure 12), and 4) single-leg drop-land and vertical hop (VERT) (Figure 13). Following each task, participants were asked to evaluate the level of difficulty of the task using the following 5-point Likert scale: 1 – very difficult, 2 – difficult, 3 – neutral, 4 – easy, 5 – very easy.



**Figure 10** Single-leg drop-land (LAND) task.



**Figure 11** Single-leg drop-land and cut (CUT) task.



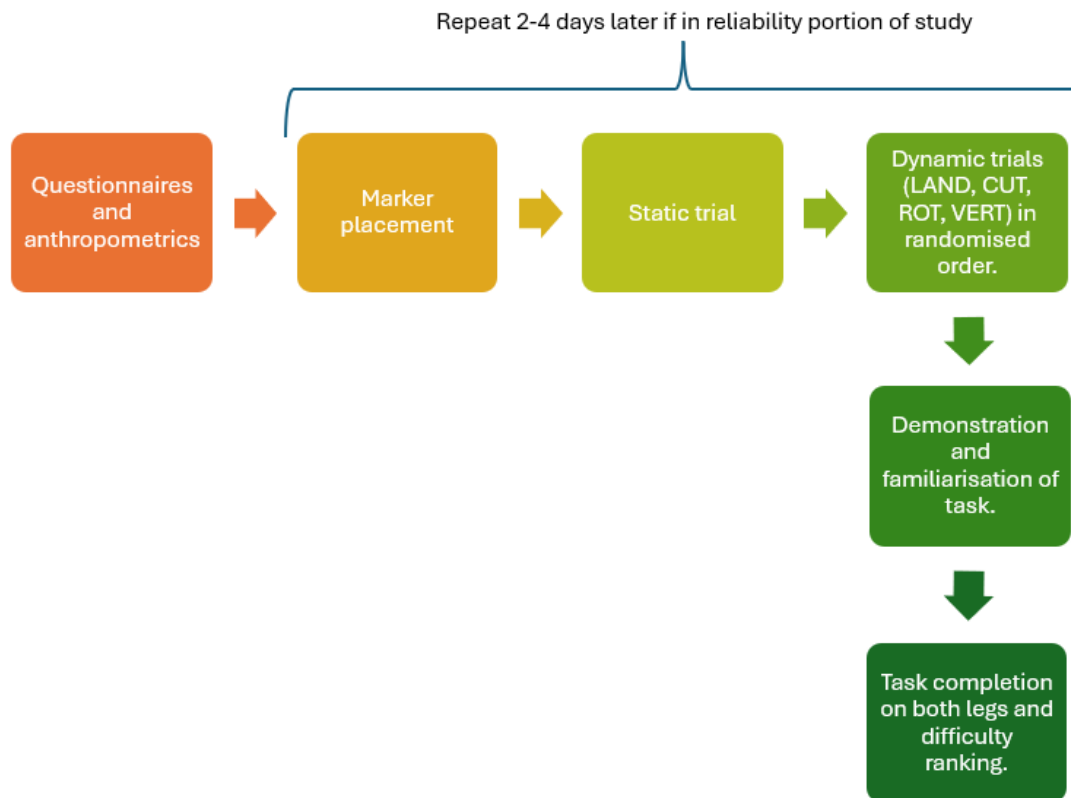
**Figure 12** Single-leg rotating drop-land and hop (ROT) task.



**Figure 13** Single-leg drop-land and vertical hop (VERT) task.

The LAND, CUT, ROT and VERT were performed from a standardised box height of 30 cm (Kim & Lim, 2014). The LAND required participants to stand on one leg at the centre of the box, to drop off the box, and to land on the same leg on a target 30 cm in front of the box, trying to remain stable on the same leg for 2-seconds (Kim & Lim, 2014). The CUT required participants to drop off the box and land on the same leg on a target 30 cm in front of the box and then immediately leap 90° laterally to land on their opposite leg (Nasseri et al., 2021) aiming for a target that had been placed at 150% of their leg length (determined based on the results of a pilot study). The ROT required participants to stand on one leg on the box and hop off to rotate 90° in the air, turning to the same side as the foot they stood on, before landing on the same leg on the target placed 30 cm in front of the box and then immediately hopping as high as possible vertically. The VERT required participants to stand on one leg on the box, drop off the box to land on the same leg on a target 30 cm in front of the box and immediately hop jump as high as possible vertically to land on the same target as the initial landing (Kim & Lim, 2014).

Each trial was separated by a rest period of 30-seconds, or until the participant felt adequately recovered (Hanzlikova et al., 2021). The participants ranked the difficulty of each task immediately after completion using the following 5-point Likert scale: 1 – very difficult, 2 – difficult, 3 – neutral, 4 – easy, 5 – very easy. The order in which the tasks were performed, and the use of the dominant and non-dominant legs were randomised. During the data collection sessions, the participants wore minimal and tight-fitting clothing such as sports bras, fitted shorts, and their own running shoes. Three successful trials were collected from each participant, as defined by the participant performing the tasks instructed in a fluid motion, and successful collection of biomechanical data. A flow chart of the data collection procedure is presented in Figure 14.



**Figure 14** Flow chart of data collection procedure. Note: LAND, single-leg drop-land; CUT, single-leg drop-land and cut; ROT, single-leg rotating drop-land and hop; VERT, single-leg drop-land and vertical hop.

#### 4.2.5 Biomechanical assessment

An 8-camera motion analysis system (Oqus 700+ cameras) and software (Qualisys Track Manager v.2019.1, Qualisys AB, Gothenburg, Sweden) was used to capture the kinematic data at a sampling rate of 200 Hz. A Kistler 9260AA6 multicomponent force plate (Kistler Group, Winterthur, Switzerland) sampling at 1,000 Hz was used to obtain kinetic data using a 5695B2 DAQ system (Kistler Group, Winterthur, Switzerland), synchronised to the 3D motion capture, and collected within the Qualisys Track Manager. The metrics collected included knee angles and moments in all three planes of motion, ground reaction force (GRF) and performance metrics; time to peak knee flexion for all tasks, stance time and flight time for CUT, ROT AND VERT, and jump height for ROT and VERT. Moments were presented normalised to body mass and height to account for the large variation in growth of the participants (Nm/kg/m). GRF were presented normalised to

multiples of body weight. Furthermore, knee marker and joint centre positions were extracted to assess the reliability of marker placement. To assess reliability of marker positioning, distances between the lateral and medial markers, between the lateral marker and the joint centre (defined as the proximal end of the tibia segment), and between the medial marker and the joint centre were extracted in the x, y, and z coordinates from the repeat visit static trials. Descriptions of the operations of included biomechanical metrics are reported in Appendix AK.

#### 4.2.6 Data analysis

Data were exported and processed using Visual3D Professional™ (v.6.01.36, HAS Motion, Kingston, CA). A biomechanical model using 13 rigid segments with six degrees of freedom at each joint was constructed (Hanzlíková et al., 2021). The local coordinates of all segments were obtained from a previously captured static trial. Any potential marker data gaps, up to 10 frames (20 ms), were interpolated using a third order polynomial fit algorithm. A fourth order low-pass Butterworth filter with a cut-off frequency of 15 Hz was then applied to the data (Hanzlíková et al., 2019). A low-pass filter with a cut-off frequency of 50 Hz was applied to the force data (Harry et al., 2022).

#### 4.2.7 Statistical analysis

A two-way mixed-effects, absolute agreement, multiple measurement Intraclass Correlation Coefficient (ICC) was used to assess the test-retest reliability the variables collected from the 3D motion analysis and force plate during a LAND, VERT, CUT and ROT task (Koo & Li, 2016; Portney & Watkins, 2009) and of the knee marker placement from the static trials. R studio (2023.12.0+369) was used for the analysis. Q-Q plots were visually inspected to assess normality of distribution. ICC values less than 0.5 were deemed *poor* reliability, values between 0.50 and 0.75 *moderate* reliability, values between 0.75 and 0.90 *good* reliability, and values greater than 0.90 indicated *excellent* reliability (Koo & Li, 2016; Portney & Watkins, 2009). Additionally, 95% confidence intervals and the p-value of the ICC were reported. F values and degrees of freedom were also calculated and presented. Between-session variability was determined using

typical error (TE) values which were calculated for each variable according to the methods of Hopkins (2000) and expressed in both unit values and coefficient of variation percentage (CV%) values. Lower and upper limits were also calculated for both TE and CV% and presented. Descriptive results were reported as mean  $\pm$  standard deviation (SD) for each trial and the difference. A paired t-test was used to explore statistically significant differences between trials. Statistical significance was acknowledged if  $p < 0.05$  (Myer et al., 2015).

Regarding the determination of group differences, participants were grouped by sex and into three maturational phases as: Pre, pre-pubertal; Mid, early-/mid-pubertal; and post, late-/post-pubertal. Normality was assessed using Shapiro-Wilk's normality test and homogeneity of variances was assessed using Levene's test for each sex by maturation group. Descriptive statistics (mean  $\pm$  SD) were used to report participant demographics and anthropometrics. Differences in demographics, anthropometrics, and biomechanical variables between sex (male, female) and maturation (pre, mid, and post) were assessed using separate 2x3 way analysis of variance (ANOVA). Pairwise comparisons were used to explore differences between groups when significant interaction effects of sex and maturation, or significant main effects of sex or maturation were detected. All statistical tests were performed using SPSS. Effect size was calculated using the Hedges'  $g$  formula as sample sizes were uneven between groups (Dhakal, 2023). Effect size was interpreted as *small*, *medium*, and *large* when reaching  $g$  thresholds of 0.2, 0.5, and 0.8, respectively (Zach, 2021).

Residual analysis was performed to test for the assumptions of the 2x3 way ANOVA. Outliers were assessed by inspection of boxplots and individually corrected if there was an input error, removed if there was marker slippage or a mistrial, or confirmed as true readings accordingly. The detected outliers were examined individually, and all were determined to be true measures, hence were maintained in the dataset. Residuals were mostly normally distributed ( $p > 0.05$ ). ANOVAs are considered relatively robust to deviations from normality (Maxwell et al., 2017). Consequently, the ANOVAs were run regardless of meeting normality of distribution to maintain consistency in reporting, but the results of the violations have been reported for transparency. (Appendices Q, S, U, and W). There was homogeneity of variances ( $p > 0.05$ ) for most metrics. Metrics which

violated the assumption of homogeneity are reported in Appendices R, T, V, and X. To account for these violations, common logarithmic transformations ( $\text{Log}(10)$ ) were performed on these data prior to running the ANOVA's. For negative values, the data were translated using a constant value to a lower limit of one, before being transformed. Statistical significance was set to  $p < 0.05$ .

Subjective ratings regarding task difficulty were described using median, mode, and frequency indicators, and compared between tasks using the Friedman test with Wilcoxon signed-rank tests during post-hoc comparisons. The Wilcoxon signed-rank tests were adjusted for multiple comparisons using a calculated Bonferroni adjustment which set the post-hoc significance level at  $p = 0.013$ .

## 5.0 Chapter 5 – Results

### 5.1 Reliability results

Reliability of knee marker position is reported in Appendix AJ. There was no systemic bias between trials based on paired  $t$  tests values ( $p \geq 0.166$ ). The mean difference in position between trials ranged from -11.41 to 7.89 mm, and was larger in the (medial lateral) than x-axis (anterior posterior) or z-axis (vertical).

#### 5.1.1 LAND

Outcomes from the test–retest reliability for the LAND task on the dominant leg are summarised in Table 10. Reliability of outcomes were *moderate* to *excellent* across most metrics between testing occasions (ICC 0.511–0.940). However, *poor* ICCs were identified for knee metrics of peak extension moment (ICC 0.336, CV 5.5%), range sagittal moment (ICC 0.287, CV 4.5%), peak varus moment (ICC 0.468, CV 96.5%), peak lateral GRF (ICC 0.257, CV 32.5%), and peak posterior GRF (ICC 0.232, CV 45.9%). Additionally, significant differences were observed between trials for the metrics of range sagittal moment ( $p = 0.036$ ), peak lateral GRF ( $p = 0.003$ ), and peak posterior GRF ( $p = 0.011$ ). The CV% values were suboptimal across most metrics (CV 4.5–110.1%) with CV < 10% observed for only five metrics, suggesting a greater level of dispersion around the mean for most variables between the first and second session. For the non-dominant leg (Table 11) reliability of outcomes were *moderate* to *excellent* across most metrics between testing occasions (ICC 0.602–0.971). However, *poor* ICCs were identified for metrics of peak extension moment (ICC 0.396, CV 5.5%) and range sagittal moment (ICC 0.397, CV 6.5%). Additionally, significant differences were observed between trials for range valgus moment ( $p = 0.012$ ). The CV% values were suboptimal across most metrics (CV 5.3–103.7%) with CV < 10% observed for only six metrics.

**Table 11** Between session reliability of metrics collected from the single-leg drop-land (LAND) task on the dominant leg.

	Trial A mean ± SD	Trial B mean ± SD	Difference mean ± SD	TE [lower, upper]	CV% [lower, upper]	ICC [95% CI]	ICC p-value	Paired t-test p-value
Peak flexion angle (°)	61.93 ± 10.08	63.44 ± 11.09	1.51 ± 4.98	3.52 [2.58, 5.55]	5.6 [4.1, 8.9]	0.940 [0.827, 0.980]	<0.001	0.260
Peak extension angle (°)	14.67 ± 5.34	16.03 ± 6.10	1.36 ± 3.27	2.32 [1.69, 3.65]	15.1 [11.0, 23.8]	0.903 [0.711, 0.967]	<0.001	0.129
Range sagittal angle (°)	47.26 ± 7.74	47.41 ± 7.66	0.15 ± 3.73	2.64 [1.93, 4.16]	5.6 [4.1, 8.8]	0.941 [0.825, 0.980]	<0.001	0.881
Peak flexion moment (Nm/kg/m)	0.37 ± 0.13	0.41 ± 0.16	0.04 ± 0.13	0.09 [0.07, 0.15]	24.4 [17.9, 38.5]	0.702 [0.082, 0.904]	0.016	0.268
Peak extension moment* (Nm/kg/m)	-1.68 ± 0.25	-1.72 ± 0.23	0.04 ± 0.13	0.09 [0.07, 0.15]	5.5 [4.1, 8.7]	0.336 [-0.045, 0.716]	0.078	0.260
Range sagittal moment* (Nm/kg/m)	2.05 ± 0.27	2.13 ± 0.30	0.08 ± 0.13	0.09 [0.07, 0.15]	4.5 [3.3, 7.1]	0.287 [-0.040, 0.670]	0.085	0.036
Peak abduction angle (°)	5.02 ± 6.02	5.81 ± 5.25	0.78 ± 4.24	3.00 [2.20, 4.73]	55.4 [40.6, 87.4]	0.840 [0.530, 0.946]	0.001	0.486
Peak varus angle (°)	-2.96 ± 3.80	-2.10 ± 4.87	0.86 ± 3.95	2.79 [2.04, 4.40]	110.1 [80.6, 173.7]	0.747 [0.259, 0.915]	0.007	0.413
Range coronal angle (°)	7.98 ± 3.22	7.91 ± 3.02	0.07 ± 3.22	2.28 [1.67, 3.59]	28.7 [21.0, 45.2]	0.653 [-0.087, 0.885]	0.034	0.930
Peak valgus moment (Nm/kg/m)	0.42 ± 0.16	0.43 ± 0.14	0.01 ± 0.13	0.09 [0.07, 0.14]	21.2 [15.5, 33.4]	0.691 [0.013, 0.904]	0.023	0.809
Peak varus moment* (Nm/kg/m)	-0.25 ± 0.18	-0.32 ± 0.35	0.07 ± 0.39	0.28 [0.20, 0.44]	96.5 [70.6, 152.1]	0.468 [-0.225, 0.804]	0.069	0.529
Range coronal moment (Nm/kg/m)	0.68 ± 0.26	0.75 ± 0.37	0.07 ± 0.40	0.28 [0.21, 0.45]	39.9 [29.2, 63.0]	0.527 [-0.065, 0.822]	0.037	0.493
Peak internal rotation angle (°)	8.49 ± 6.20	7.37 ± 5.32	1.12 ± 4.07	2.87 [2.10, 4.53]	36.3 [26.5, 57.2]	0.858 [0.589, 0.952]	<0.001	0.302
Peak external rotation angle (°)	-5.02 ± 6.63	-6.07 ± 6.51	1.05 ± 5.39	3.81 [2.79, 6.01]	68.7 [50.3, 108.3]	0.802 [0.417, 0.933]	0.002	0.463
Range transverse angle (°)	13.51 ± 3.87	13.44 ± 4.10	0.07 ± 4.00	2.83 [2.07, 4.46]	21.0 [15.3, 33.1]	0.679 [-0.001, 0.894]	0.025	0.944
Peak internal rotation moment (Nm/kg/m)	0.28 ± 0.08	0.29 ± 0.09	0.01 ± 0.07	0.05 [0.04, 0.08]	16.9 [12.4, 26.7]	0.638 [-0.039, 0.889]	0.035	0.573
Peak external rotation moment (Nm/kg/m)	-0.06 ± 0.07	-0.04 ± 0.04	0.02 ± 0.07	0.05 [0.40, 0.08]	95.6 [70.0, 150.7]	0.724 [0.363, 0.898]	0.001	0.385

<b>Range transverse moment (Nm/kg/m)</b>	0.34 ± 0.10	0.33 ± 0.10	0.01 ± 0.10	0.07 [0.05, 0.12]	21.8 [16.0, 34.4]	0.511 [-0.128, 0.827]	0.064	0.828
<b>Peak vertical GRF (BW)</b>	4.20 ± 0.86	4.15 ± 0.86	0.05 ± 0.47	0.33 [0.24, 0.53]	7.9 [5.7, 12.7]	0.924 [0.764, 0.976]	<0.001	0.711
<b>Peak anterior GRF (BW)</b>	0.14 ± 0.15	0.13 ± 0.13	0.01 ± 0.12	0.08 [0.06, 0.13]	61.1 [44.3, 98.5]	0.796 [0.344, 0.935]	0.005	0.876
<b>Peak posterior GRF* (BW)</b>	-0.14 ± 0.06	-0.24 ± 0.12	0.10 ± 0.12	0.09 [0.06, 0.14]	45.9 [33.3, 74.0]	0.232 [-0.561, 0.703]	0.261	0.011
<b>Peak lateral GRF* (BW)</b>	0.24 ± 0.08	0.15 ± 0.06	0.09 ± 0.09	0.06 [0.05, 0.10]	32.5 [23.6, 52.4]	0.257 [-0.454, 0.707]	0.238	0.003
<b>Peak medial GRF (BW)</b>	-0.61 ± 0.18	-0.64 ± 0.24	0.03 ± 0.14	0.10 [0.07, 0.16]	15.8 [11.5, 25.5]	0.881 [0.641, 0.961]	<0.001	0.371
<b>Time to PKF (s)</b>	0.23 ± 0.07	0.24 ± 0.10	-0.01 ± 0.06	0.04 [0.03, 0.06]	16.9 [12.2, 27.2]	0.885 [0.649, 0.963]	<0.001	0.452

Note: \*indicates ICC below 0.500. BW = body weight, CI = confidence interval, CV = coefficient of variation, GRF = ground reaction forces, ICC = intraclass coefficient, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

**Table 12** Between session reliability of metrics collected from the single-leg drop-land (LAND) task on the non-dominant leg.

	<b>Trial A mean ± SD</b>	<b>Trial B mean ± SD</b>	<b>Difference mean ± SD</b>	<b>TE [lower, upper]</b>	<b>CV% [lower, upper]</b>	<b>ICC [95% CI]</b>	<b>ICC p-value</b>	<b>Paired t-test p-value</b>
<b>Peak flexion angle (°)</b>	65.41 ± 10.27	63.42 ± 10.73	1.99 ± 5.03	3.56 [2.52, 6.04]	5.5 [3.9, 9.4]	0.920 [0.736, 0.977]	<0.001	0.244
<b>Peak extension angle (°)</b>	15.72 ± 2.60	13.38 ± 5.44	2.35 ± 3.99	2.82 [2.00, 4.79]	19.4 [13.7, 32.9]	0.602 [-0.209, 0.880]	0.053	0.089
<b>Range sagittal angle (°)</b>	49.68 ± 9.53	50.04 ± 7.75	-0.35 ± 3.77	2.66 [1.89, 4.52]	5.3 [3.8, 9.1]	0.941 [0.794, 0.983]	<0.001	0.778
<b>Peak flexion moment (Nm/kg/m)</b>	0.37 ± 0.20	0.42 ± 0.13	-0.05 ± 0.11	0.08 [0.05, 0.13]	19.5 [13.8, 33.1]	0.833 [0.301, 0.955]	0.005	0.162
<b>Peak extension moment* (Nm/kg/m)</b>	-1.75 ± 0.27	-1.71 ± 0.26	-0.04 ± 0.13	0.09 [0.07, 0.16]	5.5 [3.9, 9.3]	0.396 [-0.026, 0.777]	0.052	0.413
<b>Range sagittal moment* (Nm/kg/m)</b>	2.12 ± 0.37	2.13 ± 0.29	0.02 ± 0.20	0.14 [0.10, 0.23]	6.5 [4.6, 11.1]	0.397 [-0.024, 0.778]	0.050	0.818
<b>Peak valgus angle (°)</b>	4.98 ± 5.64	5.01 ± 7.75	0.03 ± 4.49	3.18 [2.25, 5.39]	63.6 [45.0, 107.9]	0.849 [0.457, 0.957]	0.003	0.984
<b>Peak varus angle (°)</b>	-3.06 ± 4.46	-4.09 ± 7.13	-1.02 ± 5.24	3.71 [2.63, 6.29]	103.7 [73.5, 176.1]	0.686 [-0.113, 0.910]	0.036	0.559
<b>Range coronal angle (°)</b>	8.05 ± 2.27	9.10 ± 3.66	-1.05 ± 2.57	1.82 [1.29, 3.08]	21.2 [15.0, 36.0]	0.708 [0.057, 0.914]	0.020	0.227
<b>Peak valgus moment (Nm/kg/m)</b>	0.39 ± 0.14	0.48 ± 0.17	-0.09 ± 0.10	0.07 [0.05, 0.12]	15.7 [11.1, 26.7]	0.799 [0.146, 0.948]	0.011	0.012
<b>Peak varus moment (Nm/kg/m)</b>	-0.23 ± 0.13	-0.23 ± 0.20	0.00 ± 0.12	0.08 [0.06, 0.14]	35.6 [25.2, 60.5]	0.854 [0.476, 0.958]	0.001	0.986
<b>Range coronal moment (Nm/kg/m)</b>	0.62 ± 0.15	0.71 ± 0.25	-0.09 ± 0.10	0.10 [0.07, 0.17]	15.5 [11.0, 26.3]	0.685 [-0.017, 0.914]	0.029	0.084
<b>Peak internal rotation angle (°)</b>	7.88 ± 6.52	8.36 ± 6.29	0.48 ± 4.56	3.22 [2.28, 5.47]	39.7 [28.1, 67.4]	0.820 [0.357, 0.949]	0.005	0.753
<b>Peak external rotation angle (°)</b>	-4.63 ± 6.40	-5.38 ± 8.97	0.75 ± 6.63	4.69 [3.32, 7.96]	93.7 [66.4, 159.1]	0.717 [-0.031, 0.919]	0.028	0.734
<b>Range transverse angle (°)</b>	12.51 ± 3.85	13.74 ± 5.43	1.23 ± 3.67	2.60 [1.84, 4.41]	19.8 [14.0, 33.6]	0.764 [0.219, 0.931]	0.010	0.322
<b>Peak internal rotation moment (Nm/kg/m)</b>	0.26 ± 0.09	0.26 ± 0.09	0.00 ± 0.08	0.06 [0.04, 0.09]	21.1 [15.0, 35.9]	0.632 [-0.056, 0.891]	0.035	0.939

<b>Peak external rotation moment (Nm/kg/m)</b>	-0.07 ± 0.05	-0.07 ± 0.06	0.01 ± 0.03	0.02 [0.01, 0.03]	29.2 [20.7, 49.6]	0.920 [0.712, 0.977]	<0.001	0.405
<b>Range transverse moment (Nm/kg/m)</b>	0.33 ± 0.09	0.34 ± 0.09	0.01 ± 0.07	0.05 [0.03, 0.08]	14.7 [10.4, 24.9]	0.625 [-0.053, 0.892]	0.039	0.662
<b>Peak vertical GRF (BW)</b>	4.05 ± 0.68	3.97 ± 0.69	0.08 ± 0.36	0.25 [0.18, 0.41]	6.3 [4.6, 10.2]	0.928 [0.781, 0.977]	<0.001	0.421
<b>Peak anterior GRF (BW)</b>	0.14 ± 0.13	0.11 ± 0.08	0.03 ± 0.11	0.07 [0.05, 0.12]	58.1 [42.1, 93.6]	0.675 [0.022, 0.895]	0.023	0.327
<b>Peak posterior GRF (BW)</b>	-0.12 ± 0.07	-0.12 ± 0.07	-0.01 ± 0.03	0.02 [0.02, 0.03]	18.5 [13.4, 29.9]	0.950 [0.848, 0.984]	<0.001	0.399
<b>Peak lateral GRF (BW)</b>	0.31 ± 0.13	0.30 ± 0.12	0.01 ± 0.07	0.05 [0.04, 0.08]	16.6 [12.1, 26.8]	0.911 [0.727, 0.971]	<0.001	0.547
<b>Peak medial GRF (BW)</b>	-0.60 ± 0.16	-0.60 ± 0.16	0.01 ± 0.06	0.04 [0.03, 0.06]	6.5 [4.7, 10.5]	0.971 [0.911, 0.991]	<0.001	0.551
<b>Time to PKF (s)</b>	0.24 ± 0.07	0.24 ± 0.07	0.00 ± 0.05	0.03 [0.02, 0.06]	14.0 [10.1, 22.5]	0.908 [0.712, 0.971]	<0.001	0.801

Note: \*indicates ICC below 0.500. BW = body weight, CI = confidence interval, CV = coefficient of variation, GRF = ground reaction forces, ICC = intraclass coefficient, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

### 5.1.2 CUT

Test–retest reliability results for the CUT task on the dominant leg are summarised in Table 12. Reliability of outcomes were *moderate* to *excellent* across most metrics between testing occasions (ICC 0.516–0.977). *Poor* ICCs were identified for metrics of peak extension moment (ICC 0.485, CV 11.5%), range sagittal moment (ICC 0.420, CV 10.1%), range transverse moment (ICC 0.466, CV 19.4%), peak anterior GRF (ICC 0.213, CV 59.1%), and peak medial GRF (ICC 0.185, CV 30.9%). Further, significant differences were observed between trials for the metrics of peak lateral GRF ( $p = 0.016$ ), and peak medial GRF ( $p = 0.000$ ). The CV% values were suboptimal across most metrics (CV 7.5–119.3%) with CV < 10% observed for only three metrics. The results for the non-dominant leg are displayed in Table 13. Reliability of metrics were mostly *moderate* to *excellent* between testing occasions (ICC 0.655–0.988). However, *poor* ICCs were identified for metrics of peak extension moment (ICC 0.394, CV 12.1%) and range sagittal moment (ICC 0.423, CV 11.0%). The CV% values were suboptimal across most metrics (CV 4.3–125.6%) with CV < 10% observed for only three metrics.

**Table 13** Between session reliability of metrics collected from the single-leg drop-land and cut (CUT) task on the dominant leg.

	<b>Trial A mean ± SD</b>	<b>Trial B mean ± SD</b>	<b>Difference mean ± SD</b>	<b>TE [lower, upper]</b>	<b>CV% [lower, upper]</b>	<b>ICC [95% CI]</b>	<b>ICC p-value</b>	<b>Paired t-test p-value</b>
<b>Peak flexion angle (°)</b>	66.51 ± 7.47	64.46 ± 6.69	2.05 ± 6.91	4.89 [3.58, 7.71]	7.5 [5.5, 11.8]	0.684 [0.098, 0.892]	0.016	0.270
<b>Peak extension angle (°)</b>	17.69 ± 4.58	18.16 ± 6.09	0.49 ± 5.24	3.71 [2.71, 5.84]	20.7 [15.1, 32.6]	0.703 [0.088, 0.901]	0.018	0.732
<b>Range sagittal angle (°)</b>	48.82 ± 5.59	46.30 ± 5.64	2.52 ± 5.11	3.61 [2.64, 5.69]	7.6 [5.6, 12.0]	0.706 [0.160, 0.900]	0.011	0.076
<b>Peak flexion moment (Nm/kg/m)</b>	0.27 ± 0.14	0.25 ± 0.14	0.02 ± 0.12	0.08 [0.06, 0.13]	31.8 [23.3, 50.2]	0.795 [0.263, 0.936]	0.005	0.529
<b>Peak extension moment* (Nm/kg/m)</b>	-1.76 ± 0.38	-1.82 ± 0.30	0.07 ± 0.29	0.21 [0.15, 0.32]	11.5 [8.4, 18.2]	0.485 [-0.116, 0.815]	0.071	0.386
<b>Range sagittal moment* (Nm/kg/m)</b>	2.03 ± 0.38	2.08 ± 0.35	0.05 ± 0.29	0.21 [0.15, 0.33]	10.1 [7.4, 15.9]	0.420 [-0.104, 0.779]	0.085	0.538
<b>Peak valgus angle (°)</b>	8.17 ± 5.89	9.42 ± 5.55	1.25 ± 5.06	3.58 [2.62, 5.64]	40.7 [29.8, 64.1]	0.758 [0.299, 0.918]	0.005	0.354
<b>Peak varus angle (°)</b>	-2.12 ± 4.38	-1.50 ± 4.51	0.62 ± 3.05	2.16 [1.58, 3.41]	119.3 [87.3, 188.1]	0.868 [0.615, 0.956]	<0.001	0.445
<b>Range coronal angle (°)</b>	10.29 ± 3.60	10.92 ± 2.66	0.63 ± 3.64	2.57 [1.88, 4.05]	24.2 [17.7, 38.2]	0.516 [-0.472, 0.838]	0.096	0.511
<b>Peak valgus moment (Nm/kg/m)</b>	0.36 ± 0.13	0.35 ± 0.10	0.01 ± 0.08	0.05 [0.04, 0.09]	15.4 [11.3, 24.3]	0.713 [0.030, 0.913]	0.021	0.484
<b>Peak varus moment (Nm/kg/m)</b>	-0.26 ± 0.16	-0.29 ± 0.20	0.03 ± 0.12	0.09 [0.06, 0.14]	32.2 [23.6, 50.8]	0.876 [0.643, 0.958]	<0.001	0.363
<b>Range coronal moment (Nm/kg/m)</b>	0.62 ± 0.17	0.64 ± 0.20	0.02 ± 0.14	0.10 [0.07, 0.15]	15.2 [11.1, 24.0]	0.622 [-0.057, 0.880]	0.038	0.662
<b>Peak internal rotation angle (°)</b>	8.25 ± 7.85	9.82 ± 5.42	1.57 ± 5.53	3.91 [2.87, 6.17]	43.3 [31.7, 68.3]	0.796 [0.412, 0.931]	0.002	0.292
<b>Peak external rotation angle (°)</b>	-6.39 ± 6.73	-5.94 ± 7.69	0.46 ± 5.93	4.19 [3.07, 6.61]	68.0 [49.8, 107.3]	0.807 [0.415, 0.936]	0.002	0.771
<b>Range transverse angle (°)</b>	14.64 ± 3.88	15.75 ± 5.26	1.11 ± 3.84	2.72 [1.99, 4.28]	17.9 [13.1, 28.2]	0.788 [0.392, 0.928]	0.002	0.281
<b>Peak internal rotation moment (Nm/kg/m)</b>	0.28 ± 0.11	0.23 ± 0.08	0.05 ± 0.11	0.08 [0.06, 0.13]	31.9 [23.4, 50.3]	0.546 [-0.110, 0.840]	0.050	0.133

<b>Peak external rotation moment (Nm/kg/m)</b>	-0.09 ± 0.09	-0.08 ± 0.06	0.01 ± 0.07	0.05 [0.04, 0.08]	61.8 [45.2, 97.5]	0.818 [0.562, 0.934]	<0.001	0.709
<b>Range transverse moment* (Nm/kg/m)</b>	0.36 ± 0.10	0.32 ± 0.07	0.05 ± 0.09	0.07 [0.05, 0.10]	19.4 [14.2, 30.6]	0.466 [-0.124, 0.805]	0.077	0.072
<b>Peak vertical GRF (BW)</b>	6.71 ± 2.50	7.09 ± 3.04	-0.38 ± 0.90	0.64 [0.47, 1.00]	9.2 [6.7, 14.5]	0.970 [0.910, 0.990]	<0.001	0.124
<b>Peak anterior GRF* (BW)</b>	0.37 ± 0.23	0.32 ± 0.20	0.04 ± 0.29	0.20 [0.15, 0.32]	59.1 [43.3, 93.3]	0.213 [-1.499, 0.741]	0.335	0.558
<b>Peak posterior GRF (BW)</b>	-0.79 ± 0.47	-0.91 ± 0.59	0.12 ± 0.23	0.16 [0.12, 0.26]	19.2 [14.1, 30.3]	0.943 [0.815, 0.981]	<0.001	0.073
<b>Peak lateral GRF (BW)</b>	0.14 ± 0.22	0.10 ± 0.20	0.04 ± 0.05	0.04 [0.03, 0.06]	30.4 [22.2, 47.9]	0.977 [0.892, 0.993]	<0.001	0.016
<b>Peak medial GRF* (BW)</b>	-0.85 ± 0.26	-0.35 ± 0.19	-0.50 ± 0.29	0.19 [0.14, 0.29]	30.9 [22.6, 48.7]	0.185 [-0.224, 0.618]	0.290	0.000
<b>Flight time (s)</b>	0.13 ± 0.05	0.13 ± 0.05	0.00 ± 0.03	0.02 [0.02, 0.04]	16.9 [12.4, 26.7]	0.893 [0.678, 0.964]	<0.001	0.770
<b>Time to PKF (s)</b>	0.29 ± 0.12	0.25 ± 0.08	0.04 ± 0.09	0.07 [0.05, 0.10]	25.0 [18.3, 39.5]	0.717 [0.199, 0.903]	0.009	0.118
<b>Stance time (s)</b>	0.56 ± 0.19	0.50 ± 0.14	0.06 ± 0.11	0.08 [0.06, 0.12]	14.6 [10.7, 23.0]	0.849 [0.520, 0.951]	0.001	0.054

Note: \*indicates ICC below 0.500. BW = body weight, CI = confidence interval, CV = coefficient of variation, GRF = ground reaction forces, ICC = intraclass coefficient, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

**Table 14** Between session reliability of metrics collected from the single-leg drop-land and cut (CUT) task on the non-dominant leg.

	Trial A mean $\pm$ SD	Trial B mean $\pm$ SD	Difference mean $\pm$ SD	TE [lower, upper]	CV% [lower, upper]	ICC [95% CI]	ICC p-value	Paired t-test p-value
Peak flexion angle (°)	67.01 $\pm$ 6.72	64.50 $\pm$ 6.60	2.52 $\pm$ 3.96	2.80 [2.01, 4.62]	4.3 [3.1, 7.0]	0.858 [0.475, 0.960]	0.002	0.068
Peak extension angle (°)	18.15 $\pm$ 3.11	17.67 $\pm$ 4.23	0.48 $\pm$ 2.87	2.03 [1.45, 3.35]	11.3 [8.1, 18.7]	0.778 [0.217, 0.936]	0.011	0.617
Range sagittal angle (°)	48.86 $\pm$ 5.85	46.82 $\pm$ 5.63	2.04 $\pm$ 3.96	2.80 [2.01, 4.62]	5.8 [4.2, 9.7]	0.813 [0.379, 0.945]	0.003	0.134
Peak flexion moment (Nm/kg/m)	0.36 $\pm$ 0.12	0.36 $\pm$ 0.11	0.00 $\pm$ 0.06	0.04 [0.30, 0.07]	11.5 [8.2, 18.9]	0.734 [0.021, 0.931]	0.021	0.896
Peak extension moment* (Nm/kg/m)	-1.66 $\pm$ 0.36	-1.72 $\pm$ 0.18	0.06 $\pm$ 0.29	0.21 [0.15, 0.34]	12.1 [8.7, 20.2]	0.394 [-0.134, 0.779]	0.102	0.539
Range sagittal moment* (Nm/kg/m)	2.02 $\pm$ 0.44	2.08 $\pm$ 0.27	0.06 $\pm$ 0.32	0.22 [0.16, 0.37]	11.0 [7.9, 18.1]	0.423 [-0.105, 0.797]	0.086	0.591
Peak valgus angle (°)	7.54 $\pm$ 6.37	7.61 $\pm$ 5.54	0.07 $\pm$ 4.50	3.18 [2.28, 5.25]	42.0 [30.1, 69.3]	0.794 [0.250, 0.941]	0.009	0.961
Peak varus angle (°)	-2.41 $\pm$ 4.93	-2.04 $\pm$ 4.49	0.36 $\pm$ 3.96	2.80 [2.01, 4.62]	125.6 [90.1, 207.4]	0.728 [0.006, 0.923]	0.025	0.782
Range coronal angle (°)	9.94 $\pm$ 3.29	9.65 $\pm$ 3.22	0.29 $\pm$ 1.89	1.33 [0.96, 2.21]	13.7 [9.8, 22.6]	0.887 [0.607, 0.967]	0.001	0.645
Peak valgus moment (Nm/kg/m)	0.40 $\pm$ 0.16	0.39 $\pm$ 0.12	0.01 $\pm$ 0.08	0.06 [0.04, 0.09]	14.3 [10.3, 23.6]	0.749 [0.059, 0.933]	0.018	0.657
Peak varus moment (Nm/kg/m)	-0.21 $\pm$ 0.15	-0.19 $\pm$ 0.17	0.02 $\pm$ 0.07	0.05 [0.04, 0.09]	26.4 [19.0, 43.6]	0.907 [0.538, 0.976]	0.001	0.343
Range coronal moment (Nm/kg/m)	0.61 $\pm$ 0.23	0.57 $\pm$ 0.19	0.04 $\pm$ 0.09	0.07 [0.05, 0.11]	11.3 [8.1, 18.6]	0.743 [0.029, 0.934]	0.020	0.267
Peak internal rotation angle (°)	10.12 $\pm$ 6.35	10.38 $\pm$ 5.38	0.26 $\pm$ 4.05	2.86 [2.05, 4.72]	27.9 [20.0, 46.1]	0.835 [0.408, 0.953]	0.004	0.849
Peak external rotation angle (°)	-4.80 $\pm$ 5.78	-4.84 $\pm$ 5.20	0.04 $\pm$ 4.03	2.85 [2.04, 4.70]	59.0 [42.3, 97.5]	0.808 [0.304, 0.945]	0.007	0.977
Range transverse angle (°)	14.92 $\pm$ 4.84	15.22 $\pm$ 5.20	0.30 $\pm$ 2.84	2.0 [1.4, 3.3]	13.3 [9.6, 22.0]	0.895 [0.629, 0.970]	0.001	0.754
Peak internal rotation moment (Nm/kg/m)	0.25 $\pm$ 0.10	0.26 $\pm$ 0.12	0.00 $\pm$ 0.10	0.07 [0.05, 0.11]	26.6 [19.1, 44.0]	0.719 [0.091, 0.919]	0.015	0.942

<b>Peak external rotation moment (Nm/kg/m)</b>	-0.07 ± 0.05	-0.07 ± 0.06	0.00 ± 0.03	0.02 [0.01, 0.03]	28.2 [20.2, 46.5]	0.905 [0.677, 0.973]	<0.001	0.940
<b>Range transverse moment (Nm/kg/m)</b>	0.32 ± 0.12	0.32 ± 0.13	0.00 ± 0.09	0.07 [0.05, 0.11]	20.4 [14.6, 33.7]	0.710 [0.027, 0.919]	0.021	0.922
<b>Peak vertical GRF (BW)</b>	4.34 ± 1.67	4.42 ± 1.66	-0.08 ± 0.37	0.26 [0.19, 0.41]	5.9 [4.3, 9.3]	0.988 [0.965, 0.996]	<0.001	0.434
<b>Peak anterior GRF (BW)</b>	0.25 ± 0.29	0.21 ± 0.26	0.03 ± 0.09	0.06 [0.04, 0.10]	26.6 [19.5, 41.9]	0.974 [0.923, 0.991]	<0.001	0.186
<b>Peak posterior GRF (BW)</b>	-0.45 ± 0.12	-0.49 ± 0.15	0.04 ± 0.13	0.09 [0.07, 0.15]	20.2 [14.8, 31.9]	0.655 [0.016, 0.882]	0.023	0.964
<b>Peak lateral GRF (BW)</b>	0.08 ± 0.10	0.06 ± 0.09	0.01 ± 0.06	0.04 [0.03, 0.07]	60.2 [44.1, 94.9]	0.898 [0.705, 0.966]	<0.001	0.380
<b>Peak medial GRF (BW)</b>	-0.52 ± 0.16	-0.54 ± 0.16	0.02 ± 0.09	0.06 [0.05, 0.10]	12.0 [8.8, 18.9]	0.916 [0.758, 0.972]	<0.001	0.306
<b>Flight time (s)</b>	0.14 ± 0.05	0.14 ± 0.06	0.01 ± 0.03	0.02 [0.01, 0.03]	13.4 [9.8, 21.1]	0.947 [0.845, 0.982]	<0.001	0.418
<b>Time to PKF (s)</b>	0.26 ± 0.09	0.26 ± 0.10	0.00 ± 0.07	0.05 [0.03, 0.07]	18.0 [13.2, 28.4]	0.875 [0.620, 0.958]	<0.001	0.964
<b>Stance time (s)</b>	0.51 ± 0.13	0.50 ± 0.11	0.01 ± 0.08	0.05 [0.04, 0.08]	10.7 [7.8, 16.8]	0.914 [0.744, 0.971]	<0.001	0.713

Note: \*indicates ICC below 0.500. BW = body weight, CI = confidence interval, CV = coefficient of variation, GRF = ground reaction forces, ICC = intraclass coefficient, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

### 5.1.3 ROT

For the ROT task on the dominant leg, outcomes of test–retest reliability are summarised in Table 14. Reliability of outcomes were *moderate* to *excellent* across most metrics between testing occasions (ICC 0.553–0.949). However, *poor* ICCs were identified for metrics of peak extension moment (ICC 0.489, CV 8.3%), range sagittal moment (ICC 0.446, CV 9.4%), peak lateral GRF (ICC 0.475, CV 402.2%). Additionally, significant differences were observed between trials for the metrics of peak external rotation angle ( $p = 0.003$ ), range sagittal angle ( $p = 0.028$ ), and peak lateral GRF ( $p = 0.004$ ). The CV% values were suboptimal across most metrics (CV 6.9-402.2%) with CV < 10% observed for only six metrics. Reliability outcomes of the non-dominant leg are presented in Table 15 showing reliability of outcomes were *moderate* to *excellent* across most metrics between testing occasions (ICC 0.530–0.977). *Poor* ICCs were identified for metrics of peak extension angle (ICC 0.290, CV 7.5%), range coronal angle (ICC 0.336, CV 24.5%), and peak lateral GRF (ICC 0.489, CV 702.8%). The CV% values were suboptimal across most metrics (CV 5.8-702.8%) with CV < 10% observed for only four metrics.

**Table 15** Between session reliability of metrics collected from the single-leg rotating drop-land and hop (ROT) task on the dominant leg.

	<b>Trial A mean ± SD</b>	<b>Trial B mean ± SD</b>	<b>Difference mean ± SD</b>	<b>TE [lower, upper]</b>	<b>CV% [lower, upper]</b>	<b>ICC [95% CI]</b>	<b>ICC p-value</b>	<b>Paired t-test p-value</b>
<b>Peak flexion angle (°)</b>	62.23 ± 9.02	62.25 ± 8.51	0.01 ± 6.10	4.31 [3.16, 6.80]	6.9 [5.1, 10.9]	0.870 [0.607, 0.957]	<0.001	0.993
<b>Peak extension angle (°)</b>	14.72 ± 4.62	18.23 ± 5.50	3.51 ± 3.72	2.63 [1.93, 4.15]	16.0 [11.7, 25.2]	0.749 [-0.071, 0.927]	0.032	0.003
<b>Range sagittal angle (°)</b>	47.51 ± 6.07	44.01 ± 5.23	-3.50 ± 5.51	3.90 [2.85, 6.14]	8.5 [6.2, 13.4]	0.625 [-0.079, 0.873]	0.035	0.028
<b>Peak flexion moment (Nm/kg/m)</b>	0.40 ± 0.13	0.42 ± 0.14	0.02 ± 0.11	0.08 [0.06, 0.13]	19.6 [14.3, 30.9]	0.710 [0.046, 0.910]	0.019	0.472
<b>Peak extension moment* (Nm/kg/m)</b>	-1.59 ± 0.34	-1.59 ± 0.24	-0.01 ± 0.19	0.13 [0.10, 0.21]	8.3 [6.1, 13.1]	0.489 [-0.072, 0.820]	0.061	0.897
<b>Range sagittal moment* (Nm/kg/m)</b>	1.99 ± 0.41	2.01 ± 0.26	0.02 ± 0.27	0.19 [0.14, 0.30]	9.4 [6.9, 14.9]	0.446 [-0.088, 0.795]	0.075	0.828
<b>Peak valgus angle (°)</b>	5.68 ± 5.09	6.30 ± 5.26	0.62 ± 3.50	2.47 [1.81, 3.90]	41.3 [30.3, 65.2]	0.875 [0.632, 0.958]	<0.001	0.505
<b>Peak varus angle (°)</b>	-1.69 ± 4.38	-1.01 ± 5.40	0.68 ± 3.26	2.30 [1.69, 3.63]	170.1 [124.5, 268.3]	0.879 [0.647, 0.959]	<0.001	0.434
<b>Range coronal angle (°)</b>	7.37 ± 2.22	7.31 ± 2.12	0.06 ± 2.19	1.55 [1.13, 2.44]	21.1 [15.5, 33.3]	0.672 [-0.023, 0.892]	0.027	0.918
<b>Peak valgus moment (Nm/kg/m)</b>	0.31 ± 0.14	0.28 ± 0.08	-0.03 ± 0.13	0.08 [0.06, 0.13]	28.3 [20.7, 44.6]	0.669 [0.052, 0.889]	0.019	0.362
<b>Peak varus moment (Nm/kg/m)</b>	-0.27 ± 0.15	-0.28 ± 0.16	0.00 ± 0.12	0.08 [0.06, 0.14]	30.0 [22.0, 47.3]	0.812 [0.412, 0.938]	0.002	0.951
<b>Range coronal moment (Nm/kg/m)</b>	0.59 ± 0.20	0.56 ± 0.19	-0.03 ± 0.13	0.09 [0.07, 0.14]	15.7 [11.5, 24.8]	0.680 [-0.015, 0.905]	0.028	0.422
<b>Peak internal rotation angle (°)</b>	5.72 ± 6.16	7.36 ± 6.42	-1.63 ± 4.49	3.17 [2.32, 5.00]	48.5 [35.5, 76.5]	0.846 [0.556, 0.948]	<0.001	0.181
<b>Peak external rotation angle (°)</b>	-4.61 ± 6.82	-3.79 ± 7.80	-0.82 ± 4.64	3.28 [2.40, 5.17]	78.1 [57.2, 123.1]	0.892 [0.683, 0.964]	<0.001	0.503
<b>Range transverse angle (°)</b>	10.34 ± 3.63	11.14 ± 3.42	-0.81 ± 2.99	2.12 [1.55, 3.34]	19.7 [14.4, 31.1]	0.779 [0.363, 0.925]	0.003	0.314
<b>Peak internal rotation moment (Nm/kg/m)</b>	0.36 ± 0.11	0.35 ± 0.07	-0.01 ± 0.09	0.06 [0.05, 0.10]	17.5 [12.8, 27.6]	0.553 [-0.095, 0.849]	0.053	0.727

<b>Peak external rotation moment (Nm/kg/m)</b>	-0.03 ± 0.03	-0.03 ± 0.02	0.00 ± 0.03	0.02 [0.01, 0.03]	60.6 [44.4, 95.6]	0.758 [0.434, 0.911]	<0.001	0.745
<b>Range transverse moment* (Nm/kg/m)</b>	0.39 ± 0.10	0.38 ± 0.07	0.01 ± 0.09	0.06 [0.04, 0.10]	15.8 [11.6, 24.9]	0.481 [-0.105, 0.814]	0.070	0.648
<b>Peak vertical GRF (BW)</b>	3.92 ± 0.73	3.78 ± 0.74	0.14 ± 0.42	0.30 [0.22, 0.47]	7.7 [5.7, 12.2]	0.907 [0.729, 0.968]	<0.001	0.213
<b>Peak anterior GRF (BW)</b>	0.55 ± 0.28	0.52 ± 0.27	0.03 ± 0.12	0.09 [0.06, 0.14]	16.1 [11.8, 25.3]	0.949 [0.851, 0.983]	<0.001	0.391
<b>Peak posterior GRF (BW)</b>	-0.45 ± 0.13	-0.46 ± 0.13	0.01 ± 0.10	0.07 [0.05, 0.11]	15.7 [11.5, 24.8]	0.833 [0.496, 0.944]	0.001	0.746
<b>Peak lateral GRF* (BW)</b>	0.01 ± 0.02	-0.01 ± 0.02	0.02 ± 0.02	0.02 [0.01, 0.03]	402.2 [294.5, 634.4]	0.475 [-0.374, 0.818]	0.114	0.004
<b>Peak medial GRF (BW)</b>	-0.40 ± 0.12	-0.40 ± 0.10	0.00 ± 0.06	0.04 [0.03, 0.07]	10.8 [7.9, 17.0]	0.916 [0.748, 0.972]	<0.001	0.975
<b>Flight time (s)</b>	0.27 ± 0.06	0.27 ± 0.07	0.00 ± 0.04	0.03 [0.02, 0.04]	9.8 [7.2, 15.4]	0.919 [0.758, 0.973]	<0.001	0.694
<b>Time to PKF (s)</b>	0.25 ± 0.09	0.25 ± 0.07	0.00 ± 0.08	0.06 [0.04, 0.09]	22.6 [16.6, 35.7]	0.688 [0.033, 0.897]	0.022	0.823
<b>Stance time (s)</b>	0.56 ± 0.15	0.53 ± 0.17	0.02 ± 0.09	0.06 [0.05, 0.10]	11.7 [8.6, 18.5]	0.913 [0.749, 0.971]	<0.001	0.354
<b>Jump height (cm)</b>	9.28 ± 4.19	9.77 ± 5.27	-0.49 ± 2.38	1.68 [1.23, 2.65]	17.6 [12.9, 27.8]	0.935 [0.810, 0.978]	<0.001	0.435

Note: \*indicates ICC below 0.500. BW = body weight, CI = confidence interval, CV = coefficient of variation, GRF = ground reaction forces, ICC = intraclass coefficient, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

**Table 16** Between session reliability of metrics collected from the single-leg rotating drop-land and hop (ROT) task on the non-dominant leg.

	Trial A mean ± SD	Trial B mean ± SD	Difference mean ± SD	TE [lower, upper]	CV% [lower, upper]	ICC [95% CI]	ICC p- value	Paired t- test p- value
Peak flexion angle (°)	62.19 ± 6.38	61.55 ± 7.08	0.64 ± 5.99	4.23 [3.07, 6.82]	6.8 [5.0, 11.0]	0.743 [0.177, 0.918]	0.012	0.707
Peak extension angle* (°)	15.08 ± 4.15	14.69 ± 2.73	0.39 ± 4.39	3.10 [2.25, 5.00]	20.8 [15.1, 33.6]	0.290 [-1.457, 0.779]	0.283	0.754
Range sagittal angle (°)	47.11 ± 4.85	46.86 ± 4.91	0.25 ± 4.22	2.99 [2.16, 4.81]	6.4 [4.6, 10.2]	0.761 [0.229, 0.924]	0.009	0.836
Peak flexion moment (Nm/kg/m)	0.41 ± 0.14	0.45 ± 0.17	-0.05 ± 0.08	0.06 [0.04, 0.10]	13.8 [10.0, 22.2]	0.768 [0.074, 0.936]	0.016	0.062
Peak extension moment (Nm/kg/m)	-1.54 ± 0.34	-1.56 ± 0.33	0.02 ± 0.23	0.16 [0.12, 0.26]	10.6 [7.7, 17.1]	0.531 [-0.037, 0.847]	0.044	0.785
Range sagittal moment* (Nm/kg/m)	1.49 ± 0.39	2.01 ± 0.38	0.06 ± 0.21	0.15 [0.11, 0.24]	7.5 [5.5, 12.1]	0.492 [-0.024, 0.827]	0.041	0.286
Peak valgus angle (°)	4.97 ± 6.09	4.77 ± 6.48	-0.20 ± 4.00	2.83 [2.05, 4.56]	58.1 [42.1, 93.6]	0.885 [0.636, 0.963]	<0.001	0.856
Peak varus angle (°)	-2.62 ± 5.92	-2.65 ± 5.99	-0.03 ± 3.81	2.70 [1.96, 4.35]	102.4 [74.2, 164.9]	0.884 [0.631, 0.963]	<0.001	0.975
Range coronal angle* (°)	7.59 ± 2.64	7.42 ± 1.44	0.17 ± 2.61	1.84 [1.34, 2.97]	24.5 [17.8, 39.5]	0.336 [-1.298, 0.793]	0.248	0.817
Peak valgus moment (Nm/kg/m)	0.34 ± 0.15	0.38 ± 0.17	-0.04 ± 0.12	0.08 [0.06, 0.13]	22.7 [16.4, 36.6]	0.791 [0.257, 0.937]	0.006	0.238
Peak varus moment (Nm/kg/m)	-0.21 ± 0.15	-0.22 ± 0.18	0.00 ± 0.09	0.06 [0.05, 0.10]	29.8 [21.6, 48.0]	0.901 [0.645, 0.970]	<0.001	0.885
Range coronal moment (Nm/kg/m)	0.56 ± 0.17	0.60 ± 0.20	-0.04 ± 0.10	0.07 [0.05, 0.12]	12.6 [9.1, 20.3]	0.717 [0.011, 0.921]	0.023	0.149
Peak internal rotation angle (°)	8.00 ± 6.94	8.94 ± 6.95	0.94 ± 4.50	3.18 [2.31, 5.13]	37.6 [27.3, 60.6]	0.876 [0.622, 0.960]	<0.001	0.466
Peak external rotation angle (°)	-4.64 ± 7.24	-3.91 ± 7.74	-0.73 ± 5.96	4.21 [3.05, 6.79]	98.6 [71.5, 158.8]	0.805 [0.383, 0.938]	0.003	0.665
Range transverse angle (°)	12.64 ± 3.86	12.84 ± 4.04	0.20 ± 4.07	2.88 [2.09, 4.63]	22.6 [16.4, 36.4]	0.618 [-0.265, 0.879]	0.055	0.859
Peak internal rotation moment (Nm/kg/m)	0.32 ± 0.08	0.35 ± 0.10	0.02 ± 0.07	0.05 [0.04, 0.08]	15.3 [11.1, 24.6]	0.573 [-0.090, 0.861]	0.049	0.239

<b>Peak external rotation moment (Nm/kg/m)</b>	-0.03 ± 0.03	-0.04 ± 0.05	0.01 ± 0.04	0.03 [0.02, 0.04]	73.0 [52.9, 117.6]	0.808 [0.541, 0.932]	<0.001	0.620
<b>Range transverse moment (Nm/kg/m)</b>	0.36 ± 0.08	0.39 ± 0.11	0.03 ± 0.08	0.06 [0.04, 0.09]	15.1 [11.0, 24.4]	0.530 [-0.108, 0.842]	0.060	0.195
<b>Peak vertical GRF (BW)</b>	3.89 ± 0.83	3.93 ± 0.70	-0.04 ± 0.32	0.23 [0.17, 0.36]	5.8 [4.2, 9.1]	0.957 [0.873, 0.986]	<0.001	0.663
<b>Peak anterior GRF (BW)</b>	0.51 ± 0.23	0.47 ± 0.20	0.05 ± 0.15	0.11 [0.08, 0.17]	22.1 [16.2, 34.8]	0.851 [0.572, 0.949]	<0.001	0.255
<b>Peak posterior GRF (BW)</b>	-0.40 ± 0.10	-0.44 ± 0.13	0.04 ± 0.10	0.07 [0.05, 0.11]	16.7 [12.2, 26.4]	0.778 [0.367, 0.924]	0.003	0.061
<b>Peak lateral GRF* (BW)</b>	0.01 ± 0.04	-0.01 ± 0.02	0.02 ± 0.04	0.03 [0.02, 0.04]	702.8 [514.5, 1108.3]	0.489 [-0.336, 0.820]	0.088	0.084
<b>Peak medial GRF (BW)</b>	-0.39 ± 0.11	-0.42 ± 0.13	0.03 ± 0.09	0.07 [0.05, 0.10]	16.5 [12.1, 26.1]	0.809 [0.453, 0.935]	0.001	0.240
<b>Flight time (s)</b>	0.27 ± 0.07	0.27 ± 0.07	0.00 ± 0.02	0.02 [0.01, 0.03]	6.4 [4.7, 10.1]	0.967 [0.902, 0.989]	5.016	0.637
<b>Time to PKF (s)</b>	0.26 ± 0.09	0.23 ± 0.06	0.04 ± 0.07	0.05 [0.04, 0.08]	21.2 [15.5, 33.4]	0.648 [0.011, 0.879]	0.024	0.061
<b>Stance time (s)</b>	0.55 ± 0.16	0.50 ± 0.13	0.05 ± 0.11	0.08 [0.06, 0.12]	14.7 [10.8, 23.2]	0.815 [0.451, 0.938]	0.001	0.093
<b>Jump height (cm)</b>	9.55 ± 4.78	9.31 ± 4.40	0.24 ± 1.41	1.00 [0.73, 1.57]	10.6 [7.7, 16.7]	0.977 [0.933, 0.992]	<0.001	0.519

Note: \*indicates ICC below 0.500. BW = body weight, CI = confidence interval, CV = coefficient of variation, GRF = ground reaction forces, ICC = intraclass coefficient, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

#### 5.1.4 VERT

The outcomes (Table 16) of test–retest reliability for the VERT task on the dominant leg. Reliability of outcomes were *moderate* to *excellent* across most metrics between testing occasions (ICC 0.520–0.913). However, *poor* ICCs were observed for metrics of peak extension moment (ICC 0.472, CV 6.5%), range sagittal moment (ICC 0.322, CV 7.0%), and range transverse moment (ICC 0.496, CV 16.6%). The CV% values were suboptimal across most metrics (CV 6.5-104.8%) with CV < 10 % observed for only four metrics. Table 17 displays the non-dominant leg results, showing reliability of metrics were mostly *moderate* to *excellent* between testing occasions (ICC 0.551–0.920). *Poor* ICCs were identified for metrics of peak extension angle (ICC 0.477, CV 17.4%), peak extension moment (ICC 0.472, CV 10.1%), range sagittal moment (ICC 0.422, CV 8.5%), and time to PKF (ICC 0.406, CV 46.8%). The CV% values were suboptimal across most metrics (CV 8.4-115.3%) with CV < 10% observed for only five metrics.

**Table 17** Between session reliability of metrics collected from the single-leg drop-land and vertical hop (VERT) task on the dominant leg.

	<b>Trial A mean ± SD</b>	<b>Trial B mean ± SD</b>	<b>Difference mean ± SD</b>	<b>TE [lower, upper]</b>	<b>CV% [lower, upper]</b>	<b>ICC [95% CI]</b>	<b>ICC p- value</b>	<b>Paired t- test p- value</b>
<b>Peak flexion angle (°)</b>	63.81 ± 9.08	63.20 ± 8.10	-0.61 ± 6.15	4.35 [3.15, 7.01]	6.8 [5.0, 11.0]	0.849 [0.523, 0.952]	0.001	0.726
<b>Peak extension angle (°)</b>	15.44 ± 4.87	18.11 ± 5.66	2.67 ± 4.73	3.35 [2.43, 5.39]	19.9 [14.5, 32.1]	0.688 [0.071, 0.899]	0.018	0.060
<b>Range sagittal angle (°)</b>	48.37 ± 8.70	45.09 ± 5.83	-3.28 ± 6.43	4.55 [3.30, 7.32]	9.7 [7.1, 15.7]	0.720 [0.167, 0.909]	0.011	0.086
<b>Peak flexion moment (Nm/kg/m)</b>	0.41 ± 0.16	0.39 ± 0.16	-0.02 ± 0.09	0.07 [0.05, 0.11]	16.5 [12.0, 26.6]	0.764 [0.061, 0.935]	0.017	0.526
<b>Peak extension moment* (Nm/kg/m)</b>	-1.67 ± 0.34	-1.69 ± 0.27	0.01 ± 0.15	0.11 [0.08, 0.18]	6.5 [4.7, 10.5]	0.472 [-0.039, 0.816]	0.052	0.769
<b>Range sagittal moment* (Nm/kg/m)</b>	2.08 ± 0.34	2.08 ± 0.29	0.00 ± 0.21	0.15 [0.11, 0.24]	7.0 [5.1, 11.3]	0.322 [-0.038, 0.708]	0.075	0.946
<b>Peak valgus angle (°)</b>	4.65 ± 5.25	6.21 ± 5.31	1.56 ± 3.93	2.78 [2.01, 4.47]	51.2 [37.1, 82.4]	0.816 [0.451, 0.940]	0.001	0.174
<b>Peak varus angle (°)</b>	-2.83 ± 3.42	-1.12 ± 4.56	1.71 ± 2.93	2.07 [1.50, 3.34]	104.8 [76.0, 168.9]	0.805 [0.366, 0.938]	0.003	0.054
<b>Range coronal angle (°)</b>	7.48 ± 2.92	7.33 ± 1.84	0.15 ± 2.34	1.66 [1.20, 2.67]	22.4 [16.2, 36.0]	0.686 [-0.023, 0.901]	0.027	0.822
<b>Peak valgus moment (Nm/kg/m)</b>	0.37 ± 0.15	0.35 ± 0.17	-0.02 ± 0.14	0.10 [0.07, 0.16]	27.1 [19.6, 43.7]	0.706 [0.061, 0.909]	0.018	0.618
<b>Peak varus moment (Nm/kg/m)</b>	-0.21 ± 0.10	-0.22 ± 0.16	0.01 ± 0.10	0.07 [0.05, 0.11]	32.1 [23.3, 51.7]	0.842 [0.413, 0.951]	0.002	0.789
<b>Range coronal moment (Nm/kg/m)</b>	0.58 ± 0.21	0.57 ± 0.23	-0.01 ± 0.11	0.08 [0.06, 0.13]	13.9 [10.1, 22.4]	0.740 [0.029, 0.929]	0.020	0.701
<b>Peak internal rotation angle (°)</b>	6.57 ± 5.87	7.06 ± 5.58	-0.48 ± 3.98	2.82 [2.04, 4.54]	41.3 [30.0, 66.6]	0.858 [0.554, 0.954]	0.001	0.668
<b>Peak external rotation angle (°)</b>	-5.42 ± 6.11	-4.28 ± 7.13	-1.14 ± 5.19	3.67 [2.66, 5.91]	75.6 [54.8, 121.8]	0.808 [0.412, 0.938]	0.002	0.441
<b>Range transverse angle (°)</b>	12.00 ± 3.66	11.34 ± 3.97	0.66 ± 3.03	2.14 [1.55, 3.45]	18.3 [13.3, 29.5]	0.802 [0.392, 0.936]	0.003	0.447
<b>Peak internal rotation moment (Nm/kg/m)</b>	0.32 ± 0.09	0.30 ± 0.10	-0.02 ± 0.07	0.05 [0.03, 0.08]	15.6 [11.3, 25.2]	0.612 [-0.047, 0.881]	0.039	0.326

<b>Peak external rotation moment (Nm/kg/m)</b>	-0.03 ± 0.03	-0.03 ± 0.03	-0.01 ± 0.04	0.03 [0.02, 0.04]	86.5 [62.7, 139.4]	0.655 [0.183, 0.878]	0.008	0.597
<b>Range transverse moment* (Nm/kg/m)</b>	0.34 ± 0.08	0.33 ± 0.11	0.01 ± 0.08	0.06 [0.04, 0.09]	16.6 [12.0, 26.8]	0.496 [-0.092, 0.827]	0.065	0.549
<b>Peak vertical GRF (BW)</b>	3.87 ± 0.85	3.84 ± 0.71	0.03 ± 0.62	0.44 [0.32, 0.70]	11.4 [8.4, 18.1]	0.821 [0.454, 0.940]	0.002	0.851
<b>Peak anterior GRF (BW)</b>	0.20 ± 0.17	0.16 ± 0.11	0.04 ± 0.13	0.09 [0.07, 0.14]	49.7 [36.4, 78.4]	0.745 [0.267, 0.913]	0.006	0.281
<b>Peak posterior GRF (BW)</b>	-0.15 ± 0.07	-0.15 ± 0.08	-0.01 ± 0.06	0.04 [0.03, 0.06]	26.5 [19.4, 41.8]	0.844 [0.531, 0.948]	0.001	0.705
<b>Peak lateral GRF (BW)</b>	0.20 ± 0.09	0.20 ± 0.09	0.00 ± 0.06	0.05 [0.03, 0.07]	22.4 [16.4, 35.4]	0.867 [0.598, 0.956]	<0.001	0.854
<b>Peak medial GRF (BW)</b>	-0.55 ± 0.17	-0.57 ± 0.16	0.02 ± 0.10	0.07 [0.05, 0.11]	12.1 [8.9, 19.1]	0.913 [0.744, 0.970]	<0.001	0.478
<b>Flight time (s)</b>	0.29 ± 0.08	0.28 ± 0.07	0.01 ± 0.09	0.06 [0.05, 0.10]	22.4 [16.4, 35.4]	0.520 [-0.517, 0.842]	0.100	0.760
<b>Time to PKF (s)</b>	0.25 ± 0.08	0.24 ± 0.09	0.01 ± 0.09	0.06 [0.04, 0.10]	24.4 [17.9, 38.5]	0.662 [-0.042, 0.888]	0.029	0.715
<b>Stance time (s)</b>	0.56 ± 0.16	0.52 ± 0.15	0.04 ± 0.15	0.10 [0.08, 0.16]	19.4 [14.2, 30.6]	0.713 [0.171, 0.902]	0.011	0.314
<b>Jump height (cm)</b>	10.90 ± 6.38	10.22 ± 5.11	0.68 ± 6.23	4.41 [3.23, 6.95]	41.7 [30.6, 65.8]	0.603 [-0.228, 0.868]	0.052	0.680

Note: \*indicates ICC below 0.500. BW = body weight, CI = confidence interval, CV = coefficient of variation, GRF = ground reaction forces, ICC = intraclass coefficient, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

**Table 18** Between session reliability of metrics collected from the single-leg drop-land and vertical hop (VERT) task on the non-dominant leg.

	<b>Trial A mean ± SD</b>	<b>Trial B mean ± SD</b>	<b>Difference mean ± SD</b>	<b>TE [lower, upper]</b>	<b>CV% [lower, upper]</b>	<b>ICC [95% CI]</b>	<b>ICC p- value</b>	<b>Paired t- test p- value</b>
<b>Peak flexion angle (°)</b>	62.01 ± 8.83	62.74 ± 7.04	-0.73 ± 7.43	5.26 [3.81, 8.47]	8.4 [6.1, 13.6]	0.710 [0.064, 0.908]	0.020	0.730
<b>Peak extension angle* (°)</b>	15.58 ± 3.58	16.15 ± 3.25	-0.57 ± 3.90	2.75 [2.00, 4.44]	17.4 [12.6, 28.0]	0.477 [-0.712, 0.835]	0.135	0.605
<b>Range sagittal angle (°)</b>	46.44 ± 7.55	46.59 ± 6.25	-0.15 ± 5.53	3.91 [2.83, 6.29]	8.4 [6.1, 13.5]	0.805 [0.374, 0.938]	0.004	0.921
<b>Peak flexion moment (Nm/kg/m)</b>	0.37 ± 0.13	0.40 ± 0.14	-0.04 ± 0.09	0.06 [0.04, 0.10]	16.0 [11.6, 25.7]	0.750 [0.005, 0.930]	0.018	0.168
<b>Peak extension moment* (Nm/kg/m)</b>	-1.63 ± 0.33	-1.61 ± 0.28	-0.02 ± 0.23	0.16 [0.12, 0.26]	10.1 [7.4, 16.3]	0.472 [-0.052, 0.815]	0.057	0.730
<b>Range sagittal moment* (Nm/kg/m)</b>	2.00 ± 0.38	2.01 ± 0.30	0.01 ± 0.24	0.17 [0.12, 0.28]	8.5 [6.2, 13.8]	0.422 [-0.043, 0.785]	0.060	0.856
<b>Peak valgus angle (°)</b>	4.92 ± 6.36	5.74 ± 7.65	0.82 ± 5.08	3.59 [2.61, 5.79]	67.5 [48.9, 108.7]	0.843 [0.513, 0.950]	0.001	0.571
<b>Peak varus angle (°)</b>	-2.81 ± 4.79	-2.62 ± 5.66	0.19 ± 4.42	3.13 [2.27, 5.04]	115.3 [83.6, 185.8]	0.776 [0.277, 0.929]	0.007	0.878
<b>Range coronal angle (°)</b>	7.73 ± 2.65	8.35 ± 3.34	-0.63 ± 3.26	2.31 [1.67, 3.71]	28.7 [20.8, 46.2]	0.551 [-0.422, 0.857]	0.083	0.500
<b>Peak valgus moment (Nm/kg/m)</b>	0.39 ± 0.16	0.35 ± 0.17	0.04 ± 0.10	0.07 [0.05, 0.11]	19.0 [13.8, 30.7]	0.765 [0.076, 0.934]	0.016	0.199
<b>Peak varus moment (Nm/kg/m)</b>	-0.19 ± 0.11	-0.22 ± 0.19	-0.03 ± 0.13	0.09 [0.07, 0.15]	44.3 [32.1, 71.4]	0.834 [0.556, 0.944]	<0.001	0.433
<b>Range coronal moment (Nm/kg/m)</b>	0.58 ± 0.19	0.57 ± 0.26	0.01 ± 0.11	0.08 [0.06, 0.13]	13.9 [10.0, 22.3]	0.752 [0.039, 0.933]	0.018	0.811
<b>Peak internal rotation angle (°)</b>	8.37 ± 5.95	8.73 ± 7.19	0.37 ± 4.06	2.87 [2.08, 4.62]	33.6 [24.3, 54.1]	0.893 [0.664, 0.966]	<0.001	0.749
<b>Peak external rotation angle (°)</b>	-4.65 ± 6.28	-3.40 ± 7.31	-1.25 ± 5.37	3.80 [2.75, 6.12]	94.3 [68.4, 152.0]	0.803 [0.400, 0.936]	0.003	0.415
<b>Range transverse angle (°)</b>	13.02 ± 4.36	12.13 ± 3.87	-0.88 ± 3.76	2.66 [1.93, 4.29]	21.2 [15.3, 34.1]	0.716 [0.131, 0.908]	0.014	0.411
<b>Peak internal rotation moment (Nm/kg/m)</b>	0.26 ± 0.10	0.28 ± 0.09	0.02 ± 0.06	0.04 [0.03, 0.07]	16.6 [12.0, 26.8]	0.753 [0.089, 0.929]	0.015	0.326

<b>Peak external rotation moment (Nm/kg/m)</b>	-0.06 ± 0.06	-0.06 ± 0.06	0.00 ± 0.03	0.02 [0.02, 0.04]	39.1 [28.4, 63.1]	0.924 [0.773, 0.975]	<0.001	0.732
<b>Range transverse moment (Nm/kg/m)</b>	0.32 ± 0.12	0.34 ± 0.09	0.02 ± 0.08	0.05 [0.04, 0.09]	16.1 [11.7, 26.0]	0.714 [0.035, 0.915]	0.020	0.328
<b>Peak vertical GRF (BW)</b>	3.95 ± 0.63	3.90 ± 0.63	0.05 ± 0.49	0.34 [0.25, 0.54]	8.8 [6.4, 13.8]	0.832 [0.494, 0.944]	0.001	0.721
<b>Peak anterior GRF (BW)</b>	0.19 ± 0.13	0.16 ± 0.12	0.03 ± 0.10	0.07 [0.05, 0.12]	43.0 [31.5, 67.9]	0.782 [0.369, 0.926]	0.003	0.338
<b>Peak posterior GRF (BW)</b>	-0.13 ± 0.09	-0.16 ± 0.13	0.02 ± 0.12	0.08 [0.06, 0.13]	57.0 [41.7, 89.9]	0.650 [-0.049, 0.883]	0.030	0.237
<b>Peak lateral GRF (BW)</b>	0.27 ± 0.12	0.26 ± 0.11	0.00 ± 0.06	0.04 [0.03, 0.07]	16.3 [11.9, 25.7]	0.924 [0.772, 0.975]	<0.001	0.950
<b>Peak medial GRF (BW)</b>	-0.54 ± 0.16	-0.53 ± 0.12	-0.02 ± 0.07	0.05 [0.04, 0.08]	9.7 [7.1, 15.3]	0.926 [0.784, 0.975]	<0.001	0.430
<b>Flight time (s)</b>	0.29 ± 0.07	0.28 ± 0.06	0.01 ± 0.08	0.05 [0.04, 0.08]	18.6 [13.6, 29.4]	0.588 [-0.265, 0.863]	0.058	0.614
<b>Time to PKF* (s)</b>	0.29 ± 0.19	0.23 ± 0.06	0.06 ± 0.17	0.12 [0.09, 0.19]	46.8 [34.3, 73.9]	0.406 [-0.655, 0.796]	0.158	0.237
<b>Stance time (s)</b>	0.57 ± 0.20	0.51 ± 0.14	0.06 ± 0.18	0.13 [0.10, 0.20]	24.2 [17.7, 38.1]	0.624 [-0.066, 0.872]	0.033	0.249
<b>Jump height (cm)</b>	10.98 ± 5.74	10.10 ± 4.42	0.88 ± 5.47	3.87 [2.83, 6.10]	36.7 [26.9, 57.9]	0.610 [-0.181, 0.870]	0.047	0.544

Note: \*indicates ICC below 0.500. BW = body weight, CI = confidence interval, CV = coefficient of variation, GRF = ground reaction forces, ICC = intraclass coefficient, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

## 5.2 Cross sectional results

Sixty-nine individuals were recruited and completed this study. However, data from six individuals (different individuals for the dominant and nondominant legs) for CUT, five from the dominant leg and nine from the non-dominant leg for LAND, did not meet the criteria for statistical analysis due to poor movement execution, discrepancies in marker tracking, or data capture issues. Therefore, 63 participants were included in the analysis for CUT and 64 (dominant) and 60 (non-dominant) were included for LAND. Four participants were left leg dominant (roughly 5%) with the rest being right leg dominant. Demographic data of the groups by sex and maturation stage are shown in Table 18. Effect sizes are presented as interpretations of Hedge's  $g$ , where  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size.

**Table 19** Demographic data for all participants in the single-leg drop-land (LAND), single-leg drop-land and cut (CUT), single-leg rotating drop-land and hop (ROT), and single-leg drop-land and vertical hop (VERT) tasks grouped by sex and maturation stage.

	Pre	Males Mid	Post	Pre	Females Mid	Post
<i>LAND dominant leg</i>						
<b>Sample (n)</b>	14	11	11	9	9	10
<b>Mass (kg)</b>	34.3 ± 8.9	60.9 ± 11.7	82.5 ± 21.8	36.0 ± 6.4	50.9 ± 9.0	61.5 ± 12.5
<b>Height (cm)</b>	138.6 ± 9.6	169.4 ± 10.7	177.1 ± 5.4	142.7 ± 9.9	163.9 ± 9.4	162.4 ± 11.4
<b>Age (y)</b>	9.7 ± 1.6	14.5 ± 1.5	17.9 ± 1.9	10.3 ± 1.5	13.6 ± 2.0	16.6 ± 2.7
<b>BMI (kg/m<sup>2</sup>)</b>	17.3 ± 2.7	21.0 ± 2.5	26.2 ± 7.3	17.4 ± 2.5	18.9 ± 2.4	22.9 ± 3.7
<i>LAND non-dominant leg</i>						
<b>Sample (n)</b>	12	10	11	8	9	10
<b>Mass (kg)</b>	33.1 ± 8.4	59.5 ± 11.2	83.09 ± 21.9	37.6 ± 4.7	50.9 ± 9.0	61.5 ± 12.5
<b>Height (cm)</b>	138.5 ± 9.8	168.9 ± 11.1	178.3 ± 5.8	144.1 ± 9.4	163.9 ± 9.4	162.4 ± 11.4
<b>Age (y)</b>	9.6 ± 1.7	14.3 ± 1.5	18.0 ± 1.9	10.6 ± 1.4	13.6 ± 2.0	16.6 ± 2.7
<b>BMI (kg/m<sup>2</sup>)</b>	16.8 ± 2.1	20.6 ± 2.3	26.1 ± 7.3	17.9 ± 2.2	18.9 ± 2.4	22.9 ± 3.7
<i>CUT dominant leg</i>						
<b>Sample (n)</b>	12	11	10	10	9	10
<b>Mass (kg)</b>	32.7 ± 8.4	60.9 ± 11.7	84.1 ± 22.9	34.7 ± 7.4	50.9 ± 9.0	61.5 ± 12.5
<b>Height (cm)</b>	137.5 ± 10.0	169.4 ± 10.7	178.4 ± 6.2	140.2 ± 12.2	163.9 ± 9.4	162.4 ± 11.4
<b>Age (y)</b>	9.7 ± 1.5	14.5 ± 1.5	17.9 ± 1.9	10.0 ± 1.6	13.3 ± 1.9	16.6 ± 2.7
<b>BMI (kg/m<sup>2</sup>)</b>	16.7 ± 2.1	21.0 ± 2.5	26.5 ± 7.6	17.3 ± 2.4	18.7 ± 2.4	22.9 ± 3.7
<i>CUT non-dominant leg</i>						
<b>Sample (n)</b>	16	11	8	9	9	10
<b>Mass (kg)</b>	33.7 ± 8.5	60.9 ± 11.7	83.8 ± 25.9	35.9 ± 6.7	50.9 ± 9.0	61.5 ± 12.5
<b>Height (cm)</b>	138.0 ± 9.3	169.4 ± 10.7	177.1 ± 5.6	141.2 ± 12.5	163.9 ± 9.4	162.4 ± 11.4
<b>Age (y)</b>	9.7 ± 1.6	14.5 ± 1.5	18.4 ± 2.0	10.2 ± 1.6	13.3 ± 1.9	16.6 ± 2.7
<b>BMI (kg/m<sup>2</sup>)</b>	17.2 ± 2.6	21.0 ± 2.5	26.7 ± 8.6	17.7 ± 2.2	18.7 ± 2.4	22.9 ± 3.6

<b>150% of leg length (cm)</b>	109.8 ± 9.8	137.2 ± 10.0	146.7 ± 10.6	112.8 ± 11.5	134.8 ± 8.7	134.1 ± 13.5
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*ROT dominant leg*

<b>Sample (n)</b>	13	10	11	10	9	10
<b>Mass (kg)</b>	34.2 ± 9.3	61.0 ± 12.3	80.5 ± 18.3	34.7 ± 7.4	50.9 ± 9.0	61.5 ± 12.5
<b>Height (cm)</b>	138.1 ± 9.7	170.1 ± 11.0	178.1 ± 7.1	140.2 ± 12.2	163.9 ± 9.4	162.4 ± 11.4
<b>Age (y)</b>	9.6 ± 1.5	14.6 ± 1.6	17.9 ± 1.9	10.0 ± 1.6	13.3 ± 1.9	16.6 ± 2.7
<b>BMI (kg/m<sup>2</sup>)</b>	17.4 ± 2.8	20.8 ± 2.6	26.2 ± 7.3	17.3 ± 2.4	18.7 ± 2.4	22.9 ± 3.7

*ROT non-dominant leg*

<b>Sample (n)</b>	12	10	12	10	9	10
<b>Mass (kg)</b>	35.1 ± 9.0	61.0 ± 12.3	81.1 ± 17.6	34.7 ± 7.4	50.9 ± 9.0	61.5 ± 12.5
<b>Height (cm)</b>	139.4 ± 8.9	170.1 ± 11.0	178.8 ± 7.1	140.2 ± 12.2	163.9 ± 9.4	162.4 ± 11.4
<b>Age (y)</b>	9.7 ± 1.5	14.6 ± 1.6	18.0 ± 1.8	10.4 ± 1.6	13.3 ± 1.9	16.6 ± 2.7
<b>BMI (kg/m<sup>2</sup>)</b>	17.6 ± 2.8	20.8 ± 2.6	24.7 ± 4.7	17.3 ± 1.9	18.7 ± 2.4	22.9 ± 3.7

*VERT dominant leg*

<b>Sample (n)</b>	12	10	12	9	9	10
<b>Mass (kg)</b>	34.6 ± 9.2	60.8 ± 12.3	82.8 ± 21.1	35.5 ± 6.3	50.4 ± 9.0	60.9 ± 12.4
<b>Height (cm)</b>	139.3 ± 8.9	170.1 ± 11.0	177.9 ± 5.7	142.7 ± 9.9	163.9 ± 9.4	162.4 ± 11.4
<b>Age (y)</b>	10.0 ± 1.4	14.6 ± 1.6	17.9 ± 1.8	10.3 ± 1.5	13.3 ± 1.9	16.6 ± 2.7
<b>BMI (kg/m<sup>2</sup>)</b>	17.6 ± 2.8	20.8 ± 2.6	26.2 ± 6.9	17.4 ± 2.5	18.7 ± 2.4	22.9 ± 3.7

*VERT non-dominant leg*

<b>Sample (n)</b>	12	10	10	9	9	10
<b>Mass (kg)</b>	34.5 ± 9.2	60.8 ± 12.3	79.0 ± 17.8	35.5 ± 6.3	50.4 ± 9.0	60.9 ± 12.4
<b>Height (cm)</b>	139.0 ± 8.8	170.1 ± 11.1	178.9 ± 5.7	142.7 ± 9.9	163.9 ± 9.4	162.4 ± 11.4
<b>Age (y)</b>	9.7 ± 1.4	14.6 ± 1.6	18.1 ± 1.9	10.3 ± 1.5	13.3 ± 1.9	16.6 ± 2.7
<b>BMI (kg/m<sup>2</sup>)</b>	17.5 ± 2.8	20.8 ± 2.6	24.6 ± 4.9	17.4 ± 2.5	18.7 ± 2.4	22.9 ± 3.7

*Note:* BMI, body mass index; CUT, single-leg drop-land and cut; LAND, single-leg drop-land; ROT, single-leg rotating land and vertical jump; VERT, single-leg land and vertical jump.

### 5.2.1 LAND dominant leg

Statistically significant interaction effects were observed between sex and maturation for peak extension angle ( $F_{(2, 58)} = 4.490, p = 0.015$ ) and peak knee flexion moment ( $F_{(2, 58)} = 3.961, p = 0.024$ ), with the remaining metrics showing no significant interaction (Table 19). Pairwise comparisons revealed that for peak knee extension angle, within the post-pubertal group, females had a significantly greater knee extension angle than males ( $p = 0.027, g = 0.709$  *medium*). Additionally, within females, peak knee extension angle was significantly greater in the post-pubertal than pre-pubertal group ( $p = 0.002, g = 1.798$  *large*). Within males, peak knee extension angle in the mid-pubertal group was significantly greater than the pre-pubertal group ( $p = 0.005, g = 1.212$  *large*). For peak knee flexion moment, within the post-pubertal group, males had a significantly larger peak knee flexion moment than females ( $p = 0.019, g = 1.313$  *large*). Within females, pre-pubertal had greater peak knee flexion moments than both mid-pubertal and post-pubertal ( $p = 0.031, g = 0.732$  *medium*;  $p < 0.001, g = 2.163$  *large*, respectively), with mid-pubertal demonstrating larger moments than post-pubertal ( $p = 0.006, g = 2.163$  *large*).

Significant main effects of maturation were observed for peak knee varus angle ( $F_{(2, 58)} = 4.798, p = 0.012$ ), peak knee varus moment ( $F_{(2, 58)} = 7.609, p = 0.001$ ), peak knee external rotation angle ( $F_{(2, 58)} = 4.853, p = 0.011$ ), peak knee external rotation moment ( $F_{(2, 58)} = 6.525, p = 0.003$ ), peak vGRF ( $F_{(2, 58)} = 25.165, p < 0.001$ ) and time to PKF ( $F_{(2, 58)} = 3.221, p = 0.047$ ). Based on pairwise comparisons (Table 20), the pre-pubertal group exhibited significantly greater peak knee varus angle than the post-pubertal group ( $p = 0.007, g =$  *large*) and significantly greater external rotation angle than mid-pubertal and post-pubertal groups ( $p = 0.004, g =$  *large*;  $p = 0.033, g =$  *medium*, respectively). However, the mid-pubertal and the post-pubertal groups had significantly greater peak knee varus moments ( $p = 0.003, g =$  *large*;  $p < 0.001, g =$  *large*, respectively) and external rotation moments ( $p = 0.003, g =$  *large*;  $p = 0.004, g =$  *large*, respectively) than pre-pubertal. For peak vGRF, pre-pubertal and mid-pubertal groups were significantly higher than post-pubertal ( $p < 0.001, g =$  *large*) and ( $p = 0.018, g =$  *large*), respectively. The mid-pubertal group also had longer time to PKF than pre-pubertal ( $p = 0.016, g =$  *large*, respectively). No main effects of sex were observed for any of the metrics of the dominant leg.

**Table 20** The interaction between sex and maturation stage groups during single-leg drop-land (LAND) task on the dominant leg for biomechanical variables associated with anterior cruciate ligament (ACL) injury risk shown as mean and standard deviations (SD), performed by 2x3 way analysis of variance.

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak flexion angle (°) ^</b>	59.10 ± 9.01	64.09 ± 10.89	60.91 ± 16.41	58.84 ± 9.60	61.86 ± 6.43	63.84 ± 11.44	0.541 (0.02)	0.444 (0.01)	0.408 (0.03)
<b>Peak extension angle (°) ^</b>	11.91 ± 3.35	16.69 ± 4.43	12.70 ± 7.97	10.16 ± 3.18	14.00 ± 2.25	17.38 ± 4.56	0.034* (0.11)	0.546 (0.01)	0.015 <sup>†</sup> (0.13)
<b>Range sagittal angle (°)</b>	47.19 ± 7.73	47.50 ± 8.20	48.21 ± 8.94	48.28 ± 7.35	47.86 ± 6.06	46.47 ± 9.38	0.985 (0.00)	0.962 (0.00)	0.838 (0.01)
<b>Peak flexion moment (Nm/kg/m)</b>	0.49 ± 0.13	0.46 ± 0.08	0.41 ± 0.10	0.56 ± 0.14	0.44 ± 0.14	0.29 ± 0.09	<0.001* (0.29)	0.487 (0.01)	0.024 <sup>†</sup> (0.12)
<b>Peak extension moment (Nm/kg/m)</b>	-1.66 ± 0.25	-1.68 ± 0.17	-1.53 ± 0.35	-1.86 ± 0.29	-1.68 ± 0.27	-1.70 ± 0.25	0.221 (0.05)	0.074 (0.05)	0.456 (0.03)
<b>Peak valgus angle (°)</b>	8.55 ± 5.55	4.94 ± 3.87	4.24 ± 5.73	6.61 ± 2.78	5.21 ± 5.05	4.19 ± 5.82	0.081 (0.08)	0.651 (0.00)	0.739 (0.01)
<b>Peak varus angle (°)</b>	0.01 ± 3.73	-2.61 ± 3.43	-4.00 ± 3.42	-1.18 ± 2.27	-2.66 ± 4.27	-3.35 ± 3.71	0.023* (0.12)	0.832 (0.00)	0.705 (0.01)
<b>Range coronal angle (°)</b>	8.55 ± 3.35	7.55 ± 2.39	8.24 ± 3.66	7.79 ± 1.18	7.86 ± 1.78	7.54 ± 2.94	0.864 (0.01)	0.592 (0.01)	0.790 (0.01)
<b>Peak valgus moment (Nm/kg/m)</b>	0.49 ± 0.22	0.48 ± 0.17	0.49 ± 0.16	0.57 ± 0.16	0.49 ± 0.23	0.36 ± 0.11	0.140 (0.07)	0.783 (0.00)	0.174 (0.06)
<b>Peak varus moment (Nm/kg/m)</b>	-0.42 ± 0.21	-0.17 ± 0.08	-0.15 ± 0.16	-0.29 ± 0.21	-0.21 ± 0.18	-0.18 ± 0.13	0.001* (0.21)	0.674 (0.00)	0.187 (0.06)

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
Peak int rot angle (°)	9.90 ± 5.82	5.89 ± 5.62	4.79 ± 5.18	6.90 ± 5.96	4.73 ± 3.70	8.16 ± 6.67	0.205 (0.05)	0.853 (0.00)	0.170 (0.06)
Peak ext rot angle (°)	-1.46 ± 6.68	-7.69 ± 5.47	-8.89 ± 5.71	-4.80 ± 6.81	-10.12 ± 6.48	-5.87 ± 6.06	0.011* (0.14)	0.534 (0.01)	0.230 (0.05)
Range transverse angle (°) ^	11.36 ± 3.01	13.58 ± 4.89	13.49 ± 3.93	11.70 ± 3.38	14.85 ± 7.79	14.03 ± 5.03	0.306 (0.04)	0.855 (0.00)	0.999 (0.00)
Peak int rot moment (Nm/kg/m)	0.31 ± 0.12	0.32 ± 0.06	0.28 ± 0.09	0.36 ± 0.08	0.32 ± 0.11	0.28 ± 0.07	0.123 (0.07)	0.570 (0.01)	0.693 (0.01)
Peak ext rot moment (Nm/kg/m) ^	-0.12 ± 0.10	-0.04 ± 0.02	-0.06 ± 0.09	-0.09 ± 0.07	-0.03 ± 0.03	-0.03 ± 0.03	0.003* (0.18)	0.177 (0.03)	0.791 (0.008)
Peak vGRF (BW)	5.11 ± 0.68	4.18 ± 0.48	3.82 ± 0.61	4.81 ± 0.53	4.22 ± 0.28	3.73 ± 0.58	<0.001* (0.47)	0.411 (0.01)	0.625 (0.02)
Time to PKF (s)	0.19 ± 0.08	0.26 ± 0.12	0.26 ± 0.10	0.19 ± 0.08	0.26 ± 0.08	0.22 ± 0.10	0.047* (0.10)	0.541 (0.01)	0.746 (0.01)

Note: \* significant main effects ( $p < 0.05$ ) † significant interaction effect ( $p < 0.05$ ) from 2x3 way analysis of variance ^ log transformed metrics. BW = body weight, ext rot = external rotation, GRF = ground reaction force, PKF = peak knee flexion, int rot = internal rotation.

**Table 21** Pairwise comparisons for the main effects of maturation during the single-leg drop-land (LAND) task on the dominant leg, where no interactions were indicated. Hedges' *g* and interpretation provided when significant differences ( $p < 0.05$ ) indicated.

Pairwise comparison		Mean difference [95% CI]	<i>p</i> value	<i>g</i> (magnitude)
<b>Peak varus angle (°)</b>				
Pre	Mid	2.05 [-0.20, 4.29]	0.074	—
Pre	Post	3.09 [0.87, 5.31]	0.007*	0.930 ( <i>large</i> )
Mid	Post	1.04 [-1.23, 3.32]	0.361	—
<b>Peak varus moment (Nm/kg/m)</b>				
Pre	Mid	-0.16 [-0.27, -0.06]	0.003*	0.942 ( <i>large</i> )
Pre	Post	-0.19 [-0.29, -0.08]	0.001*	1.089 ( <i>large</i> )
Mid	Post	-0.03 [-0.13, 0.08]	0.639	—
<b>Peak ext rot angle (°)</b>				
Pre	Mid	5.78 [1.92, 9.64]	0.004*	0.942 ( <i>large</i> )
Pre	Post	4.15 [0.35, 7.96]	0.033*	0.719 ( <i>medium</i> )
Mid	Post	-1.63 [-5.53, 2.27]	0.408	—
<b>Peak ext rot moment (Nm/kg/m)</b>				
Pre	Mid	-0.07 [-0.11, -0.02]	0.003*	1.023 ( <i>large</i> )
Pre	Post	-0.06 [-0.10, -0.02]	0.004*	0.809 ( <i>large</i> )
Mid	Post	0.00 [-0.04, 0.05]	0.840	—
<b>Peak vGRF (BW)</b>				
Pre	Mid	0.76 [0.42, 1.11]	<0.000*	1.472 ( <i>large</i> )
Pre	Post	1.19 [0.85, 1.53]	<0.000*	1.964 ( <i>large</i> )
Mid	Post	0.42 [0.07, 0.77]	0.018*	0.823 ( <i>large</i> )
<b>Time to PKF (s)</b>				
Pre	Mid	-0.07 [-0.13, -0.01]	0.016*	0.805 ( <i>large</i> )
Pre	Post	-0.05 [-0.10, 0.01]	0.102	—
Mid	Post	0.02 [-0.03, 0.08]	0.406	—

Note: \*Significant difference ( $p < 0.05$  from pairwise comparisons).  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size. BW = body weight, CI = confidence intervals, ext rot = external rotation, vGRF = vertical ground reaction force.

### 5.2.2 LAND non-dominant leg

A statistically significant interaction effect was observed between sex and maturation stage for peak knee flexion moment ( $F_{(2, 54)} = 3.657, p = 0.032$ ) with the remaining metrics showing no interaction (Table 21). Within the post-pubertal group, males had a significantly higher peak knee flexion moment than females ( $p = 0.035, g = 1.311$  *large*). Within females, both pre-pubertal and mid-pubertal exhibited greater peak knee flexion moments than post-pubertal ( $p < 0.001, g = 1.894$  *large*) and ( $p = 0.002, g = 0.653$  *large*), respectively.

Significant main effects of maturation were observed for peak knee varus moment ( $F_{(2, 54)} = 5.703, p = 0.006$ ), peak knee external rotation moment ( $F_{(2, 54)} = 3.878, p = 0.027$ ) and peak vGRF ( $F_{(2, 54)} = 15.382, p = 0.024$ ). Based on pairwise comparisons (Table 22), the mid-pubertal and post-pubertal groups had significantly greater peak knee varus moment than pre-pubertal ( $p = 0.013, g =$  *medium*;  $p = 0.002, g =$  *large*, respectively). The post-pubertal group also had significantly higher peak knee external rotation moment than pre-pubertal ( $p = 0.008, g =$  *large*). Peak vGRF was higher in both pre-pubertal and mid-pubertal than post-pubertal ( $p < 0.001, g =$  *large*;  $p = 0.017, g =$  *medium*, respectively), and higher in pre-pubertal than mid-pubertal ( $p = 0.004, g =$  *large*).

No significant main effects of sex were observed. The results of the dominant and non-dominant legs for the LAND task are summarised in Figure 15.

**Table 22** The interaction between sex and maturation stage groups during the single-leg drop-land (LAND) task on the non-dominant leg for biomechanical variables associated with anterior cruciate ligament (ACL) injury risk shown as mean and standard deviations (SD), performed by 2x3 way analysis of variance.

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak flexion angle (°)</b>	58.18 ± 13.77	59.35 ± 9.43	60.57 ± 12.80	61.13 ± 10.21	59.36 ± 6.88	61.72 ± 10.10	0.858 (0.01)	0.635 (0.00)	0.917 (0.00)
<b>Peak extension angle (°)</b>	10.41 ± 6.16	13.50 ± 3.16	11.60 ± 6.01	11.28 ± 2.82	11.84 ± 5.45	15.47 ± 5.16	0.246 (0.05)	0.441 (0.01)	0.238 (0.05)
<b>Range sagittal angle (°)</b>	47.77 ± 10.85	45.85 ± 8.40	48.98 ± 8.18	49.85 ± 9.19	47.51 ± 7.10	46.25 ± 6.59	0.746 (0.01)	0.880 (0.00)	0.617 (0.02)
<b>Peak flexion moment (Nm/kg/m)</b>	0.48 ± 0.11	0.39 ± 0.10	0.41 ± 0.08	0.50 ± 0.13	0.46 ± 0.12	0.31 ± 0.07	<0.001* (0.24)	0.996 (0.00)	0.032* (0.12)
<b>Peak extension moment (Nm/kg/m)</b>	-1.55 ± 0.31	-1.61 ± 0.18	-1.57 ± 0.29	-1.85 ± 0.40	-1.68 ± 0.26	-1.58 ± 0.29	0.392 (0.03)	0.102 (0.05)	0.283 (0.05)
<b>Peak valgus angle (°)</b>	9.01 ± 6.80	4.79 ± 3.92	3.81 ± 3.07	7.57 ± 6.68	5.38 ± 4.24	5.29 ± 5.30	0.059 (0.10)	0.878 (0.00)	0.663 (0.02)
<b>Peak varus angle (°)</b>	0.57 ± 4.05	-2.49 ± 3.26	-3.25 ± 2.44	-1.09 ± 4.97	-3.31 ± 3.91	-2.23 ± 4.61	0.070 (0.09)	0.637 (0.00)	0.541 (0.02)
<b>Range coronal angle (°) ^</b>	8.45 ± 3.79	7.28 ± 1.59	7.06 ± 1.40	8.65 ± 2.39	8.69 ± 3.09	7.51 ± 1.82	0.465 (0.03)	0.335 (0.02)	0.945 (0.00)
<b>Peak valgus moment (Nm/kg/m)</b>	0.52 ± 0.23	0.48 ± 0.12	0.43 ± 0.14	0.49 ± 0.23	0.47 ± 0.16	0.37 ± 0.16	0.175 (0.06)	0.477 (0.01)	0.892 (0.00)
<b>Peak varus moment (Nm/kg/m)</b>	-0.32 ± 0.21	-0.18 ± 0.13	-0.11 ± 0.08	-0.30 ± 0.18	-0.20 ± 0.13	-0.21 ± 0.13	0.006* (0.17)	0.384 (0.01)	0.432 (0.03)

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
Peak int rot angle (°)	9.58 ± 5.87	8.03 ± 5.28	7.52 ± 6.08	8.19 ± 5.28	6.06 ± 4.88	7.92 ± 5.58	0.586 (0.02)	0.498 (0.01)	0.780 (0.01)
Peak ext rot angle (°)	-2.32 ± 5.39	-4.58 ± 5.28	-3.99 ± 5.92	-3.74 ± 5.97	-5.84 ± 6.15	-5.99 ± 5.59	0.431 (0.03)	0.300 (0.02)	0.977 (0.00)
Range transverse angle (°)	11.91 ± 4.21	12.61 ± 2.86	11.51 ± 3.89	11.93 ± 2.89	11.91 ± 3.88	13.91 ± 3.75	0.792 (0.01)	0.554 (0.01)	0.379 (0.04)
Peak int rot moment (Nm/kg/m)	0.29 ± 0.12	0.25 ± 0.09	0.27 ± 0.08	0.34 ± 0.11	0.24 ± 0.10	0.23 ± 0.08	0.097 (0.08)	0.872 (0.00)	0.274 (0.05)
Peak ext rot moment (Nm/kg/m)	-0.11 ± 0.08	-0.08 ± 0.05	-0.06 ± 0.05	-0.10 ± 0.06	-0.08 ± 0.06	-0.04 ± 0.05	0.027* (0.126)	0.670 (0.00)	0.857 (0.01)
Peak vGRF (BW)	4.75 ± 0.59	4.17 ± 0.51	3.62 ± 0.61	4.54 ± 0.45	4.09 ± 0.45	3.81 ± 0.49	<0.001* (0.36)	0.796 (0.00)	0.487 (0.03)
Time to PKF (s)	0.19 ± 0.09	0.27 ± 0.06	0.25 ± 0.12	0.21 ± 0.07	0.23 ± 0.06	0.23 ± 0.10	0.380 (0.04)	0.640 (0.00)	0.747 (0.01)

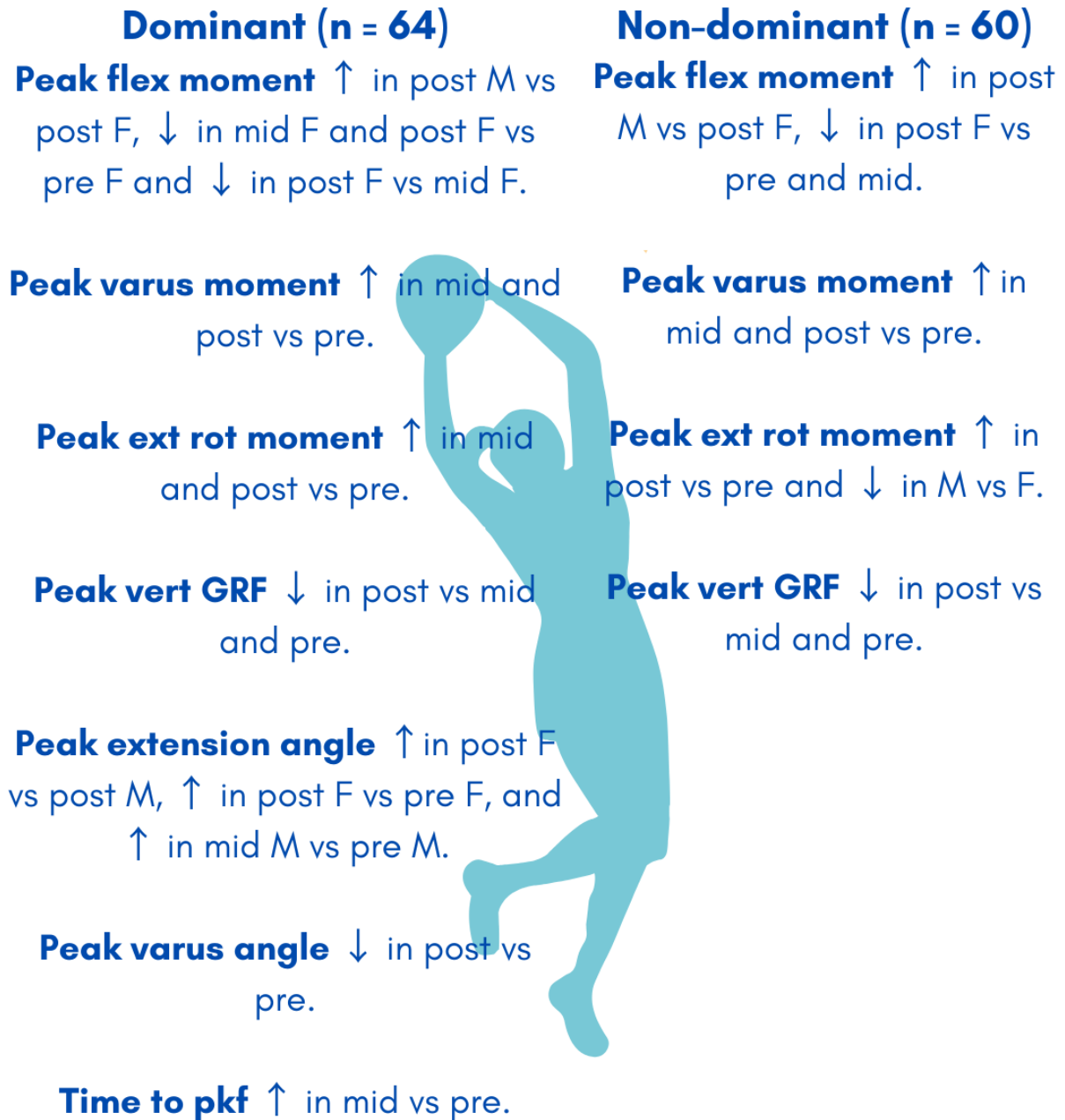
Note: \* significant main effects ( $p < 0.05$ ) † significant interaction effect ( $p < 0.05$ ) from 2x3 way analysis of variance ^ log transformed metrics. BW = body weight, ext rot = external rotation, GRF = ground reaction force, PKF = peak knee flexion, int rot = internal rotation.

**Table 23** Pairwise comparisons for the main effects of maturation during the single-leg drop-land (LAND) task on the non-dominant leg, where no interactions were indicated. Hedges' *g* and interpretation provided when significant differences ( $p < 0.05$ ) indicated.

Pairwise comparison		Mean differences [95% CI]	<i>p</i> value	<i>g</i> (magnitude)
<b>Peak varus moment (Nm/kg/m)</b>				
Pre	Mid	-0.12 [-0.22, -0.03]	0.013*	0.774 ( <i>medium</i> )
Pre	Post	-0.15 [-0.24, -0.06]	0.002*	0.989 ( <i>large</i> )
Mid	Post	-0.03 [-0.12, 0.07]	0.593	—
<b>Peak ext rot moment (Nm/kg/m)</b>				
Pre	Mid	-0.02 [-0.06, 0.02]	0.231	—
Pre	Post	-0.05 [-0.09, -0.01]	0.008*	0.876 ( <i>large</i> )
Mid	Post	-0.03 [-0.07, 0.01]	0.133	—
<b>Peak vGRF (BW)</b>				
Pre	Mid	0.52 [0.17, 0.86]	0.004*	1.034 ( <i>large</i> )
Pre	Post	0.93 [0.59, 1.26]	<0.000*	1.715 ( <i>large</i> )
Mid	Post	0.41 [0.08, 0.75]	0.017*	0.794 ( <i>medium</i> )

Note: \*Significant difference ( $p < 0.05$  from pairwise comparisons).  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size. BW = body weight, CI = confidence intervals, ext rot = external rotation, vGRF = vertical ground reaction force.

# Biomechanical differences in maturation and sex during a land task



**Figure 15** Single-leg drop-land (LAND) task results infographic. *Note:* ext, external; F, females; flex, flexion; GRF, ground reaction force; M, males; mid, early/mid-pubertal; pkf, peak knee flexion; post, late/post-pubertal; pre, pre-pubertal; rot, rotation; vert, vertical.

### 5.2.3 CUT dominant leg

No significant interaction effects between sex and maturation were found for any of the CUT metrics on the dominant leg (Table 23). For maturation, significant main effects were observed for peak knee flexion moment ( $F_{(2, 56)} = 6.825, p = 0.002$ ), peak knee internal rotation moment ( $F_{(2, 56)} = 3.571, p = 0.035$ ) and peak vGRF ( $F_{(2, 55)} = 12.228, p < 0.001$ ). Pairwise comparisons, however, revealed no significant differences ( $p > 0.392$ ) between the maturation stages for peak knee flexion moment (Table 24). For knee internal rotation moments, the pre-pubertal group demonstrated significantly greater moments than the mid-pubertal ( $p = 0.027, g = \text{medium}$ ) and post-pubertal ( $p = 0.024, g = \text{medium}$ ) groups. Significantly larger peak vGRFs were observed in the mid-pubertal and post-pubertal groups compared to the pre-pubertal group ( $p < 0.001, g = \text{large}$ ;  $p < 0.001, g = \text{large}$ , respectively).

For sex, a significant main effect was found for peak vGRF ( $F_{(1, 55)} = 4.771, p = 0.033$ ), and pairwise comparisons revealed significantly larger peak vGRFs in males than females ( $p = 0.033, g = \text{small}$ ).

**Table 24** The interaction between sex and maturation stage groups during the single-leg drop-land and cut (CUT) task on the dominant leg for biomechanical variables associated with anterior cruciate ligament (ACL) injury risk shown as mean and standard deviations (SD), performed by 2x3 way analysis of variance.

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak flexion angle (°)</b>	64.49 ± 7.62	65.08 ± 8.81	62.47 ± 6.69	65.71 ± 7.69	63.13 ± 4.39	67.89 ± 7.25	0.874 (0.01)	0.403 (0.01)	0.287 (0.04)
<b>Peak extension angle (°)</b>	14.25 ± 4.40	18.89 ± 5.40	16.84 ± 7.65	15.57 ± 4.86	17.00 ± 3.73	18.24 ± 5.10	0.142 (0.07)	0.839 (0.00)	0.539 (0.02)
<b>Range sagittal angle (°)</b>	50.24 ± 6.95	46.19 ± 5.74	45.63 ± 6.59	50.14 ± 6.97	46.14 ± 5.31	49.64 ± 4.73	0.109 (0.08)	0.415 (0.01)	0.478 (0.03)
<b>Peak flexion moment (Nm/kg/m) ^</b>	0.43 ± 0.20	0.28 ± 0.13	0.31 ± 0.16	0.44 ± 0.14	0.35 ± 0.22	0.19 ± 0.07	0.002* (0.20)	0.769 (0.00)	0.147 (0.07)
<b>Peak extension moment (Nm/kg/m)</b>	-1.79 ± 0.24	-1.90 ± 0.26	-1.70 ± 0.37	-1.85 ± 0.32	-1.88 ± 0.26	-1.87 ± 0.34	0.560 (0.02)	0.399 (0.01)	0.613 (0.02)
<b>Peak valgus angle (°) ^</b>	10.46 ± 6.03	8.92 ± 2.69	7.85 ± 6.69	8.84 ± 2.90	9.93 ± 4.13	8.21 ± 6.50	0.271 (0.05)	0.986 (0.00)	0.827 (0.01)
<b>Peak varus angle (°)</b>	0.79 ± 3.33	-0.32 ± 2.39	-2.92 ± 4.73	-0.26 ± 3.26	-0.50 ± 2.83	-1.99 ± 4.69	0.051 (0.10)	0.915 (0.00)	0.679 (0.01)
<b>Range coronal angle (°)</b>	9.67 ± 4.72	9.23 ± 3.12	10.77 ± 3.56	9.10 ± 2.08	10.43 ± 2.63	10.20 ± 3.04	0.575 (0.02)	0.986 (0.00)	0.632 (0.02)
<b>Peak valgus moment (Nm/kg/m)</b>	0.36 ± 0.14	0.35 ± 0.10	0.39 ± 0.19	0.40 ± 0.19	0.32 ± 0.16	0.32 ± 0.19	0.689 (0.01)	0.604 (0.01)	0.545 (0.02)
<b>Peak varus moment (Nm/kg/m)</b>	-0.46 ± 0.19	-0.26 ± 0.14	-0.20 ± 0.19	-0.31 ± 0.19	-0.33 ± 0.24	-0.29 ± 0.24	0.063 (0.09)	0.928 (0.00)	0.084 (0.09)

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
Peak int rot angle (°)	8.40 ± 5.52	8.52 ± 7.05	7.83 ± 7.50	4.74 ± 6.00	8.42 ± 6.57	9.11 ± 7.73	0.573 (0.02)	0.633 (0.00)	0.476 (0.03)
Peak ext rot angle (°)	-4.97 ± 5.85	-5.81 ± 5.00	-6.32 ± 9.36	-8.60 ± 6.34	-7.40 ± 6.58	-6.38 ± 7.25	0.979 (0.00)	0.315 (0.02)	0.696 (0.01)
Range transverse angle (°)	13.36 ± 4.18	14.33 ± 5.11	14.16 ± 4.74	13.34 ± 4.78	15.82 ± 7.97	15.49 ± 2.65	0.493 (0.03)	0.472 (0.01)	0.867 (0.01)
Peak int rot moment (Nm/kg/m)	0.28 ± 0.11	0.27 ± 0.07	0.24 ± 0.08	0.34 ± 0.10	0.23 ± 0.08	0.25 ± 0.09	0.035* (0.11)	0.716 (0.00)	0.225 (0.05)
Peak ext rot moment (Nm/kg/m)	-0.10 ± 0.06	-0.08 ± 0.07	-0.07 ± 0.07	-0.10 ± 0.06	-0.08 ± 0.06	-0.07 ± 0.09	0.377 (0.03)	0.871 (0.00)	0.991 (0.00)
Peak vGRF (BW)	4.72 ± 1.55	7.46 ± 2.05	8.33 ± 2.86	4.94 ± 1.06	6.15 ± 0.89	6.47 ± 1.16	<0.001* (0.31)	0.033* (0.08)	0.152 (0.07)
Flight time (s)	0.12 ± 0.03	0.16 ± 0.06	0.15 ± 0.05	0.16 ± 0.08	0.15 ± 0.06	0.15 ± 0.03	0.582 (0.020)	0.508 (0.008)	0.229 (0.052)
Time to peak knee flexion (s) ^	0.24 ± 0.08	0.24 ± 0.05	0.26 ± 0.11	0.28 ± 0.12	0.21 ± 0.05	0.23 ± 0.04	0.351 (0.037)	0.842 (0.001)	0.258 (0.048)
Stance time (s)	0.51 ± 0.12	0.49 ± 0.09	0.51 ± 0.12	0.51 ± 0.16	0.44 ± 0.10	0.48 ± 0.08	0.604 (0.018)	0.515 (0.008)	0.556 (0.021)

Note: \* significant main effects ( $p < 0.05$ ) † significant interaction effect ( $p < 0.05$ ) from 2x3 way analysis of variance ^ log transformed metrics. BW = body weight, ext rot = external rotation, GRF = ground reaction force, PKF = peak knee flexion, int rot = internal rotation.

**Table 25** Pairwise comparisons for the main effects of maturation during the single-leg drop-land and cut (CUT) task on the dominant leg, where no interactions were indicated. Hedges' *g* and interpretation provided when significant differences ( $p < 0.05$ ) indicated.

Pairwise comparison		Mean difference [95% CI]	<i>p</i> value	<i>g</i> (magnitude)
Peak flexion moment (Nm/kg/m)				
Pre	Mid	0.04 [-0.06, 0.14]	0.392	—
Pre	Post	0.02 [-0.08, 0.12]	0.631	—
Mid	Post	-0.02 [-0.12, 0.08]	0.711	—
Peak int rot moment (Nm/kg/m)				
Pre	Mid	0.06 [0.01, 0.12]	0.027*	0.642 ( <i>medium</i> )
Pre	Post	0.06 [0.01, 0.12]	0.024*	0.651 ( <i>medium</i> )
Mid	Post	0.00 [-0.05, 0.06]	0.972	—
Peak vGRF (BW)				
Pre	Mid	-1.98 [-3.07, -0.88]	<0.001*	1.316 ( <i>large</i> )
Pre	Post	-2.57 [-3.68, -1.47]	<0.001*	1.374 ( <i>large</i> )
Mid	Post	-0.60 [-1.73, -0.53]	0.294	—
M	F	0.99 [0.08, 1.89]	0.033*	0.426 ( <i>small</i> )

Note: \*Significant difference ( $p < 0.05$  from pairwise comparisons).  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size. BW = body weight, CI = confidence intervals, vGRF = vertical ground reaction force.

#### 5.2.4 CUT non-dominant leg

No significant interaction effects between sex and maturation were found for any of the CUT metrics on the non-dominant leg (Table 25). Significant main effects of maturation were observed for peak knee varus angle ( $F_{(2, 57)} = 3.746, p = 0.030$ ), peak knee varus moment ( $F_{(2, 57)} = 6.756, p = 0.002$ ), peak knee external rotation moment ( $F_{(2, 57)} = 4.449, p = 0.016$ ) and peak vGRF ( $F_{(2, 56)} = 13.912, p < 0.001$ ). Pairwise comparisons (Table 26) revealed that the pre-pubertal group had a significantly greater peak varus angle than post-pubertal ( $p = 0.013, g = 0.865$  large), but lower peak knee varus and external rotation moments than both the post-pubertal ( $p < 0.001, g = large; p = 0.008, g = large$ , respectively) and mid-pubertal ( $p = 0.012, g = medium; p = 0.026, g = medium$ , respectively) groups. The pre-pubertal group had greater peak vGRFs than both the mid-pubertal and post-pubertal groups ( $p < 0.001, g = large; p < 0.001, g = large$ , respectively). For sex, a significant main effect was present for peak knee external rotation moment ( $F_{(1, 57)} = 4.125, p = 0.047$ ). Pairwise comparisons indicated significantly greater peak external rotation moments in females ( $p = 0.047, g = medium$ ) than males.

The results of the dominant and non-dominant legs for the CUT task are summarised in Figure 16.

**Table 26** The interaction between sex and maturation stage groups during the single-leg drop-land and cut (CUT) task on the non-dominant leg for biomechanical variables associated with anterior cruciate ligament (ACL) injury risk shown as mean and standard deviations, performed by 2x3 way analysis of variance.

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak flexion angle (°)</b>	60.38 ± 9.72	62.44 ± 7.30	60.84 ± 10.34	63.90 ± 9.10	58.83 ± 5.94	66.37 ± 6.00	0.555 (0.02)	0.404 (0.01)	0.209 (0.05)
<b>Peak extension angle (°)</b>	12.92 ± 7.23	15.46 ± 5.02	16.06 ± 8.22	14.20 ± 3.04	12.58 ± 3.38	18.16 ± 5.71	0.136 (0.07)	0.911 (0.00)	0.372 (0.03)
<b>Range sagittal angle (°) ^</b>	47.70 ± 7.55	47.00 ± 3.73	44.77 ± 10.40	49.69 ± 6.05	46.24 ± 5.73	48.21 ± 3.80	0.607 (0.02)	0.312 (0.02)	0.506 (0.02)
<b>Peak flexion moment (Nm/kg/m)</b>	0.46 ± 0.14	0.38 ± 0.06	0.42 ± 0.06	0.42 ± 0.12	0.40 ± 0.10	0.32 ± 0.10	0.145 (0.07)	0.179 (0.03)	0.241 (0.05)
<b>Peak extension moment (Nm/kg/m) ^</b>	-1.48 ± 0.41	-1.57 ± 0.19	-1.50 ± 0.41	-1.77 ± 0.30	-1.60 ± 0.21	-1.66 ± 0.27	0.764 (0.01)	0.124 (0.04)	0.428 (0.03)
<b>Peak valgus angle (°)</b>	11.06 ± 6.52	7.90 ± 6.64	6.23 ± 4.25	10.44 ± 5.80	8.69 ± 5.57	8.01 ± 7.10	0.163 (0.06)	0.683 (0.00)	0.824 (0.01)
<b>Peak varus angle (°)</b>	0.74 ± 3.60	-2.05 ± 3.80	-2.16 ± 3.80	-0.19 ± 4.12	-2.17 ± 3.77	-3.66 ± 4.63	0.030* (0.12)	0.405 (0.01)	0.862 (0.01)
<b>Range coronal angle (°)</b>	10.32 ± 4.33	9.95 ± 3.22	8.39 ± 3.49	10.63 ± 2.96	10.86 ± 2.96	11.67 ± 3.37	0.915 (0.00)	0.106 (0.05)	0.396 (0.03)
<b>Peak valgus moment (Nm/kg/m)</b>	0.38 ± 0.15	0.45 ± 0.12	0.32 ± 0.12	0.43 ± 0.18	0.36 ± 0.17	0.35 ± 0.17	0.290 (0.04)	0.888 (0.00)	0.372 (0.03)
<b>Peak varus moment (Nm/kg/m)</b>	-0.36 ± 0.21	-0.24 ± 0.21	-0.14 ± 0.10	-0.36 ± 0.17	-0.21 ± 0.19	-0.20 ± 0.10	0.002* (0.19)	0.816 (0.00)	0.740 (0.01)

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak int rot angle (°)</b>	12.00 ± 7.63	10.51 ± 7.56	10.49 ± 5.73	10.67 ± 4.81	9.44 ± 7.73	9.11 ± 7.73	0.730 (0.01)	0.479 (0.01)	0.997 (0.00)
<b>Peak ext rot angle (°)</b>	-3.38 ± 6.80	-5.01 ± 6.87	-3.23 ± 4.57	-3.57 ± 3.58	-6.24 ± 6.65	-8.73 ± 7.38	0.381 (0.03)	0.162 (0.03)	0.389 (0.03)
<b>Range transverse angle (°)</b>	15.39 ± 4.57	15.52 ± 4.11	13.72 ± 6.34	14.24 ± 2.93	15.67 ± 4.31	17.80 ± 3.39	0.753 (0.01)	0.365 (0.01)	0.161 (0.06)
<b>Peak int rot moment (Nm/kg/m)</b>	0.23 ± 0.08	0.25 ± 0.08	0.19 ± 0.07	0.30 ± 0.12	0.20 ± 0.09	0.23 ± 0.08	0.120 (0.07)	0.381 (0.01)	0.069 (0.00)
<b>Peak ext rot moment (Nm/kg/m)</b>	-0.14 ± 0.07	-0.07 ± 0.05	-0.09 ± 0.07	-0.09 ± 0.05	-0.08 ± 0.05	-0.04 ± 0.04	0.016* (0.14)	0.047* (0.07)	0.172 (0.06)
<b>Peak vGRF (BW)</b>	4.83 ± 0.77	3.91 ± 0.72	3.93 ± 0.68	4.41 ± 0.32	3.89 ± 0.25	3.51 ± 0.25	<0.001* (0.332)	0.062 (0.061)	0.461 (0.027)
<b>Flight time (s)</b>	0.14 ± 0.04	0.18 ± 0.07	0.15 ± 0.07	0.13 ± 0.03	0.15 ± 0.05	0.15 ± 0.04	0.189 (0.058)	0.503 (0.008)	0.530 (0.022)
<b>Time to peak knee flexion (s) ^</b>	0.24 ± 0.10	0.24 ± 0.04	0.23 ± 0.11	0.29 ± 0.13	0.20 ± 0.04	0.24 ± 0.06	0.252 (0.048)	0.718 (0.002)	0.300 (0.042)
<b>Stance time (s) ^</b>	0.45 ± 0.13	0.49 ± 0.06	0.48 ± 0.16	0.53 ± 0.16	0.44 ± 0.10	0.49 ± 0.10	0.747 (0.010)	0.664 (0.003)	0.255 (0.048)

Note: \* significant main effects ( $p < 0.05$ ) † significant interaction effect ( $p < 0.05$ ) from 2x3 way analysis of variance ^ log transformed metrics. BW = body weight, ext rot = external rotation, GRF = ground reaction force, PKF = peak knee flexion, int rot = internal rotation.

**Table 27** Pairwise comparisons for the main effects of maturation during the single-leg drop-land and cut (CUT) task on the non-dominant leg, where no interactions were indicated. Hedges' *g* and interpretation provided when significant differences ( $p < 0.05$ ) indicated.

Pairwise comparison		Mean difference [95% CI]	<i>p</i> value	<i>g</i> (magnitude)
<b>Peak varus angle (°)</b>				
Pre	Mid	2.39 [-0.02, 4.79]	0.052	—
Pre	Post	3.18 [0.71, 5.66]	0.013*	0.865 ( <i>large</i> )
Mid	Post	0.79 [-1.77, 3.36]	0.537	—
<b>Peak varus moment (Nm/kg/m)</b>				
Pre	Mid	-0.14 [-0.25, -0.03]	0.012*	0.716 ( <i>medium</i> )
Pre	Post	-0.19 [-0.30, -0.08]	0.001*	1.189 ( <i>large</i> )
Mid	Post	-0.05 [-0.17, 0.06]	0.343	—
<b>Peak ext rot moment (Nm/kg/m)</b>				
Pre	Mid	-0.04 [-0.08, -0.01]	0.026*	0.781 ( <i>medium</i> )
Pre	Post	-0.05 [-0.09, -0.01]	0.008*	0.945 ( <i>large</i> )
Mid	Post	-0.01 [-0.05, 0.03]	0.626	—
F	M	0.03 [0.00, 0.06]	0.047*	0.613 ( <i>medium</i> )
<b>Peak vGRF (BW)</b>				
Pre	Mid	0.73 [0.37, 1.08]	<0.001*	1.245 ( <i>large</i> )
Pre	Post	0.90 [0.53, 1.28]	<0.001*	1.548 ( <i>large</i> )
Mid	Post	0.18 [-0.21, 0.56]	0.363	—

Note: \*Significant difference ( $p < 0.05$  from pairwise comparisons).  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size. BW = body weight, CI = confidence intervals, ext rot = external rotation, vGRF = vertical ground reaction force.

## Biomechanical differences in maturation and sex during a land and cut task

**Dominant (n = 63)**

**Non-dominant (n = 63)**

**Peak vert GRF** ↑ in mid and post vs pre and ↑ in M vs F.

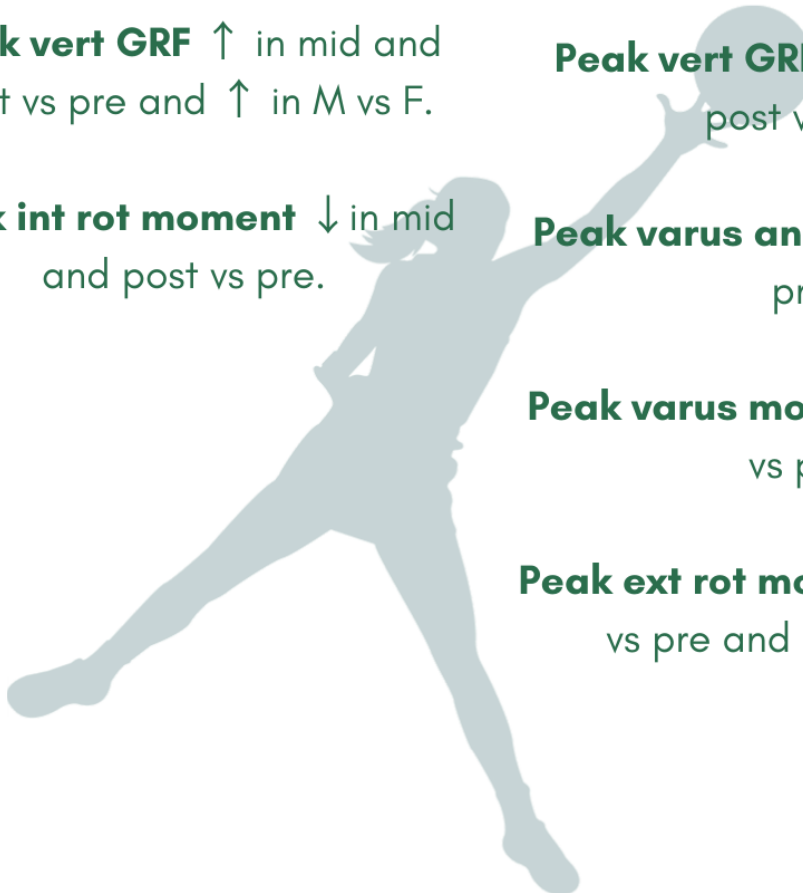
**Peak vert GRF** ↓ in mid and post vs pre.

**Peak int rot moment** ↓ in mid and post vs pre.

**Peak varus angle** ↓ in post vs pre.

**Peak varus moment** ↑ in post vs pre.

**Peak ext rot moment** ↑ in post vs pre and ↓ in M vs F.



**Figure 16** Single-leg drop-land and cut (CUT) task results infographic. *Note:* ext, external; F, females; flex, flexion; GRF, ground reaction force; int, internal; M, males; mid, early/mid-pubertal; post, late/post-pubertal; pre, pre-pubertal; rot, rotation; vert, vertical.

### 5.2.5 ROT dominant leg

A significant interaction effect between sex and maturation was found for jump height ( $F_{(2, 57)} = 6.356, p = 0.003$ ) with the remaining metrics showing no significant interaction effects (Table 27). Pairwise comparisons revealed that mid-pubertal jumped higher than pre-pubertal within both the females ( $p = 0.019, g = 1.193$  *large*) and the males ( $p < 0.001, g = 1.667$  *large*). Within the males, the post-pubertal group also jumped higher than the mid-pubertal ( $p = 0.050, g = 0.634$  *medium*) and the pre-pubertal ( $p < 0.001, g = 2.721$  *large*) groups. Furthermore, within the post-pubertal group, males jumped higher than females ( $p < 0.001, g = 0.433$  *small*).

Statistically significant main effects were observed for maturation stage for peak knee flexion moment ( $F_{(2, 57)} = 7.453, p = 0.001$ ), peak knee valgus angle ( $F_{(2, 57)} = 4.235, p = 0.019$ ), peak knee varus angle ( $F_{(2, 57)} = 3.169, p = 0.050$ ), peak knee varus moment ( $F_{(2, 57)} = 9.378, p < 0.001$ ), peak knee external rotation angle ( $F_{(2, 57)} = 3.787, p = 0.029$ ), peak knee external rotation moment ( $F_{(2, 57)} = 8.733, p < 0.001$ ), and peak vGRF ( $F_{(2, 57)} = 12.847, p < 0.001$ ). Pairwise comparisons revealed significant differences between maturation stages (Table 28). For peak knee flexion moment, the pre-pubertal ( $p = 0.001, g =$  *large*) and mid-pubertal ( $p = 0.002, g =$  *large*) groups had significantly greater moments than post-pubertal. The pre-pubertal group had a significantly greater peak knee valgus angle than mid-pubertal ( $p = 0.036, g =$  *medium*) and post-pubertal ( $p = 0.008, g =$  *large*). Pre-pubertal also had significantly greater peak knee varus angle than post-pubertal ( $p = 0.023, g =$  *medium*), and peak knee external rotation angle than mid-pubertal ( $p = 0.008, g =$  *large*). In contrast, the pre-pubertal group had significantly lower peak knee varus moments and knee external rotation moments than the mid-pubertal ( $p = 0.002, g =$  *large*;  $p = 0.002, g =$  *large*, respectively) and post-pubertal ( $p < 0.001, g =$  *large*;  $p < 0.001, g =$  *large*, respectively) groups. Peak vGRF was higher in the pre-pubertal group compared to the post-pubertal ( $p = 0.009, g =$  *large*) and mid-pubertal ( $p = 0.000, g =$  *large*), and higher in mid-pubertal than post-pubertal ( $p = 0.007, g =$  *large*).

No main effects of sex were observed for any of the metrics of the dominant leg.

**Table 28** The interaction between sex and maturation stage groups during the single-leg rotating drop-land and hop (ROT) task on the dominant leg for biomechanical variables associated with anterior cruciate ligament (ACL) injury risk shown as mean and standard deviations (SD), performed by 2x3 way analysis of variance.

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak flexion angle (°)</b>	59.71 ± 8.92	58.75 ± 12.54	62.72 ± 9.74	61.65 ± 9.61	59.79 ± 7.05	65.51 ± 7.37	0.249 (0.05)	0.422 (0.01)	0.958 (0.00)
<b>Peak extension angle (°)</b>	14.29 ± 4.47	16.07 ± 5.96	14.89 ± 5.58	11.90 ± 4.01	14.85 ± 3.13	16.76 ± 5.35	0.142 (0.07)	0.640 (0.00)	0.343 (0.04)
<b>Range sagittal angle (°)</b>	45.42 ± 7.30	42.68 ± 9.63	47.82 ± 7.93	49.75 ± 8.98	44.94 ± 7.52	48.76 ± 5.24	0.167 (0.06)	0.214 (0.03)	0.773 (0.01)
<b>Peak flexion moment (Nm/kg/m)</b>	0.51 ± 0.15	0.52 ± 0.13	0.42 ± 0.06	0.52 ± 0.14	0.52 ± 0.16	0.35 ± 0.11	0.001* (0.21)	0.621 (0.00)	0.554 (0.02)
<b>Peak extension moment (Nm/kg/m)</b>	-1.61 ± 0.18	-1.63 ± 0.25	-1.51 ± 0.34	-1.74 ± 0.31	-1.66 ± 0.24	-1.69 ± 0.30	0.679 (0.01)	0.104 (0.05)	0.692 (0.01)
<b>Peak valgus angle (°)</b>	9.75 ± 4.88	4.56 ± 3.59	4.17 ± 4.96	7.36 ± 2.45	6.55 ± 4.57	5.47 ± 5.57	0.019* (0.13)	0.794 (0.00)	0.237 (0.05)
<b>Peak varus angle (°)</b>	1.41 ± 3.98	-2.51 ± 2.98	-2.67 ± 3.48	-0.64 ± 3.47	-1.46 ± 5.01	-2.16 ± 4.56	0.006* (0.17)	0.872 (0.00)	0.397 (0.03)
<b>Range coronal angle (°) ^</b>	8.34 ± 3.29	7.06 ± 1.36	6.98 ± 2.33	8.00 ± 2.20	8.01 ± 2.53	7.63 ± 1.77	0.217 (0.05)	0.680 (0.00)	0.399 (0.03)
<b>Peak valgus moment (Nm/kg/m)</b>	0.35 ± 0.17	0.34 ± 0.11	0.34 ± 0.17	0.39 ± 0.12	0.31 ± 0.14	0.27 ± 0.14	0.297 (0.04)	0.528 (0.01)	0.427 (0.03)
<b>Peak varus moment (Nm/kg/m)</b>	-0.46 ± 0.19	-0.23 ± 0.09	-0.20 ± 0.12	-0.39 ± 0.20	-0.30 ± 0.12	-0.26 ± 0.18	<0.001* (0.25)	0.628 (0.00)	0.281 (0.04)

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
Peak int rot angle (°)	7.63 ± 4.47	2.28 ± 4.50	3.45 ± 6.18	4.95 ± 4.77	7.40 ± 7.15	5.89 ± 5.21	0.187 (0.06)	0.244 (0.02)	0.202 (0.06)
Peak ext rot angle (°)	-2.64 ± 4.02	-8.88 ± 4.39	-7.16 ± 7.29	-4.63 ± 5.41	-8.00 ± 6.59	-3.94 ± 5.67	0.029* (0.12)	0.624 (0.00)	0.317 (0.04)
Range transverse angle (°)	10.34 ± 3.72	11.16 ± 5.00	10.60 ± 3.75	10.52 ± 3.35	12.95 ± 6.89	11.34 ± 4.49	0.520 (0.02)	0.439 (0.01)	0.850 (0.01)
Peak int rot moment (Nm/kg/m)	0.30 ± 0.09	0.34 ± 0.07	0.35 ± 0.12	0.40 ± 0.10	0.33 ± 0.10	0.35 ± 0.10	0.790 (0.01)	0.224 (0.03)	0.153 (0.06)
Peak ext rot moment (Nm/kg/m)	-0.10 ± 0.07	-0.03 ± 0.02	-0.03 ± 0.04	-0.06 ± 0.04	-0.05 ± 0.03	-0.03 ± 0.03	<0.001* (0.24)	0.377 (0.01)	0.120 (0.07)
Peak vGRF (BW) ^	4.65 ± 0.83	4.00 ± 0.79	3.22 ± 0.35	4.44 ± 0.72	3.99 ± 0.17	3.61 ± 0.75	<0.001* (0.31)	0.860 (0.00)	0.279 (0.04)
Time to peak knee flexion (s)	0.27 ± 0.11	0.23 ± 0.09	0.25 ± 0.05	0.24 ± 0.09	0.22 ± 0.07	0.25 ± 0.06	0.530 (0.02)	0.555 (0.01)	0.847 (0.01)
Stance time (s)	0.51 ± 0.15	0.52 ± 0.16	0.54 ± 0.13	0.49 ± 0.13	0.50 ± 0.13	0.59 ± 0.16	0.267 (0.05)	0.883 (0.00)	0.647 (0.02)
Jump height (cm) ^	5.41 ± 2.55	12.12 ± 5.12	15.23 ± 4.32	6.41 ± 2.45	10.34 ± 3.75	8.65 ± 2.33	<0.001* (0.40)	0.007* (0.12)	0.003† (0.18)

Note: \* significant main effects ( $p < 0.05$ ) † significant interaction effect ( $p < 0.05$ ) from 2x3 way analysis of variance ^ log transformed metrics. BW = body weight, ext rot = external rotation, GRF = ground reaction force, PKF = peak knee flexion, int rot = internal rotation.

**Table 29** Pairwise comparisons for the main effects of maturation during the single-leg rotating drop-land and hop (ROT) task on the dominant leg, where no interactions were indicated. Hedges' *g* and interpretation provided when significant differences ( $p < 0.05$ ) indicated.

Pairwise comparison		Mean difference [95% CI]	<i>p</i> value	<i>g</i> (magnitude)
<b>Peak flexion moment (Nm/kg/m)</b>				
Pre	Mid	0.00 [-0.09, 0.08]	0.903	—
Pre	Post	0.13 [0.05, 0.21]	0.001*	1.048 ( <i>large</i> )
Mid	Post	0.14 [0.05, 0.22]	0.002*	1.120 ( <i>large</i> )
<b>Peak valgus angle (°)</b>				
Pre	Mid	3.00 [0.20, 5.80]	0.036*	0.781 ( <i>medium</i> )
Pre	Post	3.73 [1.01, 6.46]	0.008*	0.844 ( <i>large</i> )
Mid	Post	0.73 [-2.12, 3.58]	0.608	—
<b>Peak varus angle (°)</b>				
Pre	Mid	2.36 [-0.29, 5.02]	0.080	—
Pre	Post	3.31 [0.72, 5.89]	0.013*	0.758 ( <i>medium</i> )
Mid	Post	0.94 [-1.76, 3.65]	0.488	—
<b>Peak varus moment (Nm/kg/m)</b>				
Pre	Mid	-0.16 [-0.26, -0.06]	0.002*	1.030 ( <i>large</i> )
Pre	Post	-0.20 [-0.29, -0.10]	<0.001*	1.151 ( <i>large</i> )
Mid	Post	-0.04 [-0.14, 0.07]	0.484	—
<b>Peak ext rot angle (°)</b>				
Pre	Mid	5.51 [1.63, 9.38]	0.006*	0.989 ( <i>large</i> )
Pre	Post	2.62 [-1.16, 6.39]	0.170	—
Mid	Post	-2.89 [-6.84, 1.05]	0.148	—
<b>Peak ext rot moment (Nm/kg/m)</b>				
Pre	Mid	-0.05 [-0.07, -0.02]	0.002*	0.979 ( <i>large</i> )
Pre	Post	-0.05 [-0.08, -0.03]	<0.001*	1.053 ( <i>large</i> )
Mid	Post	-0.01 [-0.04, 0.02]	0.625	—
<b>Peak vGRF (BW)</b>				
Pre	Mid	0.56 [0.14, 0.97]	0.009*	0.814 ( <i>large</i> )
Pre	Post	1.14 [0.74, 1.54]	<0.001*	1.651 ( <i>large</i> )
Mid	Post	0.58 [0.16, 1.00]	0.007*	0.996 ( <i>large</i> )

Note: \*Significant difference ( $p < 0.05$  from pairwise comparisons).  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size. BW = body weight, CI = confidence intervals, ext rot = external rotation, vGRF = vertical ground reaction force.

### 5.2.6 ROT non-dominant leg

A statistically significant interaction effect was observed between sex and maturation for peak knee valgus moment ( $F_{(2, 54)} = 3.353, p = 0.042$ ) and jump height ( $F_{(2, 54)} = 5.684, p = 0.006$ ). For peak knee valgus moment, pairwise comparisons showed that within males, the mid-pubertal had higher moments than pre-pubertal ( $p = 0.036, g = 1.408$  *large*). Additionally, within the pre-pubertal group, females had a higher peak knee valgus moment than males ( $p = 0.046, g = 0.392$  *small*). For jump height, pairwise comparisons showed that mid-pubertal jumped higher than pre-pubertal within both females ( $p = 0.043, g = 1.032$  *large*) and males ( $p < 0.001, g = 1.631$  *large*). Within the males, the post-pubertal group also jumped higher than the mid-pubertal ( $p = 0.015, g = 0.784$  *medium*) and the pre-pubertal ( $p < 0.001, g = 2.536$  *large*) groups. Furthermore, within the post-pubertal group, males jumped higher than females ( $p < 0.001, g = 0.516$  *medium*).

Statistically significant main effects were observed for peak knee flexion angle ( $F_{(2, 54)} = 3.310, p = 0.044$ ), peak knee flexion moment ( $F_{(2, 54)} = 7.315, p = 0.002$ ), peak knee varus moment ( $F_{(2, 54)} = 11.710, p < 0.001$ ), peak knee external rotation moment ( $F_{(2, 54)} = 11.706, p < 0.001$ ), and peak vGRF ( $F_{(2, 54)} = 22.082, p < 0.001$ ), as shown in Table 29. Pairwise comparisons (Table 30) showed that the pre-pubertal and post-pubertal groups had significantly higher peak knee flexion angles ( $p = 0.041, g =$  *medium*;  $p = 0.022, g =$  *large*, respectively) and peak knee flexion moments ( $p = 0.001, g =$  *large*;  $p = 0.003, g =$  *large*, respectively) than mid-pubertal. The mid-pubertal and post-pubertal groups had significantly higher peak knee varus moments ( $p = 0.001, g =$  *large*;  $p < 0.001, g =$  *large*, respectively) and peak knee external rotation moments ( $p = 0.001, g =$  *large*;  $p < 0.001, g =$  *large*, respectively) than pre-pubertal. Also, peak vGRF was higher in the pre-pubertal group compared to the post-pubertal and mid-pubertal ( $p = 0.001, g =$  *large*;  $p = 0.000, g =$  *large*, respectively) and higher in mid-pubertal than post-pubertal ( $p = 0.003, g =$  *large*).

No main effects of sex were observed for any of the metrics of the non-dominant leg. The results of the dominant and non-dominant legs for the ROT task are summarised in Figure 17.

**Table 30** The interaction between sex and maturation stage groups during the single-leg rotating drop-land and hop (ROT) task on the non-dominant leg for biomechanical variables associated with anterior cruciate ligament (ACL) injury risk shown as mean and standard deviations (SD), performed by 2x3 way analysis of variance.

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak flexion angle (°)</b>	61.32 ± 7.47	58.16 ± 11.10	61.27 ± 7.22	62.97 ± 5.22	55.94 ± 6.61	64.04 ± 5.36	0.044* (0.11)	0.708 (0.00)	0.555 (0.02)
<b>Peak extension angle (°)</b>	13.51 ± 4.39	13.35 ± 4.79	13.83 ± 3.75	12.24 ± 3.70	11.76 ± 4.59	16.29 ± 3.84	0.137 (0.07)	0.941 (0.00)	0.276 (0.05)
<b>Range sagittal angle (°)</b>	47.97 ± 5.24	44.80 ± 8.44	47.43 ± 6.34	50.73 ± 6.03	44.18 ± 5.91	47.76 ± 3.73	0.053 (0.10)	0.608 (0.01)	0.676 (0.01)
<b>Peak flexion moment (Nm/kg/m)</b>	0.50 ± 0.19	0.47 ± 0.13	0.39 ± 0.05	0.51 ± 0.10	0.52 ± 0.14	0.34 ± 0.11	0.002* (0.21)	0.956 (0.00)	0.552 (0.02)
<b>Peak extension moment (Nm/kg/m)</b>	-1.65 ± 0.30	-1.51 ± 0.28	-1.59 ± 0.38	-1.83 ± 0.19	-1.66 ± 0.22	-1.56 ± 0.30	0.138 (0.07)	0.180 (0.03)	0.479 (0.03)
<b>Peak valgus angle (°)</b>	10.13 ± 5.43	3.67 ± 5.80	3.24 ± 2.75	6.06 ± 3.59	6.45 ± 4.87	5.54 ± 6.21	0.053 (0.10)	0.794 (0.00)	0.065 (0.10)
<b>Peak varus angle (°)</b>	1.14 ± 4.38	-3.63 ± 3.97	-3.09 ± 2.34	-1.72 ± 3.75	-2.01 ± 5.78	-2.50 ± 6.16	0.147 (0.07)	0.853 (0.00)	0.289 (0.05)
<b>Range coronal angle (°) ^</b>	8.99 ± 3.81	7.29 ± 2.31	6.33 ± 1.44	7.78 ± 1.53	8.47 ± 3.22	8.04 ± 2.62	0.427 (0.03)	0.313 (0.02)	0.375 (0.04)
<b>Peak valgus moment (Nm/kg/m) ^</b>	0.31 ± 0.09	0.46 ± 0.11	0.38 ± 0.14	0.46 ± 0.26	0.37 ± 0.16	0.31 ± 0.17	0.410 (0.03)	0.927 (0.00)	0.042 <sup>†</sup> (0.11)
<b>Peak varus moment (Nm/kg/m)</b>	-0.43 ± 0.18	-0.21 ± 0.08	-0.15 ± 0.08	-0.32 ± 0.14	-0.23 ± 0.16	-0.20 ± 0.13	<0.001* (0.30)	0.671 (0.00)	0.144 (0.07)

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak int rot angle (°)</b>	11.10 ± 7.44	7.11 ± 5.60	7.40 ± 6.35	8.67 ± 5.67	7.21 ± 6.58	7.37 ± 5.56	0.335 (0.04)	0.633 (0.00)	0.781 (0.01)
<b>Peak ext rot angle (°)</b>	-1.89 ± 7.44	-5.61 ± 7.43	-3.69 ± 4.73	-2.73 ± 4.52	-5.11 ± 7.61	-7.19 ± 6.11	0.238 (0.05)	0.452 (0.01)	0.613 (0.02)
<b>Range transverse angle (°)</b>	12.99 ± 3.77	12.72 ± 3.16	11.09 ± 3.61	11.40 ± 4.24	12.32 ± 3.60	14.55 ± 3.82	0.866 (0.01)	0.610 (0.01)	0.085 (0.09)
<b>Peak int rot moment (Nm/kg/m) ^</b>	0.34 ± 0.09	0.32 ± 0.10	0.34 ± 0.10	0.38 ± 0.12	0.31 ± 0.11	0.30 ± 0.07	0.305 (0.04)	0.885 (0.00)	0.533 (0.02)
<b>Peak ext rot moment (Nm/kg/m)</b>	-0.10 ± 0.06	-0.04 ± 0.02	-0.03 ± 0.03	-0.06 ± 0.04	-0.04 ± 0.03	-0.03 ± 0.02	<0.001* (0.30)	0.671 (0.00)	0.144 (0.07)
<b>Peak vGRF (BW) ^</b>	4.73 ± 0.59	3.84 ± 0.75	3.15 ± 0.59	4.48 ± 0.74	4.04 ± 0.31	3.60 ± 0.40	<0.001* (0.44)	0.685 (0.00)	0.321 (0.04)
<b>Time to peak knee flexion (s)</b>	0.27 ± 0.12	0.25 ± 0.10	0.27 ± 0.08	0.23 ± 0.09	0.24 ± 0.09	0.27 ± 0.07	0.697 (0.01)	0.628 (0.00)	0.768 (0.01)
<b>Stance time (s)</b>	0.52 ± 0.14	0.54 ± 0.18	0.55 ± 0.15	0.50 ± 0.13	0.49 ± 0.12	0.60 ± 0.16	0.278 (0.04)	0.812 (0.00)	0.563 (0.02)
<b>Jump height (cm)</b>	5.84 ± 2.48	12.05 ± 4.80	16.10 ± 5.02	6.64 ± 2.61	10.24 ± 4.00	9.29 ± 2.90	<0.001* (0.38)	0.009* (0.12)	0.006† (0.17)

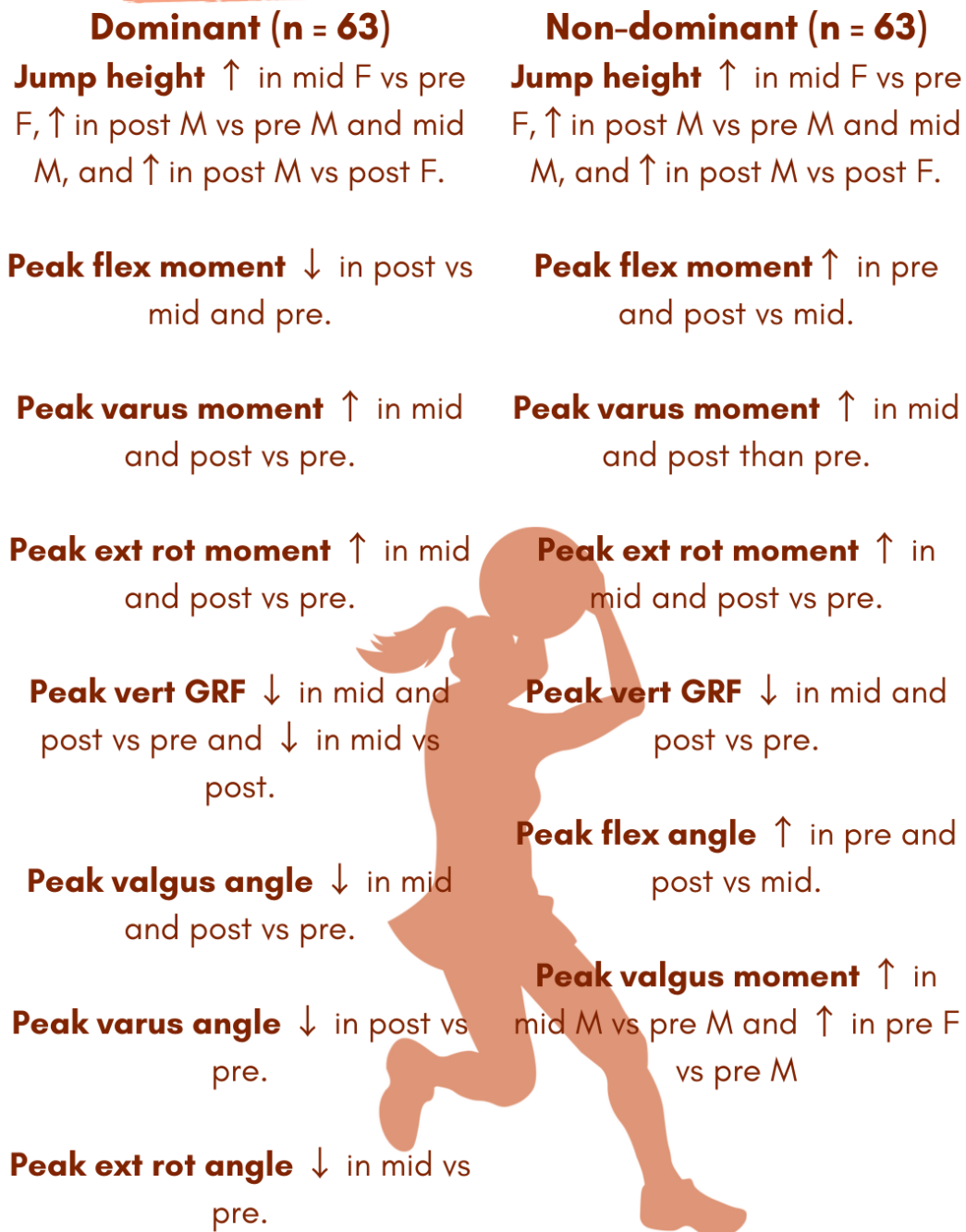
Note: \* significant main effects ( $p < 0.05$ ) † significant interaction effect ( $p < 0.05$ ) from 2x3 way analysis of variance ^ log transformed metrics. BW = body weight, ext rot = external rotation, GRF = ground reaction force, PKF = peak knee flexion, int rot = internal rotation.

**Table 31** Pairwise comparisons for the main effects of maturation during the single-leg rotating drop-land and hop (ROT) task on the non-dominant leg, where no interactions were indicated. Hedges' *g* and interpretation provided when significant differences ( $p < 0.05$ ) indicated.

Pairwise comparison		Mean difference [95% CI]	<i>p</i> value	<i>g</i> (magnitude)
<b>Peak flexion angle (°)</b>				
Pre	Mid	5.10 [0.22, 9.97]	0.041*	0.606 ( <i>medium</i> )
Pre	Post	-0.51 [-5.27, 4.24]	0.830	—
Mid	Post	-5.61 [-10.38, -0.84]	0.022*	0.833 ( <i>large</i> )
<b>Peak flexion moment (Nm/kg/m)</b>				
Pre	Mid	0.01 [-0.07, 0.10]	0.753	—
Pre	Post	0.14 [0.06, 0.22]	0.001*	1.121 ( <i>large</i> )
Mid	Post	0.13 [0.05, 0.21]	0.003*	1.024 ( <i>large</i> )
<b>Peak varus moment (Nm/kg/m)</b>				
Pre	Mid	-0.15 [-0.23, -0.06]	0.001*	1.081 ( <i>large</i> )
Pre	Post	-0.19 [-0.28, -0.11]	<0.001*	1.470 ( <i>large</i> )
Mid	Post	-0.05 [-0.13, 0.04]	0.286	—
<b>Peak ext rot moment (Nm/kg/m)</b>				
Pre	Mid	-0.04 [-0.06, -0.01]	0.002*	1.004 ( <i>large</i> )
Pre	Post	-0.05 [-0.07, -0.02]	<0.001*	1.221 ( <i>large</i> )
Mid	Post	-0.01 [-0.03, 0.01]	0.458	—
<b>Peak vGRF (BW)</b>				
Pre	Mid	0.67 [0.29, 1.04]	0.001*	1.068 ( <i>large</i> )
Pre	Post	1.23 [0.87, 1.59]	<0.001*	2.037 ( <i>large</i> )
Mid	Post	0.57 [0.19, 0.94]	0.003*	1.008 ( <i>large</i> )

Note: \*Significant difference ( $p < 0.05$  from pairwise comparisons).  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size. BW = body weight, CI = confidence intervals, ext rot = external rotation, vGRF = vertical ground reaction force.

## Biomechanical differences in maturation and sex during a rotate, land and jump task



**Figure 17** Single-leg rotating drop-land and hop (ROT) task results infographic. Note: ext, external; F, females; flex, flexion; GRF, ground reaction force; M, males; mid, early/mid-pubertal; post, late/post-pubertal; pre, pre-pubertal; rot, rotation; vert, vertical.

### 5.2.7 VERT dominant leg

A statistically significant interaction effect was observed between sex and maturation stage for peak knee extension angle ( $F_{(2, 56)} = 3.684, p = 0.031$ ) and jump height ( $F_{(2, 56)} = 6.530, p = 0.003$ ). No significant interaction effects were observed for any other metrics (Table 31). Pairwise comparisons revealed that, within the females, the post-pubertal had a greater peak knee extension angle than the pre-pubertal group ( $p = 0.010, g = 1.358$  *large*); and within the males, mid-pubertal were greater than pre-pubertal ( $p = 0.014, g = 1.045$  *large*). Furthermore, within the mid-pubertal group, peak knee extension angle was significantly greater in males than females ( $p = 0.041, g = 0.477$  *small*). For jump height, within the males, both the post-pubertal ( $p < 0.001, g = 2.584$  *large*) and the mid-pubertal ( $p < 0.001, g = 1.852$  *large*) group jumped higher than pre-pubertal. Additionally, within the post-pubertal group, males jumped higher than females ( $p < 0.001, g = 1.678$  *large*).

Statistically significant main effects of maturation were observed for peak knee flexion moment ( $F_{(2, 56)} = 10.169, p < 0.001$ ), peak knee valgus moment ( $F_{(2, 56)} = 6.819, p = 0.002$ ), peak knee varus moment ( $F_{(2, 56)} = 5.299, p = 0.008$ ), peak knee external rotation moment ( $F_{(2, 56)} = 3.754, p = 0.030$ ), and peak vGRF ( $F_{(2, 56)} = 19.359, p < 0.001$ ). Based on pairwise comparisons (Table 32), significantly greater peak knee flexion moments were observed in pre-pubertal ( $p < 0.001, g =$  *large*) and mid-pubertal ( $p = 0.008, g =$  *large*) groups than post-pubertal. The pre-pubertal group had a significantly higher peak knee valgus moment, than the mid-pubertal ( $p = 0.004, g =$  *large*) and post-pubertal groups ( $p = 0.002, g =$  *large*), but a significantly lower peak knee varus moment than post-pubertal ( $p = 0.002, g =$  *large*). For peak external rotation moment, the pre-pubertal group had significantly lower moments than post-pubertal ( $p = 0.006, g =$  *large*). Higher vGRFs were seen in pre-pubertal than post-pubertal ( $p < 0.001, g =$  *large*) and mid-pubertal ( $p < 0.001, g =$  *large*), and furthermore in mid-pubertal than post-pubertal ( $p = 0.022, g =$  *medium*).

No main effects of sex were observed for any of the metrics of the dominant leg.

**Table 32** The interaction between sex and maturation stage groups during the single-leg drop-land and vertical hop (VERT) task on the dominant leg for biomechanical variables associated with anterior cruciate ligament (ACL) injury risk shown as mean and standard deviations (SD), performed by 2x3 way analysis of variance.

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak flexion angle (°)</b>	62.51 ± 7.58	61.61 ± 11.14	61.43 ± 9.51	62.85 ± 8.83	59.06 ± 6.32	65.03 ± 8.96	0.555 (0.02)	0.839 (0.00)	0.544 (0.02)
<b>Peak extension angle (°)</b>	12.65 ± 3.95	18.21 ± 6.63	14.08 ± 6.18	11.56 ± 3.09	13.29 ± 3.82	17.83 ± 5.64	0.031* (0.12)	0.568 (0.01)	0.031 <sup>†</sup> (0.12)
<b>Range sagittal angle (°)</b>	49.87 ± 6.40	43.40 ± 8.63	47.34 ± 9.84	51.29 ± 9.90	45.77 ± 6.68	47.20 ± 7.02	0.080 (0.09)	0.565 (0.01)	0.885 (0.00)
<b>Peak flexion moment (Nm/kg/m)</b>	0.52 ± 0.14	0.43 ± 0.11	0.40 ± 0.07	0.57 ± 0.14	0.54 ± 0.18	0.35 ± 0.13	0.001* (0.27)	0.278 (0.02)	0.146 (0.07)
<b>Peak extension moment (Nm/kg/m)</b>	-1.73 ± 0.28	-1.70 ± 0.31	-1.55 ± 0.28	-1.85 ± 0.31	-1.62 ± 0.25	-1.74 ± 0.34	0.207 (0.06)	0.339 (0.02)	0.321 (0.04)
<b>Peak valgus angle (°)</b>	7.42 ± 3.84	5.37 ± 4.64	5.89 ± 5.85	7.29 ± 2.87	6.25 ± 4.75	4.22 ± 5.59	0.284 (0.04)	0.803 (0.00)	0.690 (0.01)
<b>Peak varus angle (°)</b>	-1.07 ± 4.18	-1.98 ± 3.43	-3.00 ± 4.55	-0.13 ± 2.25	-1.24 ± 5.15	-2.55 ± 4.43	0.239 (0.05)	0.505 (0.01)	0.981 (0.00)
<b>Range coronal angle (°)</b>	8.49 ± 2.51	7.35 ± 3.10	8.88 ± 3.28	7.43 ± 2.06	7.49 ± 2.83	6.77 ± 1.77	0.811 (0.01)	0.152 (0.04)	0.427 (0.03)
<b>Peak valgus moment (Nm/kg/m) ^</b>	0.56 ± 0.25	0.38 ± 0.11	0.43 ± 0.14	0.54 ± 0.14	0.41 ± 0.21	0.33 ± 0.08	0.002* (0.20)	0.412 (0.01)	0.469 (0.03)
<b>Peak varus moment (Nm/kg/m)</b>	-0.35 ± 0.21	-0.21 ± 0.07	-0.16 ± 0.11	-0.30 ± 0.17	-0.23 ± 0.15	-0.18 ± 0.11	0.004* (0.18)	0.954 (0.00)	0.745 (0.01)

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak int rot angle (°)</b>	7.61 ± 4.21	3.76 ± 5.34	5.02 ± 6.56	7.93 ± 4.09	6.29 ± 5.22	7.49 ± 6.11	0.281 (0.04)	0.200 (0.03)	0.755 (0.01)
<b>Peak ext rot angle (°)</b>	-4.39 ± 7.17	-8.63 ± 5.78	-6.52 ± 8.39	-4.86 ± 5.37	-7.14 ± 6.18	-6.02 ± 5.52	0.310 (0.04)	0.767 (0.00)	0.897 (0.00)
<b>Range transverse angle (°)</b>	12.00 ± 5.34	12.39 ± 3.52	11.53 ± 3.78	12.79 ± 3.16	13.43 ± 7.12	13.52 ± 2.98	0.573 (0.00)	0.247 (0.02)	0.732 (0.01)
<b>Peak int rot moment (Nm/kg/m) ^</b>	0.36 ± 0.09	0.33 ± 0.05	0.31 ± 0.12	0.36 ± 0.12	0.32 ± 0.09	0.32 ± 0.05	0.374 (0.03)	0.918 (0.00)	0.736 (0.01)
<b>Peak ext rot moment (Nm/kg/m) ^</b>	-0.09 ± 1.10	-0.05 ± 0.05	-0.03 ± 0.03	-0.06 ± 0.07	-0.03 ± 0.03	-0.02 ± 0.03	0.030* (0.12)	0.104 (0.05)	0.568 (0.02)
<b>Peak vGRF (BW)</b>	4.81 ± 0.65	3.81 ± 0.85	3.28 ± 0.53	4.62 ± 0.78	4.04 ± 0.31	3.59 ± 0.69	<0.001* (0.41)	0.511 (0.01)	0.858 (0.03)
<b>Time to peak knee flexion (s)</b>	0.23 ± 0.09	0.22 ± 0.05	0.24 ± 0.07	0.22 ± 0.06	0.19 ± 0.03	0.21 ± 0.08	0.541 (0.02)	0.138 (0.04)	0.923 (0.00)
<b>Stance time (s)</b>	0.48 ± 0.14	0.49 ± 0.12	0.51 ± 0.14	0.47 ± 0.13	0.42 ± 0.09	0.51 ± 0.16	0.409 (0.03)	0.419 (0.01)	0.650 (0.02)
<b>Jump height (cm) ^</b>	6.23 ± 2.34	13.21 ± 4.60	15.77 ± 4.49	7.58 ± 2.22	11.61 ± 5.35	8.14 ± 4.33	<0.001* (0.29)	0.015 (0.10)	0.003 (0.19)

Note: \* significant main effects ( $p < 0.05$ ) † significant interaction effect ( $p < 0.05$ ) from 2x3 way analysis of variance ^ log transformed metrics. BW = body weight, ext rot = external rotation, GRF = ground reaction force, PKF = peak knee flexion, int rot = internal rotation.

**Table 33** Pairwise comparisons for the main effects of maturation during the single-leg drop-land and vertical hop (VERT) task on the dominant leg, where no interactions were indicated. Hedges' *g* and interpretation provided when significant differences ( $p < 0.05$ ) indicated.

Pairwise comparison		Mean difference [95% CI]	<i>p</i> value	<i>g</i> (magnitude)
<b>Peak flexion moment (Nm/kg/m)</b>				
Pre	Mid	0.07 [-0.02, 0.15]	0.116	—
Pre	Post	0.18 [0.10, 0.26]	<0.001*	0.665 ( <i>medium</i> )
Mid	Post	0.11 [0.03, 0.19]	0.008*	0.853 ( <i>large</i> )
<b>Peak valgus moment (Nm/kg/m)</b>				
Pre	Mid	0.16 [0.05, 0.26]	0.004*	0.870 ( <i>large</i> )
Pre	Post	0.17 [0.07, 0.27]	0.002*	0.983 ( <i>large</i> )
Mid	Post	0.01 [-0.09, 0.12]	0.839	—
<b>Peak varus moment (Nm/kg/m)</b>				
Pre	Mid	-0.10 [-0.19, 0.00]	0.055	—
Pre	Post	-0.15 [-0.25, -0.06]	0.002*	0.984 ( <i>large</i> )
Mid	Post	-0.06 [-0.15, 0.04]	0.244	—
<b>Peak ext rot moment (Nm/kg/m)</b>				
Pre	Mid	-0.03 [-0.07, 0.00]	0.067	—
Pre	Post	-0.05 [-0.09, -0.01]	0.006*	0.837 ( <i>large</i> )
Mid	Post	-0.02 [-0.05, 0.02]	0.381	—
<b>Peak vGRF (BW)</b>				
Pre	Mid	0.81 [0.39, 1.23]	<0.001*	1.167 ( <i>large</i> )
Pre	Post	1.30 [0.89, 1.72]	<0.001*	1.931 ( <i>large</i> )
Mid	Post	0.49 [0.07, 0.90]	0.021*	0.751 ( <i>medium</i> )

Note: \*Significant difference ( $p < 0.05$  from pairwise comparisons).  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size. BW = body weight, CI = confidence intervals, ext rot = external rotation, vGRF = vertical ground reaction force.

### 5.2.8 VERT non-dominant leg

Statistically significant interaction effects were observed between sex and maturation stage for knee range of transverse angle ( $F_{(2, 54)} = 3.404, p = 0.041$ ) and jump height ( $F_{(2, 54)} = 3.087, p < 0.001$ ) with the other metrics showing no interaction (Table 33). Pairwise comparisons revealed that, within the post-pubertal group, females had significantly larger ranges than males ( $p = 0.038; g = 0.911$  *large*). For jump height, within the males, both the post-pubertal ( $p < 0.001, g = 2.130$  *large*) and the mid-pubertal ( $p = 0.001, g = 1.557$  *large*) group jumped higher than pre-pubertal. Furthermore, within the post-pubertal group, males jumped higher than females ( $p < 0.001, g = 1.518$  *large*).

Statistically significant main effects were observed for peak knee flexion moment ( $F_{(2, 54)} = 3.970, p = 0.025$ ), peak knee varus moment ( $F_{(2, 54)} = 4.616, p = 0.014$ ), peak knee internal rotation moment ( $F_{(2, 54)} = 3.970, p = 0.025$ ), peak knee external rotation moment ( $F_{(2, 54)} = 7.405, p < 0.001$ ), and peak vGRF ( $F_{(2, 54)} = 15.723, p < 0.001$ ). Based on pairwise comparisons (Table 34), the pre-pubertal group had a significantly higher peak knee flexion moment than post-pubertal ( $p = 0.006, g =$  *medium*). The pre-pubertal group had significant lower peak knee varus moments and peak knee external rotation moments than the mid-pubertal ( $p = 0.039, g =$  *medium*;  $p = 0.008, g =$  *large*, respectively) and post-pubertal ( $p = 0.005, g =$  *large*;  $p < 0.001, g =$  *large*, respectively). Higher vGRFs were seen in pre-pubertal than post-pubertal ( $p < 0.001, g =$  *large*) and mid-pubertal ( $p = 0.001, g =$  *large*), and in mid-pubertal than post-pubertal ( $p = 0.023, g =$  *medium*). For peak knee internal rotation moment, no significant pairwise comparisons were observed.

No main effects of sex were observed for any of the metrics of the non-dominant leg. The results of the dominant and non-dominant legs for the VERT task are summarised in Figure 18.

**Table 34** The interaction between sex and maturation stage groups during the single-leg drop-land and vertical hop (VERT) task on the non-dominant leg for biomechanical variables associated with anterior cruciate ligament (ACL) injury risk shown as mean and standard deviations (SD), performed by 2x3 way analysis of variance.

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
Peak flexion angle (°)	57.53 ± 9.29	59.43 ± 9.91	59.22 ± 7.78	61.85 ± 10.34	56.27 ± 5.57	63.26 ± 7.33	0.473 (0.03)	0.439 (0.01)	0.313 (0.04)
Peak extension angle (°)	12.39 ± 5.48	15.43 ± 6.20	13.48 ± 5.36	11.20 ± 2.91	11.92 ± 4.81	17.21 ± 4.74	0.093 (0.08)	0.808 (0.00)	0.083 (0.09)
Range sagittal angle (°)	45.14 ± 8.764	44.00 ± 8.19	45.74 ± 5.30	50.65 ± 10.38	44.35 ± 6.00	46.04 ± 6.27	0.323 (0.04)	0.308 (0.02)	0.472 (0.03)
Peak flexion moment (Nm/kg/m) ^	0.50 ± 0.20	0.43 ± 0.10	0.44 ± 0.10	0.54 ± 0.13	0.46 ± 0.11	0.36 ± 0.14	0.025* (0.13)	0.893 (0.00)	0.118 (0.08)
Peak extension moment (Nm/kg/m)	-1.63 ± 0.35	-1.46 ± 0.26	-1.47 ± 0.37	-1.79 ± 0.31	-1.65 ± 0.15	-1.56 ± 0.29	0.110 (0.08)	0.067 (0.06)	0.860 (0.01)
Peak valgus angle (°)	7.13 ± 3.33	5.16 ± 6.71	3.47 ± 3.58	7.23 ± 3.97	5.29 ± 4.00	5.16 ± 6.58	0.170 (0.06)	0.615 (0.01)	0.841 (0.01)
Peak varus angle (°)	-0.68 ± 3.51	-2.43 ± 3.85	-2.99 ± 2.95	-0.70 ± 4.70	-3.08 ± 5.00	-2.74 ± 5.30	0.186 (0.06)	0.919 (0.00)	0.941 (0.00)
Range coronal angle (°)	7.81 ± 1.66	7.59 ± 3.01	6.46 ± 1.76	7.85 ± 2.41	8.37 ± 2.94	7.90 ± 2.38	0.533 (0.02)	0.228 (0.03)	0.648 (0.02)
Peak valgus moment (Nm/kg/m)	0.49 ± 0.16	0.48 ± 0.12	0.36 ± 0.12	0.46 ± 0.26	0.38 ± 0.18	0.33 ± 0.16	0.061 (0.10)	0.259 (0.02)	0.788 (0.009)
Peak varus moment (Nm/kg/m) ^	-0.32 ± 0.25	-0.19 ± 0.08	-0.12 ± 0.07	-0.29 ± 0.16	-0.22 ± 0.15	-0.21 ± 0.12	0.014* (0.15)	0.444 (0.01)	0.480 (0.101)

Variable	Males			Females			Effects p value ( $\eta_p^2$ )		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
<b>Peak int rot angle (°)</b>	9.89 ± 8.63	7.89 ± 5.55	6.91 ± 7.15	9.45 ± 5.65	6.13 ± 5.52	7.34 ± 4.52	0.341 (0.04)	0.726 (0.00)	0.868 (0.005)
<b>Peak ext rot angle (°)</b>	-4.35 ± 7.86	-3.97 ± 7.00	-4.57 ± 5.78	-2.15 ± 4.85	-5.62 ± 5.89	-7.82 ± 5.86	0.346 (0.04)	0.588 (0.01)	0.381 (0.04)
<b>Range transverse angle (°)</b>	14.24 ± 5.19	11.86 ± 3.60	11.47 ± 4.76	11.59 ± 2.45	11.76 ± 3.60	15.17 ± 2.97	0.463 (0.03)	0.758 (0.00)	0.041 ^ (0.11)
<b>Peak int rot moment (Nm/kg/m)</b>	0.30 ± 0.09	0.31 ± 0.09	0.27 ± 0.10	0.32 ± 0.13	0.27 ± 0.11	0.23 ± 0.09	0.171 (0.06)	0.413 (0.01)	0.025 ^ (0.13)
<b>Peak ext rot moment (Nm/kg/m)</b>	-0.11 ± 0.07	-0.05 ± 0.04	-0.05 ± 0.04	-0.09 ± 0.05	-0.06 ± 0.05	-0.04 ± 0.04	< 0.001* (0.22)	0.678 (0.00)	0.747 (0.01)
<b>Peak vGRF (BW)</b>	4.74 ± 0.71	3.87 ± 0.66	3.37 ± 0.59	4.35 ± 0.59	4.02 ± 0.36	3.66 ± 0.50	<0.001* (0.36)	0.911 (0.00)	0.157 (0.07)
<b>Time to PKF (s)</b>	0.23 ± 0.09	0.24 ± 0.08	0.23 ± 0.05	0.22 ± 0.07	0.19 ± 0.03	0.23 ± 0.07	0.823 (0.01)	0.331 (0.02)	0.460 (0.03)
<b>Stance time (s)</b>	0.48 ± 0.15	0.51 ± 0.15	0.50 ± 0.13	0.46 ± 0.10	0.42 ± 0.08	0.52 ± 0.14	0.449 (0.03)	0.386 (0.01)	0.387 (0.03)
<b>Jump height (cm)</b>	7.23 ± 3.09	12.99 ± 3.94	15.56 ± 4.34	7.25 ± 2.75	10.52 ± 5.52	9.47 ± 3.33	<0.001* (0.28)	0.006* (0.13)	0.054 (0.10)

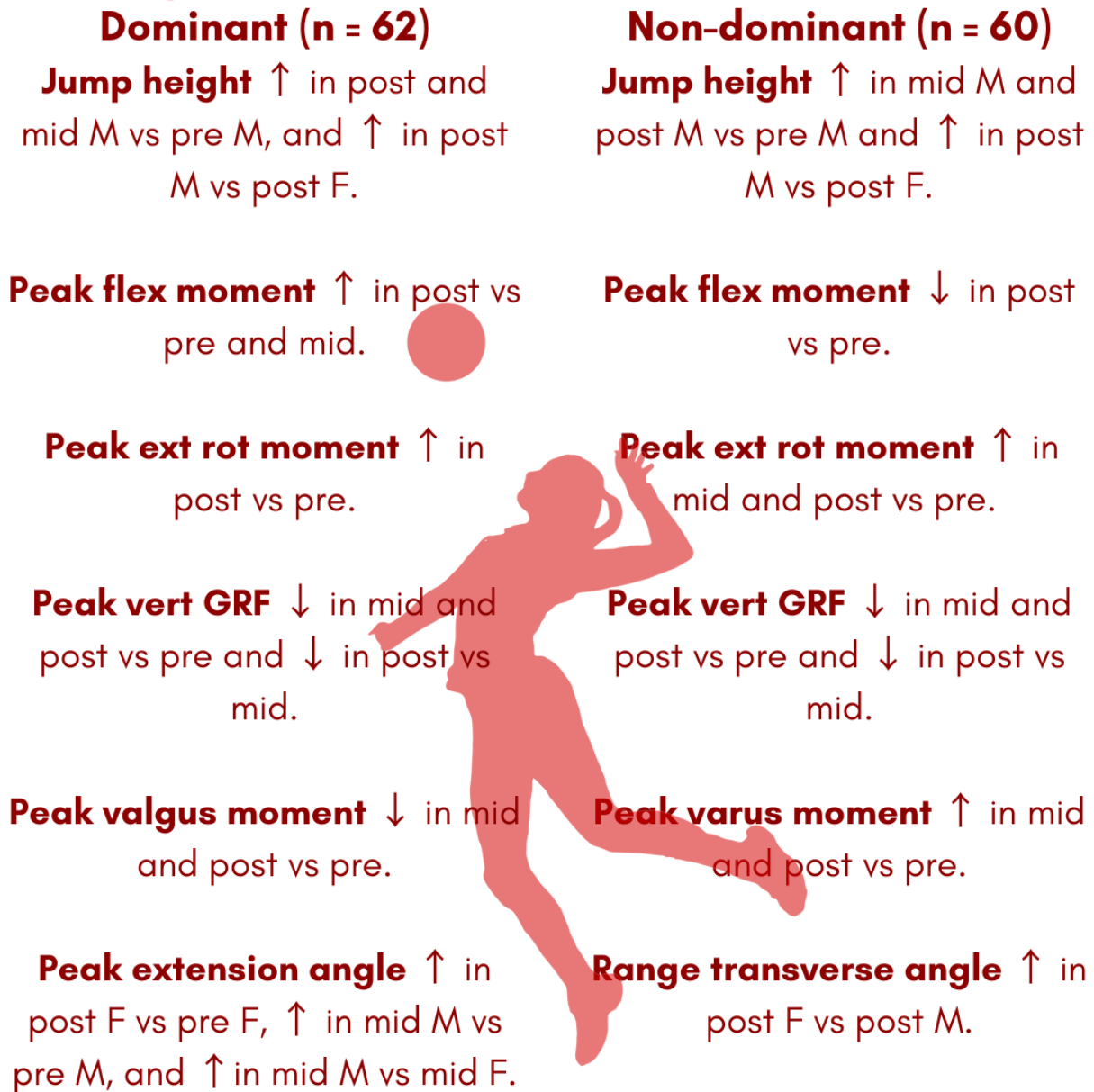
Note: \* significant main effects ( $p < 0.05$ ) † significant interaction effect ( $p < 0.05$ ) from 2x3 way analysis of variance ^ log transformed metrics. Nm = newton metres, kg = kilogram, m = metre, int rot = internal rotation, ext rot = external rotation, GRF = ground reaction force, BW = body weight, PKF = peak knee flexion, s = seconds, cm = centimetres

**Table 35** Pairwise comparisons for the main effects of maturation during the single-leg drop-land and vertical hop (VERT) task on the non-dominant leg, where no interactions were indicated. Hedges' *g* and interpretation provided when significant differences ( $p < 0.05$ ) indicated.

Pairwise Comparisons		Mean difference [95% CI]	P value	<i>g</i> (magnitude)
<b>Peak flexion moment (Nm/kg/m)</b>				
Pre	Mid	0.08 [-0.01, 0.16]	0.088	—
Pre	Post	0.12 [0.04, 0.21]	0.006*	0.791 ( <i>medium</i> )
Mid	Post	0.05 [-0.04, 0.13]	0.297	—
<b>Peak varus moment (Nm/kg/m)</b>				
Pre	Mid	-0.10 [-0.20, 0.01]	0.039*	0.624 ( <i>medium</i> )
Pre	Post	-0.14 [-0.24, -0.04]	0.005*	0.853 ( <i>large</i> )
Mid	Post	-0.04 [-0.14, 0.06]	0.446	—
<b>Peak ext rot moment (Nm/kg/m)</b>				
Pre	Mid	-0.04 [-0.08, -0.01]	0.008*	0.845 ( <i>large</i> )
Pre	Post	-0.06 [-0.09, -0.03]	0.001*	1.130 ( <i>large</i> )
Mid	Post	-0.01 [-0.05, 0.02]	0.369	—
<b>Peak vGRF (BW)</b>				
Pre	Mid	0.63 [0.18, 1.07]	0.001*	0.999 ( <i>large</i> )
Pre	Post	1.06 [0.61, 1.50]	<0.001*	1.671 ( <i>large</i> )
Mid	Post	0.43 [-0.01, 0.87]	0.023*	0.766 ( <i>medium</i> )

Note: \*Significant difference ( $p < 0.05$  from pairwise comparisons).  $g = 0.2$ , *small* effect size;  $g = 0.5$ , *medium* effect size;  $g = 0.8$ , *large* effect size. BW = body weight, CI = confidence intervals, ext rot = external rotation, vGRF = vertical ground reaction force.

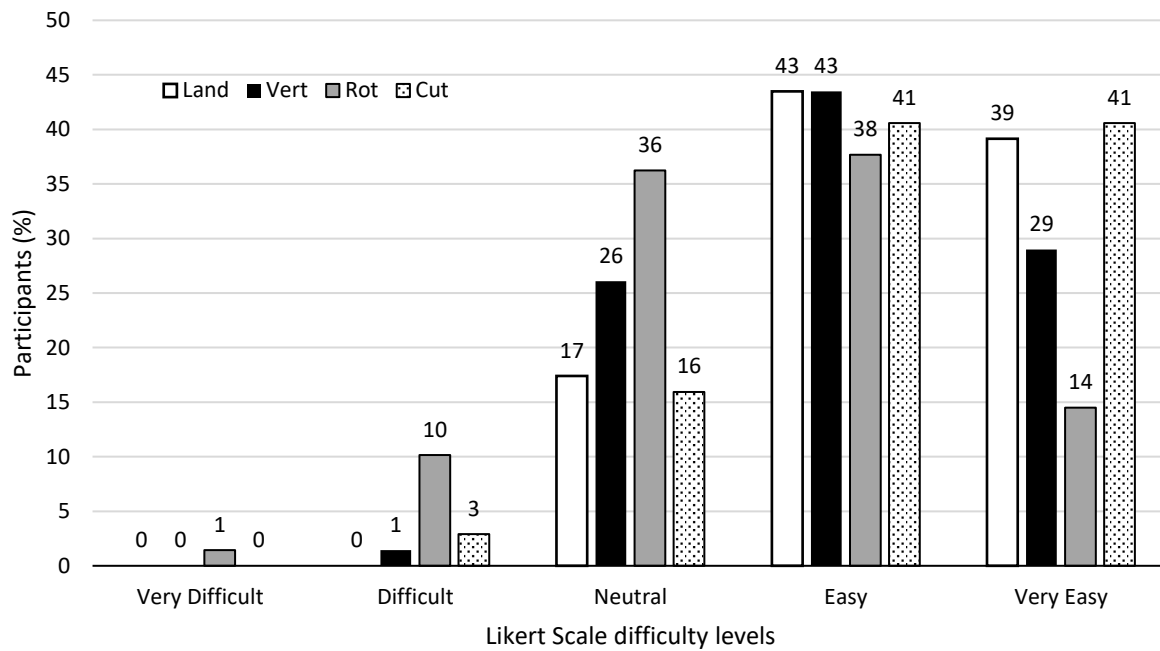
# Biomechanical differences in maturation and sex during a land and vert jump task



**Figure 18** Single-leg drop-land and vertical hop (VERT) task results infographic. *Note:* ext, external; F, females; flex, flexion; GRF, ground reaction force; M, males; mid, early/mid-pubertal; post, late/post-pubertal; pre, pre-pubertal; rot, rotation; vert, vertical.

### 5.3 Subjective task difficulty

Subjective ratings of task difficulty significantly differed between tasks ( $\chi^2(3) = 38.370, p < 0.001$ ). Post-hoc analysis revealed greater levels of difficulty in ROT compared to LAND ( $Z = -1.958, p < 0.001$ ), CUT ( $Z = -4.560, p < 0.001$ ), and VERT ( $Z = -3.654, p < 0.001$ ). No significant differences were observed between the other tasks. All tasks received a median and a mode of “easy”, except for the CUT which had a mode of “very easy”. One percent of participants rated the ROT as “very difficult” and 10% as “difficult”. The relative frequencies of the subjective difficulty rankings are presented in Figure 19.



**Figure 19** Bar chart showing the subjective ratings from participants ( $n = 69$ ) of perceived task difficulty across the four different landing tasks.

## 6.0 Chapter 6 – Discussion

It has been suggested that males and females exhibit increasingly different biomechanics during dynamic tasks as they mature (Holden et al., 2016). Currently, high-quality original research examining landing biomechanics in males and females across different maturational phases is scarce and the lack of consensus between studies that do exist limits conclusive inferences (Butcher et al., 2024). Previous studies have focussed on the metrics of knee flexion angle, knee valgus angle, knee valgus moment, and vGRF as these have previously been reported to be related to ACL injury risk mechanisms (Butcher et al., 2024). Therefore, the findings of these key metrics will be discussed before interpreting the results of each of the tasks (LAND, CUT, ROT, and VERT) in more detail.

The primary aim of the experimental studies was to explore potential differences between sex and maturation stage on biomechanics associated with risk of ACL injury. A secondary aim was to assess the reliability of knee biomechanics, vGRF, and task specific performance metrics. The reliability results are discussed first as establishing reliability is crucial before interpreting any differences in these metrics between maturation stages and sexes.

### 6.1 Reliability

The purpose of this study was to assess the reliability of 3D kinematic and kinetic variables during four different single-leg landing tasks in young athletes. Based on previous research (Hanzlíková & Hébert-Losier, 2020; Hanzlíková et al., 2021; Ortiz et al., 2016), it was hypothesised that between session reliability would be *moderate* to *excellent* for coronal and sagittal plane knee biomechanics, GRF, and performance metrics, but adequate for transverse plane metrics for all four tasks. Contrary to the hypothesis, the findings indicated that most biomechanical and performance metrics had *moderate* to *excellent* reliability, however, *poor* levels of reliability were observed across more than one task for the metrics of: peak knee extension moment, knee sagittal

and transverse moment ranges, peak medial/ lateral GRF, and peak anterior/ posterior GRF.

Furthermore, marker placement reliability of the knee markers showed no systemic bias between trials based on paired *t* tests values (see Appendix AJ). The mean difference in position between trials ranged from -11.41 to 7.89 mm and did not exceed any of their respective TE values, suggesting no clinically meaningful differences. Similarly, a study by Fonseca et al. (2023) reported that between-day marker placement precision was within 10 mm with intra evaluator precision ranging from 4.2 to 5.3 mm in the anterior-posterior direction, from 2.1 to 4 mm in the medial-lateral direction, and from 4.5 to 5.9 mm in the proximal-distal direction. The lack of variation in marker placement strengthens the findings regarding assessment of change or group differences.

#### 6.1.1 Reliability metrics

In partial alignment with our hypothesis, adequate levels of reliability were observed for all metrics across all tasks aside from peak extension moment, moment ranges, anterior/ posterior GRF, and medial/ lateral GRF when interpreting ICC values. Large CV% values were commonly observed for most metrics. As the TEs were generally small, these larger CV% values are likely a reflection of the restricted range and low average values of metrics, potentially inflating these CV%s. The CV% is advantageous as a dimensionless measure that allows direct comparison of reliability irrespective of calibration or scaling (Hopkins, 2000). However, it may be more appropriate to focus on the raw TEs to establish the meaningfulness of change in the collected metrics. For instance, a change exceeding 3.5° of knee flexion in the LAND task would exceed the typical test-retest reliability and could be considered a clinically meaningful difference.

Myer et al. (2015) reported average TEs across three different testing centres for angles and moments of knee flexion, abduction, and internal rotation on both the left and right legs during a single-leg landing task. Similarities between the results of Myer et al. (2015) and that of the current study were observed for joint angle TEs for knee abduction (L = 2.30, R = 2.17; Dom = 3.0, Non-dom = 3.2) and internal rotation (L = 3.32, R = 2.61; Dom = 2.9, Non-dom = 3.2), respectively. Furthermore, compared to Myer et al. (2015) smaller

comparative TE values were observed in the current study for knee flexion angle (L = 7.14, R = 6.47; Dom = 3.5, Non-dom = 3.6). The moment data from Myer et al. (2015) were reported in Nm as which limits the comparison of results as our moment data were reported in Nm/kg/m. The differences between the results of our study and that of Myer et al. (2015) may be attributed to the differences in participant pool as Myer et al. (2015) included 15 year old females only whereas we included a mixture of males and females of different ages.

The observed variability is likely multifactorial, owing to potential marker placement errors, skin or clothing artifacts, biological variability, and individual-level familiarity with the tasks (Colyer et al., 2018; McGinley et al., 2009; Scataglini et al., 2024). Furthermore, motion capture systems are susceptible to kinematic crosstalk errors, where primary (sagittal) calculation errors of the embedded axis affect secondary (coronal and transverse) axis calculations (Piazza & Cavanagh, 2000). Reapplication of reflective markers between days or between practitioners can reduce reliability measures and cause notable differences in knee angles and moments (Butler et al., 2021; Ramakrishnan & Kadaba, 1991). Reduction in errors can be achieved by standardizing marker placement and static alignment (Ford et al., 2007) and having one experienced practitioner position all markers, as was done in the current study.

Similarly to results of the present investigation, Alenezi et al. (2014) reported between-day kinematic metrics to exhibit *fair* to *excellent* consistency (ICCs ranging from 0.48 to 0.96) in a single-leg landing task. The consistency in reliability results between the present study and that of Alenezi et al. (2014) is likely due to the methodological similarities of task (30 cm single-leg drop height), marker placement (CAST model), and a combination of male and female participants.

### 6.1.2 Knee biomechanics

All knee angle metrics displayed *moderate* to *excellent* levels of reliability, aside from peak knee extension angle in some tasks. Commonly investigated knee angles that are related to ACL injury include knee flexion (ICCs = 0.684 to 0.940, TEs = 2.8 to 5.3), valgus (ICCs = 0.758 to 0.885, TEs = 2.5 to 3.6) and internal rotation (ICCs = 0.796 to 0.893, TEs

= 2.8 to 3.9). Our results are similar to that of a single-leg landing study by Alenezi et al. (2014), reporting a knee flexion angle ICC of 0.96, however, they found lower reliability for angles of knee valgus (ICC = 0.52) and knee internal rotation (ICC = 0.53). Furthermore, fitting within our range of results, Ford et al. (2007) reported reliability in young athletes during a double-leg drop-vertical jump task with angle ICCs of 0.616 (TE = 4.2) for flexion, 0.855 (TE = 2.3) for valgus, and 0.872 (TE = 1.9) for internal rotation. The consistency in knee angle reliability results between previous literature and the current study is promising as similar data collection methods were undertaken including use of the CAST model, the same researcher applying the markers between sessions, and standardisation of equipment set-up and calibration.

Additionally, knee moment reliability results aligned with that of Ford et al. (2007) with moment ICCs of 0.843 (TE = 0.13) for flexion, 0.870 (TE = 0.10) for valgus, and 0.592 (TE = 0.05) for internal rotation compared to our results which showed ICCs of 0.702 (TE = 0.1) for flexion, 0.691 (TE = 0.1) for valgus, and 0.638 (TE = 0.0) for internal rotation. Although the TE values for knee angles were relatively low, knee moments show even smaller values which are likely due to the smaller differences in means, magnitude of the measurements, and higher level of filtering on kinetic data that can reduce noise and smooth out potential kinematic errors caused by marker noise. The demonstrated reliability of these kinematic and kinetic knee variables during the four landing tasks indicates the potential for use to determine differences between sex and maturation groups in these angle and moment metrics associated with ACL injury risk factors.

#### 6.1.2.1 Peak knee extension moment

Sagittal plane metrics, mostly peak knee extension moment and range of sagittal moment, and occasionally peak knee extension angle, had poorer ICC values than most of the coronal and transverse plane metrics. The range of sagittal moments were likely affected by the peak knee extension moments, hence the peak extension moments will be a discussion focus. Ford et al. (2007) found opposing results to that of our study in a double-leg drop vertical jump task, describing joint moment between-session reliability as better in the sagittal plane compared to the coronal and transverse planes.

Furthermore, Ford et al. (2007) reported better reliability for sagittal plane joint moments than angles. *Good* to *excellent* ICC values were observed for peak knee extension moment during a double-leg stop jump ((Milner et al., 2011); ICC = 0.959) and a double-leg drop jump (Ford et al., 2007); ICC = 0.843). Although our results showed that the ICC values were *poor* for the peak knee extension moment and consequently range of sagittal moment, it should be noted that transverse and coronal plane CV% metrics were generally larger than sagittal plane metrics across all tasks. Whilst sagittal plane metrics are often more reliable than transverse and coronal moments, variations in knee extension moment reliability may be attributed to task complexity (Schelin et al., 2021), participant execution ability or strategy (Asaeda et al., 2024), or data capture or processing (Ogura et al., 2024).

The difficulty level of the unilateral tasks in the current study and the varied skill and maturation levels of the young athletes may have contributed to the consistently *poor* ICC values for peak knee extension moment across tasks. *Poor-to-fair* levels of reliability have previously been found for knee extension moments immediately following landing during a single leg hop for distance task (Schelin et al., 2021). Furthermore, although they did not directly examine reliability metrics, it is noteworthy that mean peak knee extension moment values reported by Hass et al. (2003) differed from those reported by Simpson and Kanter (1997) for the same task. Hass et al. (2003) attributed the divergences between studies to different jump landing strategies and the skill level of the participants. Landing position variance at the foot or hip can also influence how the force vector passes through the limb resulting in disparate moments (Schelin et al., 2021). The differences in filtering processes may also have influenced moment data during the early ground contact phase (Roewer et al., 2014). It has been suggested that a similar frequency of kinematic and kinetic data limits moment artifacts unexplained by the dynamics of the movement, but can diminish impact forces (Derrick et al., 2020). Our filtering methods differed for kinematic and kinetic data (15 Hz and 50 Hz, respectively) based on methods of Hanzlíková et al. (2019) and Harry et al. (2022) who suggested a low-pass filter with a 50-Hz cutoff can remove noise from kinetic data without altering results when compared with raw data. Similarly to our study, Alenezi et al. (2014) used different kinematic and kinetic filtering methods (12 Hz and 25 Hz), however, (Myer et al.,

2015) used 12 Hz for both kinematic and kinetic data which may explain the differences in reliability results.

#### 6.1.2.2 Range of transverse moment

Aligning with the hypothesis, range of transverse moment had consistently *poor* ICC values across trials. It has been suggested that transverse plane knee moments have generally poorer reliability outcomes, particularly in comparison to sagittal plane metrics (Fernandes et al., 2016). The smaller magnitude of the transverse metrics compared to sagittal and coronal plane metrics, may predispose transverse knee moments to a greater influence from noise or small measurement variations. Furthermore, transverse plane metrics can be more significantly impacted by anatomical landmark identification and axis alignment errors (Stief et al., 2013; Thewlis et al., 2007). The results of Szlachta et al. (2021) found between-session reliability for knee transverse angle metrics during single-leg landing tasks was the most affected following marker replacement, as demonstrated by ICC values, which they attributed to possible marker replacement errors. Previously, errors in marker re-application (Kadaba et al., 1989) have been suggested as partially responsible for variability of between-day metrics. However, the current study aimed to limit these errors by using the same investigator to attach the markers in all of the trials and using the CAST marker-based protocol (Cappozzo et al., 1995), which offers improved anatomical relevance and reduced skin movement artifact in comparison to previous models (Kadaba et al., 1989).

#### 6.1.2.3 Ground reaction forces

Aligning with our hypothesis, relative peak vGRF metrics showed consistently *excellent* reliability across tasks in comparison to the greater variability seen across many of the knee angle and moment data. Specifically, relative vGRFs demonstrated *excellent* reliability over all tasks except the VERT task where the ICCs indicated *good* reliability. These observations are consistent with previous research (Alenezi et al., 2014, 2016; Ferber et al., 2002; Kadaba et al., 1989; Winter, 1984) that suggest greater reliability of

vGRF data due to the combined as opposed to separated segmental masses, accelerations, and gravitational forces (Ferber et al., 2002; Winter, 1984). Further, GRF data do not rely on marker data, hence marker placement errors are not an influential factor (Winter, 1984). The relative vGRF data demonstrated better ICC reliability values than the angle and moment variables in both studies.

Contrary to our hypothesis, peak anterior, posterior, medial, and lateral GRFs had generally *poor* reliability based on ICC values across all tasks. Significant differences were found between trials on the dominant leg for lateral and posterior GRF during the LAND task and for lateral and medial GRF during the CUT task, potentially owing to the typically small magnitudes of GRF within these planes, the balance component of the LAND task, and the lateral force application required in the CUT task. To the best of our knowledge, no current research exists that has explicitly examined the reliability of GRFs in all three planes, however, there is some evidence to suggest that similar trends exist over different tasks and conditions. For example, higher levels of reliability for the vGRF component can likely be attributed to the larger magnitudes of force, which are consequently less affected by small variations (Golyski et al., 2018). In comparison, smaller magnitudes of medial-lateral and anterior-posterior GRF components can be more susceptible to noise and smaller variations (Munoz, 2019; Ross et al., 2005). Furthermore, it should be considered that previous research has found poorer braking and propulsive (anterior-posterior) reliability in single-leg countermovement jump tasks in comparison to a double-leg countermovement jump task (Fahey et al., 2024). It is possible that dynamic tasks performed unilaterally have poorer GRF reliability outcomes than the more commonly used, but less sport specific, bilateral tasks.

#### 6.1.2.4 Jump height

For the ROT and VERT tasks, jump height was the main performance metric, which demonstrated *moderate* to *excellent* between-session reliability (ICC dominant VERT = 0.603, non-dominant VERT = 0.610, dominant ROT = 0.935, non-dominant ROT = 0.977). Ford et al. (2007) similarly demonstrated *excellent* between session reliability (ICC = 0.936) for jump height during a drop vertical jump, and Young et al. (1997) showed high

levels of reliability for both double- and single-leg vertical jumps. Jump height was also the most reliable metric in a study examining the reliability of biomechanics in elite female athletes during a double-leg drop vertical jump task with a between session ICC value of 0.900 (Mok et al., 2016). Interestingly, jump height for the VERT task had *moderate* levels of reliability, yet the ROT task had *excellent* levels. This difference may be due to the higher perceived difficulty level of the ROT compared to the VERT task, limiting the jump heights and variability of the ROT task compared to VERT, as indicates the smaller CVs in the former.

### 6.1.3 Implications

The results indicate that all tasks had adequate reliability for kinematic angles and moments aside from peak knee extension moment, range of knee moments, anterior/posterior GRF, and medial/lateral GRF in terms of ICC values. Due to the *poor* levels of reliability and the limited use of these metrics in assessment of ACL injury risk, range of moments, anterior/posterior GRF, and medial/lateral GRF were not analysed for the purposes of group comparison in the cross-sectional study. The *poor* reliability of peak knee extension moment also justifies its removal in the cross-sectional study. However, it is worth noting that ACL injuries often occur in the early landing phase (within 40 ms of initial ground contact (Koga et al., 2010; Krosshaug et al., 2007)) and greater peak knee extension moments have been linked to a greater risk of ACL injury (Leppänen, Pasanen, Krosshaug, et al., 2017; Tait et al., 2022). Additionally, a landing without injury should apply extensor moments to reduce downward velocity (Devita & Skelly, 1992) and therefore the relationship between knee extension moments, eccentric control, and force absorption highlights the importance of peak knee extension moment data in terms of ACL injury risk. Consequently, this metric has been included in the cross-sectional study despite the *poor* reliability, however caution is warranted when interpreting any significant differences identified between groups for the peak knee extension moment metric. Although acceptable ICC values and were found for the other metrics included in the cross-sectional study, large CV% values were commonly observed; hence careful interpretation is suggested when determining differences in all metrics between groups and relying on differences in terms of the TE may be more appropriate.

## **6.2 Cross-sectional comparison**

Contrary to our hypothesis, the main findings across the four landing tasks suggested that post-pubertal participants often exhibited biomechanics that represented protective mechanisms against ACL injury such as increased knee flexion, lower relative vGRF, greater varus and external rotation moments and angles. Furthermore, no major differences in ACL injury risk related biomechanics were observed between males and females' post-puberty. Pre-pubertal participants commonly exhibited less knee flexion angles and greater relative vGRFs, which are associated with higher ACL injury risk. Differences were found between maturation stages in frontal and transverse plane biomechanics but not often between sex-specific maturation stages, and the trends varied from task to task. The ROT task was ranked as the most difficult of the four landing tasks.

### **6.2.1 Sex differences**

It is noteworthy that very few sex differences were observed, with only the CUT task demonstrating significant main effects of sex. Specifically, males had a greater relative vGRF than females on the dominant leg and females had greater external rotation moments than males on the non-dominant leg. The lack of findings coincides with previous literature suggesting no sex differences in knee biomechanics across various tasks in pre-pubertal and pubertal participants (Hewett et al., 1996; Sigg et al., 2001; Swartz et al., 2005). For example, previous research has also found no significant differences between young adult males and females in lower limb kinematics during a netball single-leg landing task (Cowling & Steele, 2001), in vGRF in 30 cm drop-landings (McNair & Prapavessis, 1999), or in muscle activation patterns during a vertical jump (Fagenbaum & Darling, 2003). However, in studies of adults or more biologically mature populations, sex differences in lower limb biomechanics become more apparent suggesting differences in landing biomechanics and landing strategies between males and females in adolescent (Holden et al., 2016) and young adult populations (Seyedahmadi et al., 2022). For example, in a population of collegiate basketball players, Fagenbaum and Darling (2003) found that females landed with greater knee flexion than

males, which also aligned with the findings of the current study of greater peak knee extension angles (i.e., more knee flexion upon landing) in post-pubertal females in a few of the tasks examined. Nonetheless, it should be considered that some significant interaction effects were observed, which suggests that there are differences between sexes for some metrics, but only when considering maturation stage as well.

## **6.2.2 Key metrics**

There are four biomechanical metrics that are commonly examined in the context of ACL injury and sex/maturation differences: knee flexion angle, knee valgus angle, knee valgus moment, and vGRF (Butcher et al., 2024), as identified in Chapter 2. These particular metrics are sequentially discussed in this section.

### **6.2.2.1 Knee flexion angle**

We hypothesised that post-pubertal females would have smaller peak knee extension and peak knee flexion angles than post-pubertal males and less mature participants. The results do not support this hypothesis, indicating that post-pubertal females generally exhibited greater knee flexion angles than post-pubertal males and when compared to females in earlier pubertal stages. Specifically, the results of the current study found that for the LAND and VERT task on the dominant leg, peak knee extension angle was greater in post-pubertal females compared to males, greater in post-pubertal than pre-pubertal females, and greater in mid-pubertal than pre-pubertal males. For the ROT task on the non-dominant leg, the pre-pubertal and post-pubertal groups had greater peak knee flexion angles than the mid-pubertal group, regardless of sex.

Landing with a reduced knee flexion angle (i.e., with a more extended knee) has been associated with an increased risk of ACL injury (Leppänen, Pasanen, Krosshaug, et al., 2017). As discussed in our systematic review (Butcher et al., 2024), there is conflicting evidence for changes in knee flexion kinematics with maturation during dynamic tasks. In contrast with our experimental results, some research has suggested that post-pubertal females land with lesser knee flexion than their male counterparts (Colby et al., 2000; Lephart et al., 2002; Malinzak et al., 2001). Furthermore, literature generally

suggests that knee flexion range of motion and knee flexion angles decrease in females with maturation (Hewett et al., 2009; Sigurðsson et al., 2021). For example, lesser knee flexion has been observed during single-leg stride jump and double-leg stop jump tasks in females after 12 years old (Hass et al., 2003; Yu et al., 2005). The results of Hass et al. (2003) showed that, in a stride jump and land task, post-pubertal females landed with the same average knee flexion angle as did the post-pubertal females during the LAND task in the current study of 17° (17.38° in the current study), however, the pre-pubertal females in their study landed with 22° flexion whereas our pre-pubertal females landed with only 10.16°. Research also exists to support the trends in our findings where knee flexion angle upon initial contact and at peak vGRF increased in females with maturation (Ford, Myer, et al., 2010; Swartz et al., 2005). For example, Swartz et al. (2005) reported knee flexion angles at initial contact of 10.47° in children compared to 12.65° in adults in a bilateral vertical jump task.

Similarly to the results of the current study for all tasks excluding the ROT, DiCesare et al. (2019) found no significantly different peak knee flexion angles between pre-pubertal females and post-pubertal females in a double-leg drop jump task with peak angles of 83.1° (dominant) and 84.3° (non-dominant) for pre-pubertal and 82.4° (dominant) 83.8 (non-dominant) for post-pubertal females. Highlighting the conflicting results, a recent review by Ramachandran et al. (2024) explored biomechanical changes in females with maturation and suggested that knee flexion angle varies at different stages of maturity, but reported little consistency regarding the direction of change with advancing maturation. Overall, the Ramachandran review identified limited evidence to support maturational phase differences in knee flexion angle at initial contact, peak knee flexion, or knee flexion range, suggesting that any differences observed were task specific (Ramachandran et al., 2024). For instance, decreases in knee flexion angle tend to be observed with maturation in tasks with a horizontal component, whereas increases in knee flexion are observed in more vertical tasks (Ramachandran et al., 2024). The differences in results between previous studies and that of the current study can potentially be attributed to task requirements. Many previous studies have examined the effect of maturation on knee flexion angles during double-leg tasks (Butcher et al., 2024). However, research has reported lesser knee flexion angles at initial contact during

single-leg tasks compared to double-leg landing tasks (Earl et al., 2007; Harty et al., 2011; Pappas et al., 2007). Single-leg tasks are more biomechanically challenging for the knee due to greater loading and motor control requirements, combined with a smaller base of support (Swartz et al., 2005). More extended knee angles at initial contact appear to occur during single-leg tasks compared to double-leg landing tasks (Earl et al., 2007; Harty et al., 2011; Pappas et al., 2007), hence task complexity may play a role in our findings compared to previous literature.

Although post-pubertal females demonstrated greater peak knee flexion angles during the ROT task, suggesting potentially ACL protective biomechanics, time to PKF was not significantly different between groups. This finding is important to consider as it suggests that the time taken for females to reach a greater peak knee flexion angle was not significantly longer than the time it took for males to reach a lesser peak flexion angle. It is possible that for post-pubertal females, the faster time and the larger angle increases loading rate on the knee, possibly due to a slower recruitment of muscles to decelerate the body. A longitudinal study by Peek et al. (2022) highlighted the differential effect of sex and maturation on knee strength in adolescent athletes, demonstrating an increase in knee extensor and flexor strength for males with maturation, but a lesser increase in extensor strength and a decrease in flexor strength for females with maturation (when normalized to body weight). Considering these observed differences in knee flexor and extensor strength development between sexes with maturation and the differences in knee flexion angles and time to PKF observed in this thesis, further research regarding muscle contraction upon landing would be beneficial to support the hypothesis that muscle strength and activation patterns may contribute to ACL injury risk upon landing.

#### 6.2.2.2 Knee valgus angle

It was hypothesised that greater knee valgus angles would be observed in post-pubertal females compared to males and less mature females. The current study did not observe any significant differences in knee valgus angle between males and females across any maturation stage or between any maturation stages with average peak knee valgus angles ranging between 3.24° and 11.06°. Partially aligning with our results, another systematic review found conflicting evidence for higher peak knee valgus angle in

females post-puberty compared to pre-puberty (Ramachandran et al., 2024). However, opposingly, a systematic review by Holden et al. (2016) found that knee valgus during landing was the only variable to exhibit an increased and meaningful difference between males and females in an older compared to a younger age group. Swartz et al. (2005) also reported significantly different knee valgus angles at initial contact between children ( $12.02 \pm 4.77^\circ$ ) and adults ( $8.14 \pm 3.91^\circ$ ) during a bilateral vertical jump task. Again, task demands should be considered as increased knee valgus angles and decreased distance in knee separation have generally been observed in females with maturation during double-leg landing tasks (Sasaki et al., 2013; Yu et al., 2005). Hence, it is possible that differences in knee valgus angle between groups were not observed for the single-leg landing tasks used in our study due to the task demands.

In line with our results, during a single-leg hopping task, Barber-Westin et al. (2006) reported no effect of age on normalised knee separation distance. Pletcher et al. (2021) also reported no significant differences between pre-pubertal ( $2.48 \pm 7.78^\circ$ ) and post-pubertal ( $2.95 \pm 4.41^\circ$ ) females for knee valgus angle at initial contact during a single-leg vertical stop jump. Furthermore, weak associations have been observed between bilateral and unilateral tasks for knee valgus moments ( $R^2$ , 0.06-0.18;  $P < .05$ ) (Taylor et al., 2016). It is therefore possible that differences between maturational groups are not observed as clearly in the more complex, sport specific tasks compared to simpler bilateral tasks. Differences in knee valgus angle that have been identified between sexes and maturation stages during bilateral tasks may not be reflective of biomechanics associated with higher ACL injury risk as most non-contact ACL injuries occur when most or all of an individual's body mass is on a single-leg (Hewett, Ford, et al., 2010). Future research could explore the association and relevance of single-leg biomechanics to ACL injury incidence as speculatively more appropriate than double-leg biomechanics.

#### 6.2.2.3 Knee valgus moment

Contrary to the hypothesis, which expected a greater peak knee valgus moment in post-pubertal females, no significant differences were observed between maturation stages in females or between sexes in the post-pubertal group. The results of the current study showed higher peak knee valgus moments in pre-pubertal females than males during the

ROT task on the non-dominant leg, although the effect size was *small*, the mean difference (0.46 Nm/kg/m for females, 0.31 Nm/kg/m for males, MD = 0.15 N/kg/m) exceeded the TE value of 0.08 N/kg/m, suggesting a meaningful difference. Furthermore, during the VERT task on the dominant leg, no significant differences were observed between sexes, but the pre-pubertal group had significantly higher peak knee valgus moments than the mid-pubertal and post-pubertal groups with a *large* effect and a meaningful difference of 0.17 N/kg/m exceeding the TE value of 0.10 N/kg/m. These findings suggest that pre-pubertal participants, and particularly pre-pubertal females during the ROT task, exhibited higher forces acting to direct the knee inwards along the frontal plane, which implies an increased load on the ACL. Previous research regarding changes to peak knee valgus moment with maturation is scarce, however one study demonstrated no interaction between sex and maturation group in knee valgus moments during a double-leg drop landing task (Sigward, Pollard, & Powers, 2012). Furthermore, a study investigating knee biomechanics during running found no significant differences between knee valgus moments of pre- (0.25 Nm/kg), mid- (0.29 Nm/kg), and post-pubertal (0.28 Nm/kg) females (Sayer et al., 2019). The significant differences between maturation groups observed in the ROT and VERT tasks in the current study could result from the differences in task demands. Knee valgus moment has been identified as a significant predictor for ACL injury risk as it demonstrates ACL injury forecasting with 73% sensitivity and 78% specificity (Hewett, Myer, Ford, et al., 2005). Despite the predictive capabilities, knee valgus moment in isolation is not a standalone ACL injury risk factor. Although it is commonly used as a predictor of ACL injury risk during jump landing injury screening tasks, other biomechanical metrics (such as knee extension angle upon landing, knee valgus angle, knee rotation angle, and anterior tibial shear) in conjunction contribute to increased injury risk (Cronström et al., 2020). Nevertheless, the greater knee valgus moments observed in pre-pubertal participants suggests potential for higher ACL injury risk biomechanics in this group. Considering the low amount of ACL injuries that occur pre-puberty (Maniar et al., 2022), future research should explore whether this risk factor is as relevant to less biologically mature populations and if other biomechanical variables pose a greater risk when combined with knee valgus moment in these younger populations.

#### 6.2.2.4 Vertical GRF

Contrary to our hypothesis, anticipating increases in relative vGRF with maturation in females, relative vGRFs appeared to decrease with maturation for both sexes during all tasks and on both the dominant and non-dominant legs. Additionally, a main effect of sex was observed during the CUT task on the dominant leg, where greater relative vGRFs were found in males than females, although the effect size was *small*. In our systematic review (Butcher et al., 2024), studies reported that relative vGRF in females generally remains the same (Colyer et al., 2021; Hewett, Myer, Ford, et al., 2006; Quatman et al., 2006) or slightly decreases (Hass et al., 2005; Sigward, Pollard, Havens, et al., 2012; Swartz et al., 2005) with maturation during dynamic tasks. In males, the literature suggests that relative vGRF tends to decrease with maturation (Colyer et al., 2021; Hewett, Myer, Ford, et al., 2006; Quatman et al., 2006). Opposingly, a review by Holden et al. (2016) reported no differences between males and females in relative vGRF, but a review by Ramachandran et al. (2024) reported strong evidence for higher relative peak vGRF in pre-pubertal than post-pubertal females. Previous research, along with the results of the current study, suggest a general improved ability to attenuate force with maturation for both sexes and better force attenuation ability in males compared to females as they mature, as reflects the decrease in relative vGRF. Relative to body weight, demonstrated improvements in attenuation of vGRF during landing with maturation have been partially attributed to skill acquisition and physical development (Angulo-Barroso et al., 2022). Additionally, in the current study, more biologically mature individuals demonstrated greater knee flexion angles, potentially influencing vGRF attenuation and force absorption (Devita & Skelly, 1992). Greater knee flexion during landing or cutting can improve force absorption, consequently protecting internal knee structures (Boden et al., 2009; Hass et al., 2005).

In the current study, peak vGRF values ranged between 3.2- and 8.3-times body weight, aligning with the findings of a recent systematic review, which reported peak vGRF to range between 3.21- and 8.42-times body weight. It is noteworthy that elite female athletes who sustained an ACL injury during an in-game landing had a modelled peak vGRF between 3.2 and 4.5 times their body weight 40 ms after initial ground contact

(Koga et al., 2010). It was beyond the scope of the study to examine the curve of vGRF over the course of the landing and hence the exact vGRF value at 40 ms post initial contact was not attained, hence directly comparing our vGRF to those when ACL injuries occur is not advisable. Pre-pubertal athletes have lower rates of ACL injuries compared to their more biologically mature peers (Maniar et al., 2022). Therefore, the findings suggest that higher relative vGRF forces are not a standalone risk factor unless combined with compromising knee joint angles and moments. Additionally, the timing of high vGRFs relative to the knee joint angles and moments, may be more important than the peak vGRF. Exploration of the benefits of teaching young athletes to better attenuate vGRF upon landing may reduce the risk of ACL injury should the athlete find themselves in a compromised position upon landing, as suggested in systematic reviews and meta-analysis' (Padua et al., 2014; Webster & Hewett, 2018).

### **6.2.3 Task-specific considerations**

Common trends existed regarding differences between sex and/or maturation stages between tasks. Some of the findings of the key metrics identified from the systematic review were previously discussed. However, each of the landing tasks had different movement demands. Hence, the results obtained from each task are discussed separately, focussing on findings around other metrics and how these may influence risk of ACL injury. The subjective difficulty results revealed that the ROT task was ranked as the most difficult, with no significant differences in perceived difficulty amongst the other three tasks.

#### **6.2.3.1 LAND task**

The motivation for incorporating the LAND task was to investigate differences in biomechanics between sexes and maturation stages during a simple, unilateral task that requires force absorption without a subsequent dynamic application of force. Significant interaction effects for peak knee flexion moment were observed on both the dominant and non-dominant legs. On both legs, post-pubertal males had *large* higher peak knee flexion moments than post-pubertal females (MD = 0.12 and 0.10 Nm/kg/m for dominant

and non-dominant, respectively), exceeding the TE of 0.09 Nm/kg/m and indicating a meaningful difference. Furthermore, pre-pubertal and mid-pubertal females had greater knee flexion moments than post-pubertal females on the non-dominant leg only. On the dominant leg, a *medium* significant interaction effect was seen for peak extension angle where post-pubertal females had greater levels of flexion than post-pubertal males (MD = 4.68 Nm/kg/m), exceeding the TE of 0.25 and suggesting a meaningful difference.

Post-pubertal females demonstrated smaller peak knee flexion moments compared to post-pubertal males and compared to females in earlier stages of maturation. Post-pubertal females also had greater knee extension angles, meaning they were more flexed at initial contact, compared to post-pubertal males on the dominant leg, but no differences were observed on the non-dominant leg. Larger knee flexion moments, particularly when coupled with a reduced knee flexion angle, have been shown to increase ACL injury risk with a hazard rate of 1.21 for every 10 Nm increase (Larwa et al., 2021; Leppänen, Pasanen, Kujala, et al., 2017; Olsen et al., 2004). The smaller knee flexion moments and larger knee flexion angles observed in the post-pubertal females suggest that they adopted a safer ‘softer’ landing strategy during this task (Griffin et al., 2000; Hewett, 2000; Kirkendall & Garrett, 2000). Conversely, post-pubertal males landed with a more extended knee and greater knee flexion moment than post-pubertal females, which may suggest a higher comparative ACL injury risk due to potential for increased anterior tibial shear (Leppänen, Pasanen, Krosshaug, et al., 2017). Aligning with our results, a study by Wild et al. (2016) found a decrease in knee flexion moment with maturation in females using a horizontal leap task, although the differences were not significant. However, in contrast with our results, a review by Ramachandran et al. (2024), found a moderate level of evidence to suggest that the peak knee flexion moment was generally greater in post-pubertal compared to pre-pubertal females, even though pre-pubertal females often had less knee flexion range of motion during single-leg land and jump tasks. The LAND task does not require a reapplication of force like the jumping tasks included in the systematic review by Ramachandran et al. (2024), hence the softer landing technique demonstrated by post-pubertal females may be a result of force absorption competence that is associated with biological maturation (Swartz et al., 2005). Furthermore, a more flexed knee upon landing is typically accompanied with

higher knee extensor moments to limit anterior tibial translation and protect against ACL strain (Podraza & White, 2010). It should be noted, that all groups had peak knee extension angles between 10 and 30°, which research suggests is high risk for ACL injury in combination with other biomechanical factors (Beaulieu et al., 2023; Boden et al., 2000; Olsen et al., 2004).

The softer landing technique in post-pubertal females observed in the current study, as indicated by the more flexed knee angle upon landing and smaller knee flexion moment, corresponds with the smaller relative vGRF and may differ from previous research due to the task demands. It should be considered that relative peak vGRF decreased with maturation by between 0.19 and 0.93 BW, with a *large* effect size and exceeding the TE of 0.33 (dominant) and 0.25 BW (non-dominant). Aligning with the findings of Swartz et al. (2005) during a double-leg vertical jump study, these results suggest an improved ability to absorb force and potential increases in lower-limb strength in the more biologically mature participants. Considering that post-pubertal females had greater knee flexion upon landing and smaller knee flexion moments, it is possible that these mechanics assisted in their ability to reduce vGRF upon landing. Conversely, the more extended landing position and greater knee flexion moments observed in the post-pubertal male group suggests a stiffer landing strategy, with meaningful mean differences exceeding the TE values. However, because their relative vGRF also decreased with maturation, post-pubertal males may have demonstrated greater task competence and reduced reliance on knee flexion during landing to effectively absorb forces compared to post-pubertal females. In a sporting situation, post-pubertal males will often land from a greater height than post-pubertal females due to generally greater jump height ability. Therefore, differences in force absorption landing strategies from the standardised 30 cm box height may be caused by differing demands and familiarity. It should also be considered that although landing with the knee in a more flexed position is considered preventative of ACL injury as opposed to a more extended angle upon initial contact, other biomechanical factors such as frontal and transverse plane rotation angles will influence the overall ACL injury risk when the knee is in a more extended position (Leppänen, Pasanen, Krosshaug, et al., 2017).

Few interaction effects were observed for the LAND task, yet the findings regarding sagittal plane and vGRF mechanics provide valuable insights. These results suggest that post-pubertal females may adopt more injury preventative landing strategies in the sagittal plane through improved knee flexion angles, smaller knee flexion moments, and lower relative vGRFs. Altered sagittal plane mechanics alone may not cause ACL injury (McLean et al., 2005). However, it should be considered that even when excluding the contribution from coronal and transverse plane knee rotations, alterations to sagittal plane biomechanics have been shown to reduce ACL loading significantly in a single-leg landing task (Laughlin et al., 2011). Exacerbations of the loads caused by unfavourable sagittal plane mechanics may occur with excessive coronal and transverse plane motions (Laughlin et al., 2011).

Significant differences in coronal and transverse plane angles and moments were observed in the LAND task between maturation stages irrespective of sex. Specifically, the post-pubertal group had lower peak knee varus and external rotation angles on the dominant leg, but higher varus and external rotation moments on both legs, suggesting a potential resistance to valgus and internal rotation with maturation. It should be noted that the *medium* and *large* respective differences between groups in peak varus angle ( $0.19^\circ$ ) and moment ( $0.16$  and  $0.19$  Nm/kg/m) on the dominant leg did not exceed the TEs of  $2.79^\circ$  and  $0.28$ , respectively, and hence cannot be considered meaningful differences. There is limited literature examining the effects of maturation on coronal and transverse plane mechanics during a single-leg drop landing task (Butcher et al., 2024). The available literature in female elite artistic gymnasts did not align with our results, finding that post-menarche females displayed decreased maximum knee flexion angle, and increased knee valgus angle, maximum internal rotation angle, maximum knee valgus moment, and ratio of hamstring-quadriceps muscle activity compared to the pre-menarche females, which they associated with increased risk of non-contact ACL injury in the post-menarche group (Kim & Lim, 2014). Our study found no differences in knee valgus moments, knee valgus angles, or internal rotation angles between groups. The differences in results between the current study and that of Kim and Lim (2014) may be attributed to the differences in maturation phase classification and the use of females only. Increased knee valgus and internal tibial rotation angles can increase the strain and

force on the ACL, increasing risk of injury (Hewett et al., 2012; Markolf et al., 1995). However, in a review by Yu and Garrett (2007), it was suggested that the ACL is not the main structure that supports knee valgus-varus moment and internal-external rotation moment. Further, increases these moments alone are not likely to result in isolated ACL injuries without injuring other knee structures (Yu & Garrett, 2007). The results of the current study demonstrating significantly larger knee varus and external rotation moments, alongside the decreases in relative vGRF, in the post-pubertal group may suggest an ACL injury preventative strategy is developed with maturation.

The *medium* smaller external rotation angles observed in the post-pubertal group (4.15° smaller than pre-pubertal) may also allude to an injury risk reduction strategy as larger external rotation angles have been associated with increased ACL injury risk when the knee is closer to full extension (Senter & Hame, 2006). A video analysis study of ACL injuries by Boden et al. (2000) found that body position for a non-contact ACL injury commonly displayed an externally rotated tibia, close to full knee extension, a planted foot, and valgus collapse. The reduced varus and external rotation angles, but larger moments observed in more biologically mature participants are likely resultant of a more controlled landing strategy due to strength development. It is possible that more biologically mature individuals were able to resist coronal or transverse plane collapse upon landing whilst generating forces to pull the knee towards a safe landing position. Increased strength and muscle activity of the lateral and medial hamstring and gluteus medius are beneficial in inhibiting excessive internal rotation and valgus during landing (Fujii et al., 2012), therefore, developing strength in these areas at an earlier maturation stage may reduce the occurrence of ACL injury risk biomechanics observed in less biologically mature individuals.

The mid-pubertal group had a significantly longer time to PKF than the pre-pubertal group on the dominant leg. As peak knee flexion angle was not significantly different between maturation groups, the time to PKF may be reflective of increased muscular control via concentric hamstrings contraction and eccentric quadriceps contraction with maturation, leading to a more controlled force absorption strategy. Russell et al. (2007) found that muscle co-contraction (hamstrings and quadriceps) prior to landing was two times greater for adults than children. Greater anticipatory muscle contraction in adults

is likely a learned response to prepare the body to adapt to varied landing tasks and a lesser preparatory contraction in children does not appear to be linked directly to ACL injury risk (Russell et al., 2007). Furthermore, no main effects of sex were observed for the LAND task, suggesting that maturation primarily drives the observed biomechanical changes.

#### 6.2.3.2 CUT task

The motivation for incorporating the CUT task was to investigate differences in biomechanics between sexes and maturation stages during a dynamic, sport- and ACL-injury specific task that requires force absorption during landing and then subsequent rapid re-application of force while changing direction in a lateral manner. No significant interaction effects were found between sex and maturation on either leg, similar to Sigward, Pollard, Havens, et al. (2012) who identified no interaction effect of sex and maturation during a 45° unanticipated cutting task. The findings of the current study suggest no significant influence of sex specific maturation on the biomechanics of this CUT task. Considering the relatively small standard deviation in most metrics, within group variability does not appear to underpin the lack of significant interaction effects. Despite the lack of significant interaction effects, differences were identified between maturation groups regardless of sex.

Significant *large* main effects of maturation were observed for peak relative vGRF on both legs, but the direction of the effects between legs were different. The differences between groups exceeded the TEs (0.64 and 0.26 BW for the dominant and non-dominant legs, respectively), suggesting meaningful differences. On the dominant leg, relative vGRF was lowest in the pre-pubertal group, but on the non-dominant leg, the pre-pubertal group had the highest relative vGRF, which decreased with maturation. The differences in trends between the dominant and non-dominant leg are noteworthy as the pre-pubertal group had similar relative vGRFs on both legs. The mid-pubertal and post-pubertal groups had greater forces than the pre-pubertal group on the dominant leg, but smaller forces than the pre-pubertal group on the non-dominant leg. These findings suggest that in the later maturation stages, the dominant leg was applying more force than the non-dominant leg. A study exploring limb-dominance and gender differences in

GRF magnitude during single-leg lateral jump-landings found that peak vGRF was not significantly different between the dominant and non-dominant legs in males (roughly 3.65 times BW) or females (roughly 4.1 times BW) (Aizawa et al., 2018). These average values correspond with the results in the current study on the non-dominant leg (3.51 to 4.83 BW), but not on the dominant leg where the mid-pubertal and post-pubertal groups had vGRFs ranging between 6.15- and 8.33-times BW. The effect of limb dominance on change of direction biomechanics has been explored in systematic review by Dos'Santos et al. (2019) who similarly observed greater peak vGRFs on the dominant leg. As this review mostly included an adult population, it aligns with our findings showing higher vGRFs in the more mature participants on the dominant leg. It is possible that with maturation and repeated performance or training, more biologically mature athletes develop a preferential use of the dominant leg during sporting manoeuvres (Virgile & Bishop, 2021), resulting in increased task familiarity and confidence in producing high levels of vGRF.

Significant *small* main effects of sex were also observed on the dominant leg with males having a 0.99 BW (17%) higher vGRF than females, exceeding the TE of 0.64 and indicating a meaningful difference. This difference was only observed on the dominant leg, the same leg that demonstrated increases in vGRF with maturation. The greater relative vGRF values in males could be resultant of higher muscle mass and confidence in withstanding higher forces on their dominant leg compared to females. The task may have been more familiar for the males as it resembles a common movement in rugby or football, which have larger male participation rates than female (Inside FIFA, 2023; Martínez-Lagunas et al., 2014; World rugby, 2025). Similarly to our results, during single-leg lateral jump-landings, Aizawa et al. (2018) also observed a significant effect of sex. However, opposingly, they found females to have a 35% greater average relative peak vGRF than males. The difference in results may be partially explained by the task requirements as participants dropped from only 20 cm and leapt 60 cm laterally (Aizawa et al., 2018) as opposed to dropping from 30 cm and leaping to 150% of leg length (equating to an average distance of 131.2 cm for males and 127.2 cm for females). Differences in kinematics can often explain differences in vGRF. During landing, the largest vGRF typically occurs when the knee is between 0° and 25° of flexion and must

withstand a sudden kinetic change (Podraza & White, 2010). Increasing knee flexion upon landing can help to attenuate these forces (Ericksen et al., 2013; Southard et al., 2012), however, as no significant differences in knee flexion were observed between males and females, it is likely that the differences in relative vGRF were not attributed to knee kinematic landing strategy. It is worth considering that ankle and hip joint motions play a role in landing mechanics with roughly 13-20% and 15-20% contributions to relative absorption, respectively (Norcross et al., 2013), however joint biomechanics aside from the knee were beyond the scope of this study. As our study focussed on knee biomechanics specifically, further exploration of whole-body mechanics may further explain the differences vGRF results. Additionally, although cut distance was normalised to account for anthropometric differences, box height was standardized to 30 cm which may have influenced vGRF results due to the potentially greater competence and familiarity for males in landing from greater heights.

Peak knee internal rotation moment was greater in the pre-pubertal group than both the mid- and post-pubertal groups on the dominant leg with *medium* effect sizes, however the group mean differences of 0.06 Nm/kg/m did not exceed the TE threshold of 0.08 Nm/kg/m and therefore cannot be considered as clinically meaningful. On the non-dominant leg, peak knee external rotation moment and peak knee varus moment were greater in the post-pubertal (0.05 and 0.19 Nm/kg/m, respectively) and mid-pubertal (0.05 and 0.14 Nm/kg/m, respectively) groups than the pre-pubertal group with *medium* to *large* effect sizes and mean differences that exceeded the TE values of 0.02 Nm/kg/m and 0.05 Nm/kg/m, respectively. Considering sex differences, the *medium* greater knee external rotation moment observed on the non-dominant leg in the females compared to the males suggests a potentially ACL injury protective strategy and may be resultant of cautious landing patterns similar to observations of the pre-pubertal group. The mean difference of 0.03 exceeded the TE of 0.02, suggesting a clinically meaningful difference. High peak knee external rotation moments have been associated with increased risk of ACL injury when the knee is in a more extended position with a large knee valgus angle and large vGRFs (Santos et al., 2023). Furthermore, the pre-pubertal group had greater knee varus angles than post-pubertal but, the other two groups had close to neutral (only

just in valgus) angles. It is unlikely that any of the groups were demonstrating frontal plane angles that exhibited a high risk of injury.

Sigward, Pollard, Havens, et al. (2012) reported greater knee valgus moments in an unanticipated run and cut task in pre-pubertal athletes compared to more biologically mature groups, suggesting that the less mature athletes adopted a strategy that contributed to a greater frontal plane moment. Conversely, no differences in knee valgus moment were observed between groups during the CUT task in the current study. Incorporating an unanticipated component to the CUT task may reveal different strategies between maturational groups, with less mature individuals potentially less able to respond appropriately to an unanticipated stimulus. Similarly to our results, a study examining longitudinal kinematic changes in males across pubertal maturation during an unanticipated 45° cutting task found changes in hip and trunk mechanics, but not in any knee kinematics typically associated with knee joint loading, such as increases in knee valgus, internal rotation, or extension (Chia et al., 2023). Furthermore, a study examining females across different maturational stages during a 90° unanticipated cutting task found no relationship between any knee biomechanics and maturation group or between bilateral differences in knee biomechanics and maturation group, suggesting that factors other than knee biomechanics alone could explain the higher rate of ACL injuries in maturing females (Colyer et al., 2021).

Our results regarding maturation are similar to previous literature in that few differences were observed regarding mechanics typically associated with increased ACL injury risk in similar types of tasks (Butcher et al., 2024). However, the few differences that were found between groups differed from that of some other cutting type tasks (Aizawa et al., 2018; Sigward, Pollard, Havens, et al., 2012), possibly due to the task demands. Based on the results of our pilot study, we set the task requirements, so the participants were required to leap to 150% of leg length as quickly as possible after the initial drop landing. Cutting tasks require single-limb control of momentum, impact absorption, sudden deceleration, and re-direction of the body's momentum (Jindrich et al., 2006; Jindrich & Qiao, 2009). Compared to post-puberty, less biologically mature individuals adopt less efficient steering and re-orientation techniques to navigate obstacles (Vallis & McFadyen, 2005) and struggle more when performing locomotor tasks that require higher levels of

precision (Michel et al., 2010). The more mature individuals had greater relative vGRF, external rotation, and varus moments on their dominant leg, possibly reflecting their ability and confidence to perform the task on this leg or indicating an increased risk of ACL injury, which could only be examined via prospective studies. With maturation often comes more years of experience in performing complex tasks that may contribute to the differences in performance in the more biologically mature groups. Less mature athletes might avoid performing more complex movements during games and therefore limit their overall exposure to potentially injurious situations and competency in performing these movements. Hence, it is possible that the task used in this study was more familiar for the more biologically mature participants who had greater developed perceptual motor processes (Michel et al., 2010). It could be that if the younger participants were to experience higher moments and vGRF situations, they would experience an ACL injury whereas the more mature individuals would not after being conditioned to these forces and moments already.

#### 6.2.3.3 ROT task

The motivation for incorporating the ROT task was to investigate differences in biomechanics between sexes and maturation stages during a sport and ACL injury specific task that requires stabilisation from stopping a rotating motion, force absorption during landing, and then quick re-application of force to jump vertically. This task was selected as it has previously been identified as more difficult compared to other drop jump tasks (Hanzlíková et al., 2021) which was also reflected in the subjective rankings of our participants who ranked the ROT task as the most difficult. Significant sex and maturation interaction effects were observed for jump height and peak knee valgus moment. Jump height increased with maturation on both legs (*medium to large* effect size, all mean differences exceeded the TEs of 1.68 and 1.00 cm for dominant and non-dominant, respectively) and post-pubertal males jumped higher than post-pubertal females (*small* effect size, MD = 6.58 cm), with no significant sex differences in pre-pubertal or mid-pubertal groups. Peak knee valgus moment was 0.15 Nm/kg/m lower in pre-pubertal males than in both mid-pubertal males (*large* effect size) and pre-pubertal

females (*small* effect size) on the non-dominant leg, with the difference exceeding the TE value of 0.08 Nm/kg/m.

The findings of the current study are consistent with previous research exploring the effects of jump height on maturation (Gantiraga et al., 2006; Papadopoulos et al., 1999; Quatman et al., 2006). Quatman et al. (2006) showed significantly increased vertical jump height with maturation in males but not females. They also described a significant reduction in landing GRFs for males but not females with maturation, and a decrease in take-off force in females but not in males (Quatman et al., 2006). Jumping performance differences between males and females reportedly become apparent around 14 years of age (Gantiraga et al., 2006), corresponding with the significant performance differences observed between post-pubertal males and females. The nature of the ROT task involves the stretch-shortening cycle whereby the eccentric component (i.e., landing) directly influences the subsequent concentric (i.e., jumping) phase (Bosco et al., 1982). Stretch-shortening cycle ability depends on muscular and nervous system processes, including knee extensor muscle force generation alongside coordination and coactivation of the agonist-antagonist muscles (Rack & Westbury, 1974). Consequently, both strength and coordination are important factors in more complicated motor tasks, which explains the increased jump performance in both males and females with maturation. Increases in muscular size, strength, and power that occur with biological maturation and the larger increases that are observed in males compared to females are likely contributing factors to these results (Gillen et al., 2021).

A significant interaction effect was also observed for peak knee valgus moment on the non-dominant leg. Within the pre-pubertal group, females had greater moments than males (although the effect size was *small*); and within the males, the mid-pubertal group had greater moments than the pre-pubertal group (*large* effect size). Based on knee valgus moments, pre-pubertal females and mid-pubertal males may be at a higher risk of injury than pre-pubertal males. Our results are supported the results of Sigward, Pollard and Powers (2012) who observed greater knee valgus moments in females than males ( $0.06 \pm 0.03$  vs  $0.01 \pm 0.02$  Nm/kg m, respectively;  $p < 0.005$ ) when averaged across maturation stages in a single-leg landing task. Furthermore, Sigward, Pollard and Powers (2012) suggested, contrary to their hypothesis, that the biomechanical profile exhibited

by females (including peak knee valgus moment) did not emerge post-puberty but was already present in pre-pubertal athletes. To this point, although significant differences between males and females in the later maturation stages were not observed in this study, it should be noted that the knee valgus angles observed in pre-pubertal females did not significantly decrease with maturation, supporting the results of Sigward, Pollard and Powers (2012) and suggesting potential for pre-established higher ACL injury risk movements patterns that do not significantly improve with maturation. It should also be considered that the ROT task was ranked as the most difficult of the four tasks assessed. Less biologically mature participants and those undergoing the adolescent awkwardness phase, such as the mid-pubertal males, could have been less familiar with the movement or have underdeveloped neuromuscular ability and motor control, leading to compromised landing mechanics during this more difficult task. It should be considered, however, that the effect of knee valgus moment on ACL strain could depend on the knee flexion angle, which tends to have an increasing effect on ACL injury risk with an increasing angle (Beaulieu et al., 2023; Miyasaka et al., 2002). Therefore, ACL injury risk regarding knee valgus moments may be better understood by considering the timing of the peak knee valgus moment in relation to knee flexion angle.

Furthermore, significant main effects of maturation were observed across multiple metrics on both the dominant and non-dominant legs. Relative peak vGRF was highest in the pre-pubertal group and decreased with maturation on both legs (*large* effect sizes, MDs exceeded the TEs of 0.30 for dominant and 0.23 for non-dominant). These results are consistent with previous research that has shown decreases in relative vGRF with maturation during a double-leg vertical jump task (Swartz et al., 2005). Additionally, in a drop jump study of female athletes, decreases in peak landing force occurred with maturation, but these differences were not statistically significant (Pedley et al., 2021). The findings of previous research support that the decreased relative vGRFs observed in our study are relevant to maturation in general, but not sex-specific maturation. Less biologically mature individuals may have a diminished ability to absorb force due to reduced eccentric strength, neuromuscular control (Quatman et al., 2006), and less familiarity with landing on one leg combined with the complexities of decelerating the body's rotational momentum. Decreased relative vGRFs alongside increased jump

height as individuals progress through biological maturation demonstrates improvements in ability to absorb impact and reapply force, concepts linked to spring-like behaviour and stretch-shorten cycle ability. Pedley et al. (2021) observed small improvements in spring-like behaviour with maturation during a drop vertical jump task, as well as improvements in biomechanics associated with moderating GRF with maturation, including centre of mass displacement and increased knee flexion.

During the ROT task, the landing leg acts as a dissipater of force and slows both the decent and the rotating momentum of the body through eccentric contraction of the knee extensors, ankle plantar flexors, and hip abductors and adductors (Devita & Skelly, 1992). The same leg then acts as an actuator through rapid concentric contraction to propel the body upwards. Often, manoeuvres where an immediate jump is produced after a landing require a greater knee flexion for an improved stretch-shortening cycle effect, and therefore, a greater jump height (Hass et al., 2005). The greater jump heights paired with the lower relative vGRF and the greater knee flexion angles observed in the post-pubertal group is likely explained by improved stretch-shorten cycle in addition to strength in the more biologically mature participants. The greater relative vGRF and lower jump heights observed in the pre-pubertal group suggests that their landing technique resulted in more force being lost into the ground, rather than reapplied through tendon elasticity, resulting in poorer jump performance. Biomechanical differences observed in different maturation stages may reflect an effect on the dynamic restrain system due to variations in strength or neuromuscular control (Hass et al., 2003). Thus, further research is required to investigate the levels of muscle contraction and timing of contractions during the ROT task across different maturation stages to determine how purposeful muscle contraction is used to achieve the observed angles, moments and GRFs.

In addition, significant main effects of maturation were observed for peak knee flexion moment and angle. Peak knee flexion moment was lowest in the mid-pubertal group on the dominant leg, but lowest in the post-pubertal group on the non-dominant leg (*large* effect sizes, exceeded TEs of 0.08 Nm/kg/m for dominant and 0.06 Nm/kg/m for non-dominant). Peak knee flexion angle was lowest in the mid-pubertal group on the non-dominant leg only (*medium to large* effect sizes, MDs of 5.10° compared to pre- and 5.61° compared to post-pubertal, exceeding TE of 4.23°). The lower knee flexion angles and

moments observed in the mid-pubertal group suggest a potentially stiffer landing and increased risk of ACL injury in this task during a time of peak growth. However, it should be considered that larger knee flexion moments coupled with a reduced knee flexion angle, have been shown to increase ACL injury risk with a hazard rate of 1.21 for every 10 Nm increase (Larwa et al., 2021; Leppänen, Pasanen, Kujala, et al., 2017; Olsen et al., 2004). Hence, the lower moments may lessen the potential risk of ACL injury influenced by reduced knee flexion angles. It is possible that rapid growth at mid-puberty combined with performing an unfamiliar and challenging task could lead to less favourable biomechanics. Implication of additional neuromuscular or proprioception challenges in mid-pubertal athletes could help develop safe jump-landing strategies in new or more challenging manoeuvres (Emery et al., 2015). We can speculate that mid-pubertal individuals may benefit from adopting more injury preventative landing strategies in the sagittal plane through increasing knee flexion angles during landing.

Furthermore, significant main effects of maturation were observed for moments and angles in the coronal and transverse planes (*large* effect sizes, with all MDs exceeding TEs of 0.08 (dominant) and 0.06 (non-dominant), and 0.02 (dominant) and 0.03 (non-dominant) Nm/kg/m for varus and external rotation moments, respectively). The varus and external rotation moments were lowest in the pre-pubertal group and increased with maturation, which, combined with the decreased relative vGRF, could suggest that more mature individuals employed strategies that reduced risk of ACL injury (Cortes et al., 2012; Fox, 2018). On the dominant leg, the pre-pubertal group had the largest peak knee valgus angle of all groups (*medium* effect size, MD = 3.00° compared to mid-pubertal; *large* effect size, MD = 3.73° compared to post-pubertal, TE of 2.47°) and a larger peak knee varus angle than the post-pubertal group (*medium* effects size, MD = 3.31°b, TE of 2.30°), suggesting that the pre-pubertal group went through a larger frontal plane range of motion. Additionally, the pre-pubertal group had a greater knee external rotation angle than the mid-pubertal group, which could contribute to an increased ACL injury risk given the larger relative vGRFs. Due to the difficulty of the task, more mature participants may have been able to control the landing of the rotation better, acquire a more stable body position, and re-apply force for an effective jump due to improved neuromuscular control and proprioception strategies, as neuromuscular control is reported to be

underdeveloped pre-puberty (de Sá et al., 2018). The ROT task requires a complex level of balance and strength; therefore, the stabilisers need to stop the rotation force, possibly leading to a larger frontal plane range of motion and larger external rotation angle in the younger individuals. Greater frontal plane joint range of motion has been observed during more difficult single-leg landings compared to double-leg landings (Yeow et al., 2011) and younger athletes tend to demonstrate greater frontal plane ranges of motion (Sasaki et al., 2013), which supports our findings.

Only peak values between touch-down and peak knee flexion were examined as waveform analysis was beyond the scope of this study. However, looking at the time course of knee motion and moments, such as statistical parametric mapping, could assist in identification of different strategies employed. Considering the timing of the peak valgus angle and moments would also assist in determining higher risk of ACL injury as a higher peak valgus values within 40 ms of initial contact have been linked to increased injury risk (Koga et al., 2010). Further research employing waveform analysis or focusing on alternate discrete metrics such as knee angles and moments at 40 ms after ground contact alongside ankle and hip angles and moments, not examined in the current study, could elucidate how individuals from different maturation group complete the ROT task.

#### 6.2.3.4 VERT task

The motivation for incorporating the VERT task was to investigate differences in biomechanics between sexes and maturation stages during a dynamic, sport specific task that requires quick force absorption and re-application of force to jump vertically. Significant interaction effects were reported for jump height, peak knee extension angle, and transverse plane knee range of motion. Jump height increased with maturation for the males. Pre-pubertal and mid-pubertal females landed with greater knee extension angles. Transverse plane knee range of motion was greater in post-pubertal females than males.

Similarly to what was observed in the ROT task, jump height increased with maturation in males and was higher in post-pubertal males than post-pubertal females (*large effect*

size, all MDs exceeded TEs of 0.04 cm). These results align with the previously discussed maturational developments of muscle mass, technical proficiency, strength, power, and neuromuscular control that are greater in males compared to females (Gillen et al., 2021). Again, the increases in jump height observed in the current study are consistent with previous research (Gantiraga et al., 2006; Papadopoulos et al., 1999; Quatman et al., 2006); however, unlike the ROT task, there were no significant changes in jump height observed across maturation in females. Similarly, Quatman et al. (2006) reported a significant maturation stage by sex interaction reflecting longitudinal increases in jump height with maturation in males, but not in females, during a bilateral drop vertical jump task. Other research has demonstrated similar trends in jump height performance attributed to the lack of a neuromuscular spurt in females during puberty (Beunen et al., 1997; Malina, 2004). Quatman et al. (2006) found that as males matured, they maintained their take-off force and increased their vertical jump height whereas as females matured they reduced their take-off force, demonstrating an increase in muscular power in males' concomitant with biological maturation. The neuromuscular spurt appears to naturally occur in maturing males more so than in maturing females, hence incorporating neuromuscular training for young females could be important for encouraging muscle strength and power developments, as well as movement proficiency (Hewett et al., 1996; Myer et al., 2005).

Considering peak knee extension angle on the dominant leg, pre-pubertal females landed with a more extended knee than post-pubertal females, with the difference representing a *large* effect size. Furthermore, both pre-pubertal males and mid-pubertal females landed with a more extended knee than mid-pubertal males, although the effect size was *small*. All MDs exceeded the TE of 3.35°, suggesting meaningful differences and potentially greater ACL injury risk in both pre-pubertal groups and the mid-pubertal females. Typically, greater knee extension angles are associated with less effective force absorption (Podraza & White, 2010), reflected in the larger relative vGRF alongside the more extended knee position apparent in the pre-pubertal groups. Contrastingly, Ford, Myer, et al. (2010) observed no significant differences between sexes or maturation groups in knee flexion angle at initial contact, however, this observation was during a bilateral drop landing task. During three different single-leg drop landing tasks, Hass et

al. (2005) found significantly greater knee flexion angles upon initial contact in post-pubertal females compared to pre-pubertal females, aligning with the results of the current study. Landing with a more extended knee, particularly on a single-leg, has been suggested as a risk factor for ACL injury as concentric hamstring contraction ability becomes limited, leading to a greater reliance on the eccentric contraction of the quadriceps to decelerate the body (Bennett et al., 2008). The forces from these contractions at the more extended knee angle can pull the knee into anterior tibial shear, placing excess strain on the ACL (Bennett et al., 2008). A more extended knee angle is particularly high risk during the first 40 ms of landing, when ACL injuries tend to occur (Koga et al., 2010). However, this study is limited in that only peak values were obtained and not the time at which these peak values were observed. However, we can reasonably assume that participants landed with a typical pattern where the peak knee extension angle would occur close to the initial contact and knee flexion angle would increase until reaching peak knee flexion. A recent review by Beaulieu et al. (2023) found consensus that the combination of knee joint compression and a knee flexion moment with an anterior tibial shear force, internal tibial torque, and a knee abduction moment, with a knee close to full extension (0 – 30°) resulted in greater ACL loads. Furthermore, they reported the greatest ACL loading to occur between 0 and 30° for various knee loading scenarios including anterior tibial shear force, internal tibial torque, and quadriceps contraction (Beaulieu et al., 2023). Miyasaka et al. (2002) reported that highest ACL forces occur in full extension and decrease with an increase in flexion angle, leading to smaller forces from 30°. Notably, all groups had peak knee extension angles between 10 and 30°, suggesting a relatively high risk for ACL injury than landing with a knee in greater flexion when considered in combination with other biomechanical risk factors (Beaulieu et al., 2023; Boden et al., 2000; Olsen et al., 2004).

Post-pubertal females displayed a larger range of transverse plane knee motion than post-pubertal males on the non-dominant leg, with a *large* effect size and a MD of 3.70°, which exceeded the TE of 2.66° and suggests a clinically meaningful difference. Whether this increased range is indicative of a corrective or risky mechanism depends on the direction of the range of motion (internal to external or external to internal) and the timing at when these peaks occurred relative to the landing pattern. Waveform analyses were

beyond the scope of this study and consequently, timing of the peak values was not obtained, which partially limits our interpretation. Landing with an initially greater internal rotation angle coupled with a greater knee extension angle within the first 40 ms would place the knee in a high ACL injury risk position (Koga & Muneta, 2016). A review by Quatman et al. (2010) reported higher ACL strain during internal tibial rotation, with smaller increases in ACL strain during external rotation compared to a neutral position. Although the differences were not statistically significant, the post-pubertal females had slightly larger internal rotation angles, but much higher external rotation angles than the post-pubertal males, suggesting that the larger range of motion was influenced by the external rotation angle. As all groups landed with a relatively extended knee position, this larger transverse plane range of motion could indicate an increased ACL injury risk in the post-pubertal female group. Greater joint laxity in post-pubertal females may have also influenced this larger transverse range of motion as general joint laxity increases with puberty in females (Quatman et al., 2008), potentially due to factors such as increased pelvic width and oestrogen (Wild et al., 2012).

Similarly to the observations for the ROT task, decreases in relative vGRF with maturation suggests improved force absorption with maturational development (*medium to large* effect sizes, all MDs exceeding the TEs of 0.44 and 0.34 BW for dominant and non-dominant, respectively). Force attenuation is poorer in the less biologically mature participants, likely due to reduced eccentric strength, neuromuscular control, and less familiarity with landing on a single leg (de Sá et al., 2018). Swartz et al. (2005) explored maturational development and sex differences in hip and knee biomechanics during a double-leg landing task and observed greater relative vGRFs in less biologically mature individuals compared to adults. They attributed the differences in vGRF to different landing strategies, primarily greater hip flexion and lesser knee valgus at initial contact, and greater knee and hip flexion angles at peak vGRF in adults (Swartz et al., 2005). Furthermore, supporting our findings of greater jump heights in post-pubertal males specifically, individuals who demonstrated better absorption of landing forces also demonstrated improved jumping skill (Hewett et al., 1996; McNair et al., 2000). Similar studies have reported improvements in force modulation upon and during landing with maturation, likely resultant of physical changes to muscle strength, skill acquisition, and

movement experiences (Ayalon et al., 1987; Sigg et al., 2001). In this study, the pre-pubertal groups landed with a more extended knee than most other groups, a biomechanical factor that has been associated with less effective force absorption (Podraza & White, 2010). Landing with greater vGRFs and a more extended knee angle, as observed in the pre-pubertal females, are risk factors for ACL injury (Griffin et al., 2000). Additionally, peak knee flexion moment was highest pre-puberty and decreased with maturation. Landing in a more extended position with higher knee flexion moments and greater vGRFs can place excessive strain on the ACL through an increased anterior tibial shear (Leppänen, Pasanen, Krosshaug, et al., 2017), contributing to a higher risk of ACL injury in the pre-pubertal participants.

The knee varus and external rotation moments increased with maturation with *medium* to *large* effects and clinically meaningful MDs (i.e., exceeding the TEs). An increased knee external rotation moment can place excess strain on the ACL when the knee is near full extension (Mizuno et al., 2009), although more so for an increased internal rotation moment (Oh et al., 2012). Although significantly more extended knee angles were observed in the less biologically mature groups, the knee extension angles were still within a higher ACL loading range (10 to 30° (Beaulieu et al., 2023)) in the post-pubertal groups. Greater knee external rotation moments alongside the more extended landing position of the knee could contribute to an increased ACL injury risk landing in more biologically mature individuals for the VERT task.

### **6.3 Practical applications**

The findings of this study are novel, providing some evidence of potentially higher ACL injury risk biomechanics in pre-pubertal athletes and potentially lower ACL injury risk biomechanics with maturation for some metrics. Few significant differences were identified between sex specific maturation stages and even fewer between sexes. It is widely accepted that sporting demands increase as children age. With an increased level of competition comes and increased number of factors to consider, and furthermore, the sporting manoeuvres required at these higher levels become exceedingly more complex and challenging. It is possible that, although some of the biomechanical metrics associated with risk of ACL injury appear to improve with maturation, they may not

improve at the same rate as the sporting demands, leading to the increased number of ACL injuries observed in late-to-post pubertal populations (Maniar et al., 2022). Although the females' ACL injury risk biomechanics appear to improve in a laboratory setting with pubertal maturation, biomechanics may be compromised when performing similar tasks in a competitive setting. Based on the findings of our study, we are able to recommend the following practical applications.

Training interventions are important to be implemented in younger (pre-pubertal) athletes and sex-specificity of these programmes is not particularly important based on the lack of significant sex-and-maturation interaction effects and main effects of sex. Previous research has shown that neuromuscular training programmes could effectively reduce the risk of ACL injury by 72% in females in their early- to mid-teens (Myer et al., 2013), however further research is required in males. Training interventions including components of strength, plyometrics, balance, speed, and agility are recommended as beneficial to reduce ACL injuries, particularly in females under the age of 19 years (Mattu et al., 2022). A recent study by Ford et al. (2025) demonstrated effective modification of knee abduction moment in adolescent female athletes during a DVJ task following an intervention using neuromuscular training with biofeedback. Further, in a recent meta-analysis, Ramachandran et al. (2025) suggest that neuromuscular training interventions can effectively increase peak knee flexion angle and reduce knee valgus motion during landing tasks in young females. Despite these promising findings, Ramachandran et al. (2025) found no significant improvements for other biomechanical risk factors and the certainty of evidence for many included studies was low, primarily due to risk of bias and imprecision, highlighting the need for more high-quality intervention studies and inclusion of males and specific maturation groups. The results of this thesis, along with the aforementioned findings of previous research, suggest that exposure to neuromuscular training interventions should start in the pre-pubertal years to improve jump-landing biomechanics and nurture fundamental movement habits. Teaching good landing techniques early affords time for positive movement patterns to be engrained so that when an individual is excessively fatigued, distracted, or reacting to a stimulus and finds themselves in a potentially injurious situation, they can adjust their body position safely and with less conscious effort to reduce their injury risk. Neuromuscular training

programmes can not only improve landing kinematics, but can also reduce vGRFs (Ramachandran et al., 2024). Reduction in vGRF of up to 1.2 times BW have been demonstrated in studies which employed a neuromuscular training programme incorporating aspects of strength and plyometrics in mid- to late-pubertal females (Hewett et al., 1996; Hopper et al., 2017). Furthermore, Rogalski et al. (2025) found that implementing unilateral strength training can target asymmetries and improve single-leg balance, enhancing neuromuscular abilities and resulting in better change of direction and landing mechanics in females.

Future research should explore the possibilities of starting these training programmes from a young age to determine the potential for strength and landing technique development to meet the progressive physical demands of sporting participation that occurs with increasing maturation. A focus on familiarity with different landing styles, knee flexion, force absorption, and control of knee angles in the coronal and transverse planes is recommended. Interventions should be progressive to meet maturation changes. Development of neuromuscular control and proprioception is important in the early- to mid-pubertal stages where rapid development is occurring, particularly in terms of anatomical changes to height and limb length. The observations of reduced relative vGRF, greater knee flexion angles, and greater knee varus moments without a larger knee varus angle in the more biologically mature groups, altogether suggest a decreased risk of ACL injury with maturation. However, all groups exhibited a relatively extended knee upon landing, the late-pubertal groups demonstrated larger knee external rotation moments, and there were few significant differences in knee valgus angles and moments between groups. Therefore, despite some potentially protective mechanisms, the lack of significant improvements in key metrics suggests more biologically mature groups may still be at risk of ACL injury. Although not assessed, foot placement may impact knee moments. Therefore, incorporating foot positioning when teaching proper landing techniques across age groups may assist in mitigating ACL injury risk. Additionally, in the early- and mid-pubertal stages, strengthening muscles that control coronal and transverse plane movements should be considered. This strengthening could target the gluteus medius, adductors, and abductors. Hip abductor and hamstring strength is

particularly recommended to assist in limiting femur adduction, tibial external rotation moments, and the possible anterior tibial shear in the mid- to post-pubertal stages.

It is possible that the biomechanical results in the current study are not directly reflective of ACL injury occurrence trends due to the imposed task demands. Screening and movement pattern analysis should implement tasks that are challenging and sport or injury specific to identify risk of ACL injury. Furthermore, it could be beneficial to examine injury risk in the field from camera footage or via live in-person analysis from a specialist to determine if higher risk biomechanics are observed in certain scenarios to provide more specific programmes to meet the needs of individual athletes. In a more controlled environment, practitioners can consider implementing cognitive challenge or fatigue alongside challenging landings to increase sport relevancy.

Development of general sports related skills should be implemented from a young age and children should be encouraged to perform progressively challenging manoeuvres to improve their physical competency so that when the performance demands of sport increase, they are better able to adapt their performance and remain injury free. There are multiple independent movement variables involved in learning a new skill, referred to as degrees of freedom (Gray, 2020). Coordination of these movement possibilities to effectively execute a skill can be challenging in maturing athletes or when a skill is new. Hence, athletes often 'freeze' some degrees of freedom to simplify the essentials of a movement pattern (Bernstein, 1967; Gray, 2020). Knee muscle (hamstrings and quadriceps) co-contraction during sports related skills requires coordination of the agonistic and antagonistic muscles to optimise degrees of freedom and force output whilst employing the necessary dynamic constraints for joint stability (Davids et al., 2000). Inhibition of an antagonist muscle group is learnt progressively during maturation and skill development (Basmajian, 1977) and excessive antagonistic contribution can reduce the degrees of freedom during skill acquisition (Schmidt et al., 2018). After a progressive increase, optimisation of the degrees of freedom occurs when muscular co-contraction is proficient and the skill is performed as efficiently as possible (Schmidt et al., 2018). However, when learning a new skill or during times of early pubertal development, the increased activation of the antagonist muscle group can cause greater joint stiffness, alongside reducing the joint moment and the agonist force output,

resulting in decreased performance (e.g., lower jump heights and greater vGRFs) (Winter, 2009). It is recommended that practitioners consider this theory of co-contraction and motor performance when introducing new skills to developing athletes. Encouraging an increased power output before the athlete is competent in the movement is not recommended as it can lead to a decreased co-contraction and therefore compromise the dynamic stability of a joint, leading to potential injury (Ford et al., 2008). Knee joint stability via muscle co-contraction is required when excessive shear forces and/or rotational moments are experienced to limit the potential compromise of passive ligament or meniscal structures (Ford et al., 2008). It is also recommended that hamstring muscle strength and activation is a development focus in maturing athletes to reduce the requirement for passive restraint to coronal plane rotations, anterior shear forces, and ACL load (Lloyd & Buchanan, 2001; MacWilliams et al., 1999), which can improve knee joint stability without compromising movement efficiency.

## **6.4 Strengths and limitations**

### **6.4.1 Reliability study**

The experimental studies in this thesis included in-house between session reliability, using a sample of participants from the cross-sectional data collection, to inform confidence in the differences identified between groups for each of the metrics. The reliability findings are limited in that, despite consistencies in settings, models, and marker placement with previously reported studies, they are specific to our laboratory conditions and our included participants, hence the ability to generalise to a wider population is limited (Alenezi et al., 2014). Additionally, there are likely differences between performing these tasks in a laboratory environment compared to sporting situation performance (Alenezi et al., 2016). Furthermore, data from some participants displayed marker dropout, which was not picked up during testing, and hence some trials were removed due to sizeable gaps in the data set. Employing real-time marker tracking in the future may help overcome this limitation (Myer et al., 2015) as marker drop out could be identified and amended during data collection. The TE values incorporate some biological variability (i.e., differences in participant performance between days) and also some data collection variability (i.e., potential error in marker placement and in 3D

motion capture). The generally smaller TEs suggests that larger CV% values likely reflect the restricted range and low average values of the metrics. As a dimensionless measure, the CV% is advantageous as it allows a direct comparison of reliability irrespective of calibration or scaling (Hopkins, 2000). Hence, the large CV% values were possibly a result of the magnitude of the considered metrics, suggesting the raw TE values may be more appropriate in this thesis to establish the meaningfulness of change in the collected metrics.

#### 6.4.2 Cross-sectional study

A standardised method was used for the box height of 30 cm for all of the tasks, which reflected that of previous literature (Kim & Lim, 2014; Nasser et al., 2021) and has been recommended for single-leg drop landing tasks (Wang & Peng, 2014). During the CUT task, the cutting distance was normalised to the leg length of participants to account for differences in anthropometrics between groups, based on the results of the pilot study. A limitation of the current study is that all participants performed the task from a standardised box height of 30 cm, rather than a height normalised to a percentage of leg length or maximal jump height. This effectively represented an average height of 39.89%, 33.37%, and 33.56% of leg length in pre-, mid-, and post-pubertal females and 41.25%, 32.80%, and 30.68% of leg length in pre-, mid-, and post-pubertal males, respectively. In a group of male college students during a single-leg drop jump task, Wang and Peng (2014) found that increasing drop height from 30 cm to 40 cm and 50 cm lead to increased peak impact forces, smaller jump heights, and lesser stiffness in the ankle, knee, and hip. Further, Weinhandl et al. (2015) found increased peak knee adductor moments in females and decreased peak hip abductor moments in males as landing height increased. It is possible that using a box height normalised to an individual's leg length or based on maximal jump height, might make the biomechanical demands more comparable between groups, revealing differences that are associated to sex and maturation stages independent of relative task challenge. However, it should be considered that the subjective measures of task difficulty reported in this thesis found no 'very difficult' ratings, suggesting that all tasks were below the threshold of physical abilities for all participants. Further regarding anthropometric considerations, this study

was limited in that males and females were not height and mass matched which is not favourable for statistical comparison. The physical changes that accompany maturation make height and weight matching difficult; however, this limitation was minimised by normalizing the moment data to height and weight and normalising the GRF data to weight.

Participant inclusion criteria required participation in court and field sports, which have a high rate of non-contact ACL injuries (Chia et al., 2022). However, this thesis is limited in that diversification of sports was not a variable considered within the statistical model, which may have influenced our results. Research has suggested that children who train in specific jump sports (e.g., volleyball) have lower impact forces and higher knee flexion angles during landing than those who participate in sports that involve less single-leg landing tasks (e.g., gymnastics) (Estevan et al., 2020). Although all the participants recruited in the current study were regularly participating in a court or field sport, some of the included sports require more single-leg landings than others, and some participants also participated in additional sports that were not classified as court or field, which could impact the results. DiCesare et al. (2019) demonstrated higher knee valgus angles in female athletes' post-puberty compared to pre-puberty and observed higher valgus angles in females who were more sport-specialised compared to those who played multiple sports (DiCesare et al., 2019). In this thesis, no differences in knee valgus angles were observed, however, it is possible that sports specialisation or generalisation at different maturational stages for males and females could impact employed landing strategies and the potential corresponding risk of ACL injury. Further research regarding the influence of sport specialisation in the context of maturational development and ACL injury risk could assist in providing training recommendations for maturing athletes to help reduce their injury risk.

This thesis incorporated a systematic review, reliability study, and large cross-sectional study that incorporated three defined maturation groups and both males and females, adding to areas of evidence that are limited in existing literature. However, an intervention study was not undertaken to inform incorporation of preventative training programmes specific to maturation phases, however this would be the next logical step. As the current study demonstrated that higher risk movement patterns were observed in

pre-pubertal groups, incorporation of training programmes aimed at developing safe movement competency in various landing and change of direction tasks prior to puberty may help in reducing overall injury risk. Our study was limited as specifics regarding previous strength and neuromuscular training experience were not disclosed prior to study participation, which may have influenced the results. Furthermore, it was beyond the scope of this thesis to explore the benefits of training interventions for modulating biomechanics relevant to ACL injury risk reduction across the different maturation stages, however, there is evidence to suggest that this could be beneficial for ACL injury prevention (Emery et al., 2015). Future research should explore the possibilities of starting these training programmes from pre-puberty to determine the potential for strength and landing technique development to meet the progressive physical demands of sporting participation that occurs with increasing maturation. Additionally, the main study was cross-sectional which limits true interpretation of the changes that occur for a given individual at different stages of maturation. Further studies that are longitudinal in nature are required to better understand the complexities of biomechanical and performance changes with biological maturation and to link potential ACL injury incidence to biomechanical observations.

A systematic review of the literature was conducted to inform the relevance of tasks and biomechanical metrics for examination in the context of sex and maturation. Nonetheless, few studies exist in the biologically maturing athlete space and the tasks that were used in the experimental portion of this thesis are not as common as in adults, limiting the potential for large inferences from the results. Therefore, a limitation of this research is that the tasks included have not been commonly assessed in different maturation stages or sexes and the tasks have not been previously assessed for their reflection of sport specific maneuverers in this population. Considering that post-pubertal females sustain more ACL injuries in comparison to their male counterparts and other females at earlier stages of maturation (Maniar et al., 2022), our results did not detect higher risk knee biomechanics in post-pubertal females compared to the other groups assessed. In fact, the post-pubertal female group often displayed knee biomechanics that were suggestive of ACL protective strategies (lower vGRFs and greater knee flexion angles). Although this result contradicted our hypothesis, ACL injury

occurrence in post-pubertal females may not be linked to their general landing mechanics assessed in a controlled, laboratory environment. The metrics we obtained likely do not directly reflect typical mechanics during a game or training situation. As this study was limited to the results obtained in a laboratory setting, future research is warranted to explore if higher levels of ACL occurrence in post-pubertal females is more dependent on other factors, inclusive of biomechanical ones, in a more ecologically valid environment.

Both the dominant and non-dominant legs were examined in this thesis as there is no clear consensus in the research to suggest that one leg is at a greater risk of ACL injury compared to the other, and differences in injury risk regarding limb dominance are apparent, but findings vary, for males and females (Brophy et al., 2010; DeLang et al., 2021; Mokhtarzadeh et al., 2017). Furthermore, a potential limitation to this study is that dominant leg was defined based on the leg used for kicking to align with similar research within a similar scope (Aizawa et al., 2018; Meylan et al., 2009). However, previous studies have defined the dominant leg as the stronger leg (Impellizzeri et al., 2007), leg which produced the highest jump height (Stephens et al., 2007), the foot used to start stair climbing (Ceroni et al., 2012), or the foot used to steady oneself after an unexpected loss of balance (Hewitt et al., 2012). The results between studies may have limited comparability due to the differences in leg dominance definition, hence, future research should aim to define a standardised method for determining leg dominance.

The scope of this study was limited to knee biomechanics, however, ankle, hip, and trunk mechanics have also been associated with increased risk of ACL injury (Blackburn & Padua, 2008; Frank et al., 2013; Hewett & Myer, 2011; Hughes, 2014; Leppänen, Pasanen, Krosshaug, et al., 2017). It could be that the increased occurrence of ACL injury in post-pubertal females is influenced by the movements of the adjoining segments and how these impact relative knee positioning and ACL loading. A recent review by Ramachandran et al. (2024) that examined ACL injury risk in female athletes reported only three studies that examined hip and ankle biomechanics across different stages of maturation. Further research is warranted given the key role of the hip and ankle joints in the deceleration phase of landing tasks (Kotsifaki et al., 2021; Podraza et al., 2018). Developing a better understanding of the whole bodies system mechanics during

different maturation stages could assist in informing the development of effective preventative training programmes that are targeted to different maturation stages.

The current study used self-reported Tanner staging, the PMOS, and PHV calculations to determine and confirm maturation stage, improving the robustness of grouping. These methods have been determined valid and reliable in the research (McEachan et al., 2014; Rasmussen et al., 2015), however, a limitation to this and all research regarding maturation phases is that, currently, there is no one commonly accepted measurement for determining maturational group, and the tools used often vary between studies (Butcher et al., 2024). A singular tool which combines aspects of these measures to create one robust tool would reduce this limitation and be beneficial for future research.

The experimental study used research grade gold standard tools, including 3D motion capture and force plate technology, to assess the movement of participants. Muscle contraction data were not collected as part of this research. Considering the influence of knee musculature co-contraction on joint stability and movement efficiency during landing tasks (Kellis et al., 2003), comparison of hamstring and quadriceps co-contraction levels in different landing tasks considering maturation stage and skill level may help to further explain the knee joint angle and moment results obtained in the current study. The addition of electromyography (EMG) and specific strength assessment profiles (i.e., agonist and antagonist isokinetics) could provide better understanding of the influence of muscle strength and contraction on the differences in landing mechanics observed, especially considering the likely influence of variations in neuromuscular development. The compromise to adding EMG is the extension of the already lengthy data collection time. Future research could explore the potential of using markerless 3D motion capture systems to improve time efficiency of data collection and lead to the incorporation of more tools, more participants, and overall larger more comprehensive studies.

The scope of this study was limited to exploring biological sex differences rather than gender differences. Boerner et al. (2024) suggest that many sex differences in areas of adult health are not observed until after pubertal onset primarily due to changes influenced by hormones. However, contributions of and interactions between factors including early developmental influences, psychosocial factors, and gender are often

overlooked in literature (Boerner et al., 2024). It is possible that biomechanical differences observed between groups are influenced by gender considerations such as societal constructs for type of sporting participation (e.g., netball is female dominated, yet rugby is male dominated), opportunities for training and coaching, sports funding, and exposure to sporting role-models. Incorporation of gender in ACL injury research may reveal potential influences beyond traditional biological considerations and inform effective approaches to ACL injury risk identification and injury prevention methods (Parsons et al., 2021). Future research should explore both sex and gender from a biopsychosocial-developmental perspective to better understand how key developmental stages for both sex and gender can affect long-term injury risk outcomes. The heightened ACL injury occurrence in post-pubertal females (Maniar et al., 2022) might be moreover linked to the gendered environmental bias experienced by females rather than specific biomechanical considerations or differences.

Regardless of the limitations, this study accurately portrays the sex and maturation differences in knee biomechanics, relative vGRF and performance that occurred during various sport reflective single-leg landing tasks.

## **6.5 Conclusion**

Previous research suggests that throughout puberty, males and females exhibit increasingly different biomechanics during sporting tasks (Holden et al., 2016). There is paucity of high-quality original research examining landing biomechanics in males and females across different maturational phases, and drawing conclusions from these few studies is limited by their disagreement, as identified in the systematic review (Butcher et al., 2024). The aims of the experimental studies in this thesis were to identify differences between groups defined by sex and maturation stage. A sub-aim was to explore the reliability of knee biomechanics, vGRF, and task specific performance metrics within a young athlete population. We hypothesised that biomechanical metrics associated with higher ACL injury risk would be observed in female athletes who were late- to post-pubertal in maturational stage and, secondly, that biomechanical metrics in the coronal and sagittal plane, and GRFs recorded from all the tasks would demonstrate high between-session reliability.

The sub-aim, regarding reliability, was firstly required to ensure reliable metrics were used to assess the primary aim. In partial alignment of our hypothesis, across all tasks, the results indicated adequate reliability for kinematic angles and moments aside from peak extension moment, range of moments, anterior/ posterior GRF, and medial/ lateral GRF when interpreting ICC values. Large CV% values were commonly observed for most metrics, however, the generally smaller TEs suggest that these larger CV% values likely reflect the restricted range and low average magnitude of the values of the metrics.

Considering the first aim, the findings indicate that pre-pubertal participants, particularly females, commonly exhibited lesser knee flexion angles, greater relative vGRFs, and lesser jump heights. Differences in coronal and transverse plane mechanics were apparent between maturation stages, but not often between sex-specific maturation stages, and the direction of the difference in non-sagittal plane biomechanics between maturation stages varied from task to task. Biomechanics that represented lower ACL injury risk such as increased knee flexion, lower vGRF, and greater varus moments and angles were frequently observed for the post-pubertal participants, particularly females, and sometimes also for the mid-pubertal participants. A summary of results for the cross-sectional portion of the thesis is presented in Table 35.

Relative peak vGRF typically decreased with maturation across all tasks and on both legs, demonstrating improved force attenuation. Peak extension angle was greater in post-pubertal females and mid-pubertal males on the dominant leg for the LAND and VERT tasks, suggesting greater knee flexion upon landing in these groups. Peak coronal plane and transverse plane angles were greater in pre-pubertal groups across most tasks, and peak varus moment was higher in the mid- and post-pubertal groups. These results suggest that, although the knee may not be physically angled in a varus and externally rotated position during landing as athletes mature, the forces acting to pull the knee in this direction are greater. The presence of these results indicates a potentially higher load on the lateral component of the knee joint that may reduce the load on the medial aspect of the knee and the ACL itself by reducing the valgus and internal rotation forces. During the LAND task, peak knee flexion moment was significantly higher in the post-pubertal males than females and higher in post-pubertal females than mid- and pre-pubertal females. Peak knee flexion moment was also significantly different between

maturation stages for the ROT task, but the moments were smaller within the more biologically mature groups. This result suggests different landing strategies were used in the more subjectively difficult task. For all tasks, peak external rotation moment was larger in either the mid- or post-pubertal groups and was larger in females than males on the non-dominant leg in the LAND and CUT tasks. This finding could indicate a higher ACL injury risk when combined with greater knee extension angles. No interaction effects were observed during the CUT task and this task had the fewest significant differences between maturation stages and between sexes. It is possible that this task was not challenging enough for all participants to elicit injury specific biomechanics. It is noteworthy that the cutting distance of this task was normalised to leg length, and the instructions were to leap as quickly as possible rather than aiming for a maximal distance, as informed by the findings of the pilot study.

Pre-pubertal individuals have reduced levels of neuromuscular control, proprioception, and strength that may explain their different biomechanics compared to more mature individuals (Tumkur Anil Kumar et al., 2021). However, as ACL injuries are not often observed pre-puberty, it is unlikely that the biomechanical metrics reported in the current study are reflective of a higher injury risk in this group. Rather, the lack of a neuromuscular spurt, in females in particular, as they progress through puberty (Wild et al., 2016) means that some aspects of their biomechanics may not sufficiently improve to meet the increased movement challenges and sporting demands. Additionally, changes in their rate of fatigue and recovery (Wild et al., 2013) alongside physical and hormonal adaptations may intensify the effects of high ACL injury risk biomechanics. The lack of significant results regarding main effects of sex suggests that maturation is a more influential factor for changes in biomechanics and task performance. Therefore, injury prevention interventions should start early and be maturation stage specific rather than sex specific.

To conclude, pre-pubertal participants exhibited greater differences in some landing mechanics associated with increased ACL injury risk, however, many metrics that are commonly associated with ACL injury risk did not appear to significantly change with maturation. As sporting demand typically increases with maturation, the lack of significant changes in some metrics could indicate a lack of injury preventative landing

strategies. Further research is necessary to explore the effects of sex specific maturation on whole body biomechanics associated with ACL injury during different movement sequences specific to what is commonly observed in injurious situations of different maturation stages. Furthermore, prospective research is needed to confirm that the metrics examined are (or are not) linked to ACL injury incidence.

**Table 36** Summary of significantly different results regarding biomechanics associated with higher anterior cruciate ligament (ACL) injury risk between maturational groups and sexes from the four landing tasks.

	Males			Females		
	Pre	Mid	Post	Pre	Mid	Post
<b>LAND</b>	↑ vGRF D/ND ↓ extension ang D	↑ external rot mom D	↑ flexion mom D ↓ extension ang D ↑ external rot mom D/ND	↑ vGRF D/ND ↑ flexion mom D ↓ extension ang D	↑ external rot mom D ↑ flexion mom D	↑ external rot mom D/ND
	↑ external rotation mom ND					
<b>CUT</b>	↑ vGRF ND	↑ vGRF D ↑ internal rot mom D	↑ vGRF D ↑ internal rot mom D ↑ external rot mom ND	↑ vGRF ND	↑ vGRF D ↑ internal rot mom D	↑ vGRF D ↑ internal rot mom D ↑ external rot mom ND
	↑ vGRF D			↑ external rot mom ND		
<b>ROT</b>	↑ vGRF D/ND ↑ flexion mom D/ND ↑ valgus ang D ↑ external rot mom D	↑ flexion mom D ↓ flexion ang ND ↑ valgus mom ND ↑ external rot mom D/ND	↑ flexion mom ND ↑ external rot mom D/ND	↑ vGRF D/ND ↑ flexion mom D/ND ↑ valgus ang D ↑ valgus mom ND ↑ external rot mom D	↑ flexion mom D ↓ flexion ang ND ↑ external rot mom D/ND	↑ flexion mom ND ↑ external rot mom D/ND
<b>VERT</b>	↑ vGRF D/ND ↑ flexion mom ND ↓ extension ang D ↑ valgus mom D	↑ external rot mom ND	↑ flexion mom D ↑ external rot mom D/ND	↑ vGRF D/ND ↑ flexion mom ND ↓ extension ang D ↑ valgus mom D	↓ extension ang D ↑ external rot mom ND	↑ flexion mom D ↑ external rot mom D/ND

Note: ang, angle; CUT, single-leg drop-land and cut; D, dominant; LAND, single-leg drop-land; mom, moment; ND, non-dominant; ROT, single-leg rotating land and vertical jump; rot, rotation; VERT, single-leg land and vertical jump

## 7.0 Chapter 7 – Thesis conclusion

The overarching aim of this PhD thesis was to assess the effect of sex and maturation on biomechanics associated with risk of ACL injury. This main aim was addressed by providing the scope and background of the topic area and introducing the direction of the experimental studies within the thesis via a systematic literature review titled “Does maturation affect the biomechanical risk factors associated with ACL injury?”. The systematic review examined studies that explored ACL related biomechanics during defined maturational phases in dynamic tasks to determine gaps in the current knowledge base, and to guide the methodology of the experimental studies included in this the thesis. Additionally, movement tasks that were deemed appropriate for assessing risk of ACL injury in young athletes were selected.

A pilot study was conducted to inform the method to be used in the experimental studies of this thesis for the CUT task by comparing a maximised and a normalised version of the task due to varied task requirements in previous research. The experimental studies of this thesis included in-house test-retest reliability and cross-sectional experiments for the four different single-leg drop landing tasks. Analysis for the reliability of the metrics was assessed alongside the cross-sectional comparison which utilised an ANOVA (2 x 3-way) statistical method to compare pre-pubertal, early-/mid-pubertal, and late-/post-pubertal maturation stages and males and females. Thus, biomechanical and performance outcomes for males and females across these three specific maturation stages were compared for the four different sport specific landing tasks. The main findings from the experimental studies have been presented firstly, in relation to the main metrics identified in the previously reported systematic review, then for each landing task separately, then the practical applications, limitations, recommendations for future research and conclusions specific to the experimental portion of the thesis. This final chapter aimed to summarise the findings of the thesis overall, provide relevant practical applications and direct future research. It also aimed to address the strengths and limitations of the thesis and draw conclusions regarding the main findings.

A disproportionate increase in ACL injuries has been identified in late-to-post pubertal females compared to other sex and maturation specific groups (Maniar et al., 2022).

Although the systematic review supported higher ACL injury risk biomechanics in the late-to-post pubertal female population, this was equivocal between studies. Furthermore, this review reported that the tasks used to assess ACL injury risk were neither sport or injury risk specific, and methods for maturation stage identification were not consistent. The experimental study used a range of sport and injury specific tasks and multiple valid and reliable methods to determine and then confirm maturation stage. We aimed to address the gaps which were identified in the systematic review and assess biomechanics associated with ACL injury across different sexes and maturation stages using metrics that were deemed reliable in these tasks and population.

Results from the experimental studies indicated that all tasks had adequate levels of reliability for kinematic angles and moments aside from peak knee extension moment, range of moments, anterior/ posterior GRF, and medial/ lateral GRF in terms of ICC values. However, large CV% values were commonly observed, hence careful interpretation is suggested when determining differences in metrics between groups. We found very few differences between males and females without accounting for maturation stage, suggestive that knee biomechanics are not significantly different between males and females (7 and 20 years old). Most differences were observed between maturation stages, where the pre-pubertal participants demonstrated high relative vGRFs, more extended knee positions, and greater variability in coronal and transverse plane angle and moments. Post-pubertal males occasionally exhibited some mechanics typically associated with increased risk of ACL injury, such as increased knee extension angle. However, it is possible that these more extended positions were associated with improved jump performance and not directly associated with an increased ACL injury risk, particularly considering the absence of high-risk mechanics in the other planes of motion.

It is important to consider that, although the results of the current experimental studies suggested that pre-pubertal participants exhibited biomechanics associated with potentially higher ACL injury risk, it is relatively rare that ACL injuries occur in this population (Maniar et al., 2022). Some of the tasks included in the experimental study were reflective of the more challenging maneuvers that are typically seen in sporting and injury situations in more biologically mature individuals. Therefore, the mechanics

observed in our less mature groups may not typically happen in sporting situations of less biologically mature individuals as they may usually avoid these more challenging types of sporting manoeuvres. Increased injury occurrence in post-pubertal females could be a result of the limited significant differences in high-risk biomechanics observed with sex-specific maturation. Specifically, post-pubertal females' biomechanics did not change significantly across most metrics examined compared to pre-puberty. This observed lack of improvement could be an influential factor for increased ACL injury risk, considering the increased demands of sport (i.e. physicality, and technical complexity) with age and the higher frequency of more challenging movements.

An increased requirement to read the play and pay more attention to others on the court or field can also influence the risk of non-contact ACL injuries due to divided attention. Changes in neurocognitive abilities with maturation alongside more situations of divided attention, could lead to higher injury risk situations as biomechanics may falter with additional pressure, fatigue, or cognitive demand (Grinberg et al., 2024). As demonstrated in the experimental studies, the pre-pubertal individuals demonstrated some biomechanical movement patterns associated with higher ACL injury risk. Grinberg et al. (2024) suggested that the slower reaction times, lower attentional capacities and reduced physical capabilities demonstrated in pre-pubertal individuals may limit competency within the often-complex scenarios occurring in sport, that can lead to ACL injury. Post-pubertal females may perform higher risk movement patterns in some sporting situations and potentially be more greatly affected by delays in neuromuscular development compared to males or their pre-pubertal counterparts (Pletcher et al., 2021). For example, Grinberg et al. (2024) found better information processing and visual attention in late-pubertal compared to early-pubertal females, but no differences in response inhibition. Future research is required to determine if the biomechanics observed in the pre-pubertal groups are still observed or even exacerbated in post-pubertal groups under more sport specific and challenging conditions, such as fatigue, cognitive load, or diverted attention and whether this differs between males and females.

Although knee valgus, internal rotation, and extension angles have been reported to influence ACL strain and consequently risk of injury (Quatman et al., 2010), we observed few differences in these angles between groups across the tasks. In contrast to the pre-pubertal participants, more biologically mature participants demonstrated a tendency towards less valgus, and sometimes more varus, moments, alongside greater knee flexion moments, and reduced peak vGRFs during the landing tasks, suggesting a lower risk for ACL injury (Hewett et al., 2015). Despite this observation, a much larger comparative number of late to post-pubertal females and males sustain ACL injuries, with a greater incidence in females (Comstock et al., 2013; Straccolini et al., 2015). Differences in landing mechanics between males and females, and particularly with consideration for developmental stages, may mean that the tasks used for injury risk screening should have different foci based on potential differences in primary injury mechanisms identified for sex and maturation groups (Steffensmeier et al., 2020).

Previous literature has highlighted the influence of coronal plane loading as a mechanism for ACL injuries (Bates et al., 2020); however, as the ACL's primary role is to limit anterior tibial translation, increased loads in the sagittal plane may be more important for ACL injury risk in some populations (Leppänen, Pasanen, Krosshaug, et al., 2017; Quatman et al., 2010). Tasks which challenge sagittal plane loading mechanisms may be better suited for the more biologically mature participants as high sagittal plane loads are associated with greater quadriceps contractions, greater knee extension moments, and knee extension angles within 30° of full extension (DeMorat et al., 2004; Leppänen, Pasanen, Krosshaug, et al., 2017; Mizuno et al., 2009; Taylor et al., 2011). Another important consideration relates to the use of bilateral jump landing or drop landing tasks are commonly performed as tests of assessing ACL injury risk (Bahr, 2016; Butcher et al., 2024; Ramachandran et al., 2024). Although, single-leg tasks are more sport and injury specific (Donohue et al., 2015; Xu et al., 2020), these may be more difficult for younger or less practiced individuals. Task constraints (i.e. strength, coordination, stability requirements) can significantly influence the biomechanical demands of a task and constraints are further influenced by individual ability (Emamian et al., 2022). Further exploration of the effects of individual training history on task performance and biomechanical outcomes may assist in determining appropriate

screening tests or interpreting results for athletes of different maturation phases or movement competence levels (Ramachandran et al., 2024).

Contrary to our hypothesis and recent systematic reviews (Butcher et al., 2024; Ramachandran et al., 2024), we did not observe lesser knee flexion, higher relative vGRF, greater knee valgus angles or moments in post-pubertal females. In fact, we found these higher ACL injury risk mechanics were more commonly observed in pre-pubertal individuals regardless of sex. In addition, post-pubertal individuals often exhibited greater knee external rotation and flexion moments which could contribute to an increased ACL injury risk when the knee was in close to full extension (less than 30°) (Beaulieu et al., 2023). However, the post-pubertal individuals more commonly exhibited biomechanics that resembled reduced ACL injury risk mechanisms, such as larger varus moments, smaller relative vGRF, and larger knee flexion angles. We can speculate that the higher occurrence of ACL injuries in post-pubertal females (Maniar et al., 2022) are likely not attributed to their regular knee biomechanics observed during single-leg landing tasks in a laboratory environment. Furthermore, the greater number of ACL injuries in more biologically mature females may be due to an absence of improved biomechanics and neuromuscular abilities during puberty and subsequent challenges keeping up with the sporting demands. In a game situation, factors such as fatigue, divided attention, increased cognitive load, and reactive movements, could lead post-pubertal females to resort to movement patterns that more closely resemble those observed in the pre-pubertal group. Therefore, it is possible that the increased demands of sport that typically progress with maturation have a greater influence on ACL injury risk than the biomechanics observed in individuals in a controlled laboratory environment.

This thesis focused on identifying the influence of sex on landing mechanics, specifically the biological differences between males and females (National Academies of Sciences & Medicine, 2022). Gender considerations are important for developing greater understanding of the societal influence of changes across the lifespan (Boerner et al., 2024), including in the context of ACL injury risk (Parsons et al., 2021). With increasing participation rates, viewership and compensation for women's professional sport, the opportunities for more women to perform at a higher level are growing (Thomson et al., 2023). Whilst all these factors are pivotal for women and sport, there is an increased

expectation of women to perform 'like men' to improve the entertainment factor of sports to encourage more spectators, viewers, media, sponsors, and money. These increased demands on women are likely to be consequently placed on younger girls who aspire to stand out early to get selected for higher teams and progress towards a professional sporting career. Opportunities for women to engage with specialist coaches and trainers, be embedded in a high-performance setting, or have sudden increases in training load when entering a high-performance setting should be considered for the impact on injury risk.

During a game or training, factors that may influence increased injury risk included: landing whilst looking elsewhere (which may affect neuromuscular control and lead to compromised biomechanics) (Belcher et al., 2022), unanticipated movement that involves reaction in response to a stimulus (Brown et al., 2009), distraction or cognitive load and fatigue (Jiménez-Martínez et al., 2024), physical fatigue or poor activation patterns of muscles which prevent risky biomechanics (McLean & Samorezov, 2009; Steffen et al., 2016), or physical and psychological effects of differing hormonal fluctuations (Shultz & Fegley, 2023). Further research is required to support the speculation that these factors may influence post-pubertal females and alter their biomechanics from baseline, possibly more than the other groups. Training programmes should aim to build robustness in female athletes as they progress through maturation by frequently exposing them to more biomechanically challenging tasks and encouraging them to practice good movement mechanics under fatigued or cognitively loaded conditions. It is also important to consider that training programmes are implemented in a way that is beneficial for both injury prevention are not at the expense of performance (Fox, 2018).

Implementation of preventative training programmes in pre-pubertal individuals should focus on teaching 'soft landing' strategies to reduce vGRF and increase knee flexion angle upon landing (Powers & Fisher, 2010). Programmes should also consider focusing on strengthening the abductor, adductor, glutes, and hamstring muscles to reduce excessive coronal and transverse plane motion and anterior tibial translation (Herman et al., 2022). As individuals progress towards a period of peak growth (aka PHV), proprioception and neuromuscular control can be compromised with sudden changes

to height and mass alongside concomitant hormonal and nervous system alterations (Quatman-Yates et al., 2012). Training programmes should consider these factors and adjust with maturation in a way that allows developing individuals to try new skills and movements frequently in a safe and controlled manner. Implementation of these strategies during a time where their bodies are evolving rapidly will likely encourage movement awareness, proprioceptive ability, and confidence. Preventative training programmes should be maturation stage specific and start from a young age as higher risk biomechanics are often observed in the pre-pubertal groups.

Based on the findings from this thesis, it appears less important for injury preventative programmes that target safe landing strategies are developed to be sex specific. Rather, it is more important that these programmes are implemented prior to the onset of puberty. That said, it may be beneficial for preventative programmes to become more sex specific in the mid- to late-pubertal stages, as non-contact ACL injury occurrence rates begin to differ between males and females. In this case, the focus could be on neuromuscular control and safe task performance with an increased cognitive load to match the increasing demands of sports. Although reducing injury risk is paramount, it is also important that injury prevention programmes do not decrease performance (Fox, 2018). Incorporating performance-based outcome metrics into these programmes can be beneficial for athletes and coaches to demonstrate that safer movement strategies can also be beneficial for sporting performance. A systematic review by Drew et al. (2017) suggested that injuries impair the long-term chances of athletes achieving successful performances. Therefore, an athlete that can move safely and effectively is less likely to sustain serious injury and consequently play for longer. Performance is an important factor in sport, but athlete wellbeing and preventing injury are crucial in enabling performance.

This thesis has contributed to the literature by providing novel information that suggests knee biomechanics during single-leg landing tasks performed in laboratory may not be able to highlight differences in biomechanics related to risk of ACL injury in post-pubertal females compared to other sex and maturation groups. Instead, this thesis identified that higher risk biomechanics for ACL injury are more prevalent in pre-pubertal participants during these tasks. These results are noteworthy as many previous studies

assessing ACL injury risk using biomechanics in the maturing athlete used double-leg landing tasks, which are less commonly linked to ACL injury occurrence. Additionally, this thesis included both males and females of three defined maturation stages, which allowed for a comprehensive view of sex and maturation, whereas previous studies have predominantly focussed on young females.

### **7.1 Strengths and limitations**

The strengths and limitations of each chapter of this thesis have been previously addressed and are summarised in Table 36. This thesis offers novel information and contributes to the existing literature as a wide range of different research designs and methodologies were used, including a systematic review, pilot study, reliability, and cross-sectional experimental design to progressively inform the different sections of the thesis. Each section of the thesis is structured in a progressive manner and informs the subsequent section (i.e. the systematic review informed the pilot study and the experimental studies, and the pilot study also informed the task design of a task in the experimental studies). The studies in the thesis included data from close to 100 participants and were sufficiently powered as informed by sample size calculations. Despite many strengths, this thesis is not without limitations. The experimental studies examined biomechanical risk factors obtained in a laboratory environment and did not include assessment of other potentially influencing factors, such as fatigue, divided attention, or task complexity. Furthermore, between group comparison from a longitudinal design could allow ACL injury incidence tracking, however, a longitudinal design was beyond the time constraints of this thesis. Finally, although our studies were sufficiently powered, a larger participant pool would increase the confidence in results by allowing for stronger statistical inferences.

### **7.2 Practical applications**

A series of practical applications can be drawn from this body of work.

- There does not appear to be a need to make screening tools or training interventions sex specific, based on the lack of significant differences found between sexes for landing mechanics.
- Screening and injury prevention should be implemented in younger athletes (starting pre-puberty) with an aim to teach safe landing strategies and develop proprioception and neuromuscular control, as higher ACL injury risk biomechanics were observed in the pre-pubertal groups.
- A focus on teaching force absorption, knee flexion and control of range of motion in the coronal and transverse planes could be beneficial for reducing high risk manoeuvres, based on the metrics associated with ACL injury risk that were more commonly observed in the pre-pubertal group. Specifically, in the pre- to early-pubertal stages, training programmes which consider the development of muscles that limit excess coronal and transverse plane moments (i.e., gluteus medius and hip adductors and abductors) may limit the potential effects of higher coronal plane moments.
- Encouraging a more flexed knee position upon landing is recommended, given the generally large peak knee extension angles across all groups and the observed larger peak knee flexion moments in the post-pubertal groups. Furthermore, developing hamstring strength to reduce peak knee flexion moments and the potential impact of the larger peak external rotation moments in the more extended positions on ACL injury risk, should be incorporated into training programmes as athletes progress through puberty. Additionally, teaching appropriate foot placement and developing balance and stability with pubertal maturation, may reduce the observed greater peak knee external rotation moment.
- Development of general sports related skills, and incorporating multiplanar movements, should be implemented from the early stages of puberty as the subjective findings regarding perceived difficulty of the tasks showed greater levels of difficulty were experienced during the ROT task. Furthermore, progressively challenging manoeuvres to improve physical competency in

alignment with increasing performance demands should be implemented to improve adaptation to performance and injury prevention strategies.

### **7.3 Future research recommendations and research questions to explore**

Based on the work conducted, the following areas of research are deemed worthy of exploring.

- Exploring tasks different to those examined could identify risk factors linked with ACL injury across maturation, considering few sex by maturation interaction effects were found in the tasks used this thesis. These new tasks could include components of fatigue, cognitive load, or reactive factors. Assessing if biomechanical risk factors of ACL injury differ for different maturation stages in different landing tasks would broaden our understanding of influencing factors for increased ACL injury risk and assist in informing effective preventative measures for specific maturation groups.
- Although commonly used and recommended in previous research, the standardised box height of 30 cm may have limited interpretation as the level of challenge likely varied in this heterogenous sample. Research should examine the potential for landing from normalised height based on percentage of leg length or maximal jump height to help in developing a method in heterogenous samples that could better match individual anthropometrics and challenge.
- Future research should explore the aetiology of ACL injury in biologically maturing populations as the systematic review identified that most research regarding ACL injury risk and maturation has been conducted in female cohorts, limiting our interpretation of the results regarding the male participants. Furthermore, most injury incidence data are in older/ elite/ specialised athletes. Such an exploration would determine whether the mechanisms linked with ACL injuries differ across maturational groups and with sport specialisation.
- Future research should explore whether biomechanics in post-pubertal female athletes differ in a game situation compared to in laboratory testing to ascertain the relevance of laboratory-based mechanics to ecologically valid settings as there is a greater relative number of ACL injuries that occur in post-pubertal

females and few sex x maturation interaction effects were observed, suggesting that post-pubertal females displayed higher risk biomechanics than any other groups.

- Longitudinal studies are required to better understand the complexities of biomechanical and performance changes and any potential link to ACL injury incidence in individuals as they progress through biological maturation. The experimental portion of this study was cross-sectional in nature and allowed comparison between different maturation groups and males and females, however, longitudinal research is needed to inform population-specific management and interventions.
- Exploration of both sex and gender from a biopsychosocial-developmental perspective could improve understanding of how key developmental stages for both sex and gender can affect long-term injury risk outcomes as this thesis was primarily concerned with differences between sexes rather than genders.
- Muscle contraction data in different landing tasks considering sex, maturation stage, and skill level, particularly of the hamstring and quadriceps co-contraction levels, should be explored to further explain their influence on knee joint angles and moments and evolution with maturation as it is likely that neuromuscular control was a contributing factor to ACL injury risk and potentially some of the differences in metrics observed between groups.
- Research to develop a standardised method for determining pubertal maturation stage will allow larger inferences to be made and consistencies in interpretation. Inconsistency in methods used for determining pubertal maturation stage in previous research limits results interpretation, although this thesis used three commonly used, reliable, and valid tools.
- Defining a standardised method for determining leg dominance will allow larger inferences to be made and consistencies in interpretation as this thesis used a common method for determining leg-dominance that has been previously used in research of a similar scope, but inconsistency exists in the literature.

**Table 37** Strengths and limitations of the thesis.

<b>Section</b>	<b>Strengths</b>	<b>Limitations</b>
Systematic review	<ul style="list-style-type: none"><li>• The PRISMA method was followed to ensure the recommended standards of searching and reporting were met.</li><li>• Risk of bias and quality of evidence (using the NOS and GRADE tools) of each of the included studies and the commonly observed metrics were examined to give scope to the ‘weight’ of the findings in the literature.</li><li>• The search criteria were not limited to males or females whereas most previous research focusses on females only.</li></ul>	<ul style="list-style-type: none"><li>• No meta-analysis was conducted due to limitations regarding the differences in definitions of maturation stages, the differences in tasks assessed, and the differences in biomechanical metrics examined.</li><li>• Limited data were available regarding males so comparisons between sexes were limited.</li></ul>

Section	Strengths	Limitations
Pilot study	<ul style="list-style-type: none"> <li>• The first study to examine the distances achieved between a maximal vs normalised method of the land and cut task.</li> <li>• Included a range of participants at different stages of pubertal development.</li> <li>• Provided informative data regarding the importance of selecting the appropriate method of a task when looking to compare groups of different maturation stages.</li> </ul>	<ul style="list-style-type: none"> <li>• This study did not include 3D or force biomechanical metrics.</li> <li>• Metrics were obtained using 2D video analysis.</li> <li>• A small group participated, and consequently specific maturation stages were not defined. Differences between maturation stages were hence not assessed.</li> </ul>

Section	Strengths	Limitations
Experimental study	<ul style="list-style-type: none"> <li>• In house between session reliability was conducted to inform confidence in the differences identified between groups for each of the metrics.</li> <li>• The sample size was relatively large in comparison to previous research and met a priori sample size calculations.</li> <li>• Both males and females across three different maturation stages were considered.</li> <li>• Numerous single-leg landing tasks were included to provide different sport specific challenges.</li> <li>• The maturation stages were clearly identified and confirmed using multiple validated tools.</li> <li>• Moment data were normalised to height and mass weight and GRF data were normalised to weight.</li> </ul>	<ul style="list-style-type: none"> <li>• Only knee biomechanics, vGRF, and performance metrics were assessed, full body kinematics could provide a more holistic view regarding sex-specific maturational changes.</li> <li>• Sport specificity and previous strength training history of the participants were not examined, which may have affected the outcomes.</li> <li>• All participants dropped from a standardised box height. Performing the tasks from a height normalised to a percentage of leg length or maximal jump height may change the outcomes.</li> <li>• Males and females were not height and mass matched, which means comparisons are affected by differences in anthropometrics. The physical changes that accompany maturation make height and mass matching difficult.</li> </ul>

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<b>Section</b>	<b>Strengths</b>	<b>Limitations</b>
	<ul style="list-style-type: none"><li data-bbox="539 276 1196 480">• The potential influence of menstrual cycle phase on movement mechanics aimed to be controlled for by testing all eumenorrheic females in the same menstrual cycle phase.</li></ul>	<ul style="list-style-type: none"><li data-bbox="1294 276 2004 544">• Other potentially influencing factors (not biomechanical factors), such as muscle contraction, cognitive ability, and balance would enhance understanding of ACL injury risk factors.</li><li data-bbox="1294 587 2004 735">• Menstrual cycle phase was based on self-report and symptomology likely differed between participants.</li></ul>

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Section	Strengths	Limitations
Overall thesis	<ul style="list-style-type: none"> <li>• The findings are novel and add to the literature.</li> <li>• The experimental study was informed by the gaps identified by the systematic review.</li> <li>• A range of different methodologies and research designs were used, including a systematic review, pilot study, reliability, and cross-sectional experimental design.</li> <li>• The thesis progressively informed different sections as the systematic review informed the pilot study and the experimental studies, and the pilot study also informed the methodology for one of the tasks in the experimental study.</li> <li>• Across the studies, close to 100 participants were included in the data for this thesis.</li> <li>• Sample size calculations were conducted for the pilot and experimental studies and were sufficiently powered.</li> </ul>	<ul style="list-style-type: none"> <li>• The thesis was limited to biomechanical risk factors obtained in laboratory environments and did not assess other influencing factors, such as fatigue, divided attention, or task complexity.</li> <li>• A longitudinal research design was beyond the constraints of this thesis, however, between group comparison from a longitudinal design could allow tracking of actual ACL injury incidence.</li> <li>• A larger pool of participants would increase the confidence in results and allow for stronger statistical inferences.</li> </ul>

*Note:* 2D, 2-dimensional; 3D, 3-dimensional; ACL, Anterior cruciate ligament; GRF, ground reaction force; PRISMA, preferred reporting items for systematic reviews; NOS, Newcastle Ottawa scale; GRADE, Grading of recommendations assessment, development, and evaluation; vGRF, vertical ground reaction force.

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# Appendices




## Appendix A Systematic review publication.

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### Maturation and biomechanical risk factors associated with anterior cruciate ligament injury: Is there a link? A systematic review

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**ABSTRACT**

**Objective:** To establish the potential link between sex-specific maturation and biomechanical factors associated with ACL injury during dynamic tasks.  
**Design:** Systematic review.  
**Literature search:** Five databases (CINHAL®, Cochrane Library, PubMed®, Scopus®, and SPORTDiscus) were searched and monitored until 27 May 2024.  
**Study selection criteria:** Cross-sectional, cohort, case-control, or interventional studies reporting one or more biomechanical variable linked with ACL injury and which assessed participants across two or more maturation phases were considered eligible.  
**Data synthesis:** Studies were assessed for risk of bias using a modified version of the Newcastle Ottawa Scale and overall quality of evidence was rated using GRADE. Metrics and effect sizes were presented where available.  
**Results:** Eighteen included studies examined 400 males, 1377 females, and 315 participants of undefined sex across various maturation phases. The methodological quality of most studies (n = 16) was considered good, and satisfactory for two. Knee abduction angle, knee abduction moment, knee flexion angle, and ground reaction forces were most commonly reported. Knee abduction angles and moments and knee flexion angles were greater in late and post-pubertal females than males and pre-pubertal females during both landing and cutting tasks. When normalised for body mass, ground reaction forces were generally greater in males compared to females overall and for less mature participants for both sexes. Overall quality of evidence was low or medium across the four biomechanical measures.  
**Conclusion:** Sex-specific maturation considerations are important in the targeted development and implementation of ACL injury risk identification and prevention strategies.

### 1. Background

Anterior cruciate ligament (ACL) injury is one of the most common and debilitating injuries among young athletes (Renstrom et al., 2008). Following the onset of puberty, ACL injury incidence rate in females appears to peak between the ages of 15–19 (Maniar et al., 2022; Renstrom et al., 2008; Shea et al., 2004; Zbrojkiewicz et al., 2018). The annual incidence of ACL rupture in those under 25 years in Australia has increased by 74% over a 15-year period (Zbrojkiewicz, Vertullo, & Grayson, 2018). Annual rates of ACL injuries at an even younger age

(5–14 years) has also increased over the last 20 years in Australia, rising 10.4% in females and 7.3% in males (Maniar, Verhagen, Bryant, & Opar, 2022). Although increases are apparent for both sexes, female athletes demonstrate a two-to-four times greater incidence of non-contact ACL injury and a younger average age of ACL injury than males across multiple sports and competition levels (Prodromos, Han, Rogowski, Joyce, & Shi, 2007; Waldén, Hägglund, Werner, & Ekstrand, 2011).

Experts have suggested that prior to puberty, ACL injury rates are similar between sexes (Shea, Pfeiffer, Wang, Curtin, & Apel, 2004) and lower than post-puberty (Shea et al., 2004; Slaughterbeck, Hickox,

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Beynon, & Hardy, 2006; Wild, Steele, & Munro, 2012). Furthermore, pre-puberty, lower-extremity biomechanics (Wild et al., 2012), neuromuscular function (DiStefano et al., 2015), and ACL morphology [e.g., size, length, and cross-sectional area (Hosseinzadeh & Kiapour, 2021)] are similar between sexes. Rapid skeletal growth; changes in body mass, anatomy, and posture; and a lack of sufficient concomitant neuromuscular adaptations all likely contribute to the development of movement patterns associated with increased ACL injury risk with maturation (Hewett et al., 2004; Holden, Boreham, & Delahunt, 2016; Renstrom et al., 2008; Shultz, Nguyen, & Schmitz, 2008). The development of neuromuscular function in maturing individuals often does not progress linearly (DiStefano et al., 2015), likely contributing to variance in ability to effectively mitigate forces to reduce ACL loading.

ACL injuries are more common from non-contact than contact mechanisms and often non-contact injury risk can be reduced with targeted interventions (Hewett, Lynch, et al., 2010; Webster & Hewett, 2018). Investigating potentially modifiable factors for reducing non-contact ACL injury risk, specifically in maturing individuals, is crucial for risk mitigation. Non-contact ACL injuries typically result from multiplanar loading during landing or cutting manoeuvres, which can involve large knee abduction angles and moments, internal tibial rotation, anterior tibial translation, and reduced knee flexion (Hewett, Ford, Xu, Khoury, & Myer, 2016; Kiapour et al., 2016; Koga et al., 2010; Levine et al., 2013; Olsen, Myklebust, Engebretsen, & Bahr, 2004; Quatman, Ford, Myer, & Hewett, 2006). Dependent on maturation phase, sex, and training history (Hewett, Myer, & Ford, 2005; Quatman-Yates, Quatman, Meszaros, Paterno, & Hewett, 2012), these neuromuscular variations can result in altered proprioceptive acuity (Lee, Ren, Kang, Geiger, & Zhang, 2015) and muscle activation patterns (Del Bel et al., 2018; Flaxman, Smith, & Benoit, 2014), which may be detrimental to sporting performance and safe landing and cutting biomechanics.

Research exploring the association between sex-specific maturation and lower-extremity biomechanics has highlighted deviations in movement mechanics and postural control across maturation (or between different maturational groups), typically during landing or cutting tasks (Chia et al., 2021; Ford, Myer, & Hewett, 2010a; Sigward et al., 2012a, 2012b; Westbrook, Taylor, Nguyen, Paterno, & Ford, 2020). Biomechanical variables potentially associated with ACL injury include; increased knee abduction angle and moment, decreased knee flexion, and increased ground reaction forces (GRFs) (Hewett, Myer, & Ford, 2005; Paterno et al., 2010). A recent review highlighted changes in biomechanical risk factors associated with ACL injuries during jump-landing tasks in female athletes at various stages of maturity (Ramachandran et al., 2024). They reported strong evidence for higher peak knee abduction angle, external knee abduction moment and internal rotation moment, and lower relative peak vertical GRF in post-pubertal female individuals compared with pre-pubertal girls (Ramachandran et al., 2024). While this review indicates maturation in females can influence biomechanical risk factors related to ACL, it did not consider maturation in males and tasks other than jump landing.

Confidence in the understanding of biomechanical differences associated with ACL injury across maturational phases requires a critical evaluation and synthesis of the research, which must also consider sex and task differences. Such an examination would aid in the development of athlete monitoring and injury risk reduction tools specific to maturation phase and sex. This systematic review aimed to establish the potential link between maturation and biomechanical factors associated with ACL injury during dynamic tasks, while accounting for potential sex-specific differences.

## 2. Methods

This systematic review was designed to meet the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (Page et al., 2021). Pre-registration was completed with the

International Prospective Register of Systematic Reviews (PROSPERO; registration ID: CRD42022345627).

### 2.1. Searches

The electronic databases CINHAL®, Cochrane Library, PubMed®, Scopus®, and SPORTDiscus were searched on 13 July 2022. These databases were also monitored for eligible studies up to 27 May 2024. The search included the following search terms: (ACL or anterior cruciate ligament) AND (matur\* OR pubert\*) AND (biomechanic\* or kinematic\* or kinetic\*) and were filtered for English language. The supplementary material contains a detailed description of the search syntax for each database (Supplement 1). References from identified papers were manually checked to ensure inclusion of all relevant articles.

### 2.2. Study inclusion and exclusion criteria

Eligible studies included those published between journal inception and 27 May 2024. Inclusion criteria of individual studies was based on the PICOS framework: Participants, Interventions, Comparisons, Outcomes, and Study Type (Eriksen & Frandsen, 2018).

**Participants:** Studies that included uninjured adolescent/pre-pubertal/pubertal/post-pubertal males or females were included. No restriction was placed on participants' level of physical activity or performance.

**Interventions:** Studies using a dynamic task relevant to the assessment of ACL injury risk, such as landing or cutting, were eligible for inclusion.

**Comparisons:** The associations between sex-specific maturation and biomechanical risk factors for ACL injury were of interest. Therefore, studies needed to operationally define maturational groups and assessment methods; otherwise, studies were excluded. For an inclusive review, we did not set the operational definition for maturational status although, studies needed to assess at least two maturational phases either at two different points in time where the maturation stage of the participant changed (longitudinal) or at the same point in time but comparing different maturational groups (cross-sectional).

**Outcomes:** Studies needed to report one or more kinematic or kinetic variable linked with ACL injuries.

**Study type:** Peer-reviewed original research that were cross-sectional, cohort, case-control, or interventional studies published in English were eligible. These study designs reflect observational, analytical study designs according to the Centre for Evidence-Based Medicine (<https://www.cebm.ox.ac.uk/resources/ebm-tools/study-designs>).

Only the baseline values from the interventional studies were included in the formal review process as these studies examined different maturational groups before and after an intervention aimed at altering their biomechanics. Qualitative studies, review articles, commentaries, case reports, protocols, conference proceedings, and full-text articles in languages other than English were excluded.

All search results were imported into EndNote (EndNote 20.4.1, Clarivate™, Philadelphia, PA, USA) and duplicates were removed. The remaining studies were imported into Rayyan, an online eligibility screening and reviewer blinding tool (Ouzzani, Hammady, Fedorowicz, & Elmagarmid, 2016) (<http://rayyan.qcri.org>). Two reviewers (AB and SW) independently screened titles and abstracts in Rayyan. The same two reviewers independently screened the full-text articles. Studies that did not meet eligibility criteria at either step were excluded. At each step, the two independent reviewers met to resolve disagreements in the screening process. A third reviewer (KHL) was available when consensus was not reached, but not required.

### 2.3. Study quality assessment

Two independent reviewers (AB and KHL) assessed the methodological quality and risk of bias of studies meeting inclusion using a modified version of the Newcastle Ottawa Scale (NOS) (Modesti et al.,

2016), shown in the supplementary material (Supplement 2). A third reviewer (SW) was available if consensus was not established, but not required. The modified NOS tool was selected as most studies were observational (Modesti et al., 2016) and the NOS is deemed a suitable alternative to the ROBINS-I (Sterne, Hernán, McAleenan, Reeves, & Higgins, 2019). The NOS uses a star system, with a maximum of five stars for selection. A star was awarded if the item was deemed low risk of bias and not awarded if deemed high risk of bias. The overall score is 10 stars, where a greater number indicates lower risk of bias and superior methodological quality. The overall quality of studies was qualitatively evaluated as very good, good, satisfactory, and unsatisfactory when correspondingly allocated 9–10, 7–8, 5–6, and 4 or less stars based on prior reviews (Naafs et al., 2020; Ortolan, Lorenzin, Felicetti, & Ramonda, 2021).

The semiquantitative synthesis (Huguet et al., 2013) undertaken involved evaluating and rating the certainty of evidence for differences in risk factors between maturation groups using a modified Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach (Group, 2004). All domain ratings were considered when assigning the overall GRADE rating. Where an equal number of studies were ranked as having no limitations and serious limitations for a specific domain, the overall GRADE rating was lowered. Risk of bias assessment, level of evidence, or study design ratings did not constitute study exclusion.

#### 2.4. Data extraction strategy

One reviewer (AB) extracted variables of interest from the included studies using a standardised data extraction template. A second reviewer (SW) verified the accuracy and completeness of data extraction. The following data were extracted from studies: study characteristics, participant characteristics, participant maturation phases, maturational assessment method, dynamic task, relevant kinematic and kinetic variables assessed, and key results. When not explicitly stated in text, the country of investigation was based on the institution granting ethical approval, followed by the affiliation of the first author. We attempted to contact the first authors of papers that appeared to involve the same participants for confirmation, as it could introduce bias in the findings of our review.

#### 2.5. Data synthesis and presentation

Data extracted were compiled and analysed using Microsoft Excel 2019 (Microsoft Corp., Redmond, WA, USA). Due to the variation in tasks used, maturation phases assessed, and biomechanical outcome variables reported, there was an insufficient amount of comparable data to perform a meta-analysis. Therefore, a systematic narrative synthesis of the included studies was conducted, organising the results based on tasks and narratively synthesising how maturation was associated with biomechanical variables when reported in at least two studies. Double and single leg performances of the same type of task were not grouped together given the significant differences in biomechanics between double leg and single leg dynamic tasks (Taylor, Ford, Nguyen, & Shultz, 2016). Hedges *g* effect size differences were calculated to quantify between group differences when data were provided in sufficient detail using <https://effect-size-calculator.herokuapp.com/>. Paired effect size differences were used when data were longitudinal in nature. Effect size inferences were determined using the thresholds <0.2, 0.2, 0.5, and 0.8 for *trivial*, *small*, *medium*, and *large*, respectively (Cohen, 2013; Ellis, 2010).

#### 2.6. Equity, diversity, and inclusion statement

The author group consists of four females and one male of whom are junior, early-career, and senior researchers from different disciplines, based in two countries. Our systematic review population included both

males and females with no inclusion restrictions regarding marginalised groups. The influence of data availability regarding sexes and cultural diversity on maturation and biomechanics associated with ACL injury is considered in the discussion.

### 3. Results

#### 3.1. Review statistics

The initial database search yielded 673 results, with 17 studies ultimately meeting inclusion. The search was monitored whilst the review was undertaken, and an additional study was included. The PRISMA flow diagram is presented in Fig. 1. Many biomechanical metrics were examined across studies; however, a minimum of three studies reporting the same metric were required for inclusion in the narrative synthesis. Knee abduction angle, knee abduction moment, knee flexion, and GRFs were the four most common metrics and were reported across at least three studies; therefore, these metrics were included in the narrative synthesis.

#### 3.2. Study quality assessment

The quality score and design for each study are reported in Table 1. The methodological quality of most studies was considered good ( $n = 16$ , 89%), and satisfactory for the remaining ( $n = 2$ , 11%) based on the NOS adapted for cross sectional studies (10-point scale: mean  $7.2 \pm 0.8$  stars; range 5–8 stars). Reductions in study quality were commonly caused by lack of selecting a representative sample, no presentation of sample size calculations, poor description of non-respondents, and incomplete statistical reporting. The individual NOS item scores are detailed for individual studies in Table 2.

#### 3.3. Semiquantitative analysis (evidence of effectiveness)

When considering phase of studies, sample sizes, risk of bias, precision levels, and consistency in findings, the GRADE ratings indicate low-to-moderate certainty of evidence regarding the link between maturation and potential ACL injury biomechanical risk factors during dynamic tasks, as summarised in Tables 3–5, respectively. For drop vertical jump (DVJ) tasks, GRADE ratings indicate moderate certainty of evidence for knee flexion angle and low certainty of evidence for knee abduction angle, knee abduction moment, and GRF. For cutting tasks, certainty of evidence was moderate for knee abduction angle and low for the other three factors. For other dynamic tasks, certainty of evidence was moderate for knee abduction angles but low for knee flexion angles, knee abduction moment, and GRF. It should be considered that the participants involved in both of the studies by Sigward and colleagues (Sigward et al., 2012a, 2012b) were the same (confirmed via personal communications), which may introduce bias, although the studies assessed different tasks. Similarly, it is fair to assume that the participants were the same in both studies by Ford and colleagues (Ford et al., 2010a, 2010b) given the reported sample size and participant demographics (unconfirmed), although the studies report different metrics for the same dynamic task.

#### 3.4. Study characteristics

Sample size ranged from 22 to 315 participants. A total of 2092 participants were represented across the 18 studies. Sex distribution was described across all studies except for one (Ford et al., 2010a) with a total of 400 males (19.1%), 1377 females (65.8%), and 315 participants of undefined sex (15.1%). Nine of the 18 studies (50%) used a DVJ task (Ford et al., 2010a, 2010b; Hass et al., 2005; Hewett et al., 2004, 2006; Otsuki et al., 2021; Quatman et al., 2006; Sigward, Pollard, & Powers, 2012; Westbrook et al., 2020), four (22.2%) used a cutting task (Chia et al., 2021, 2023; Colyer et al., 2021; Sigward, Pollard, Havens, &

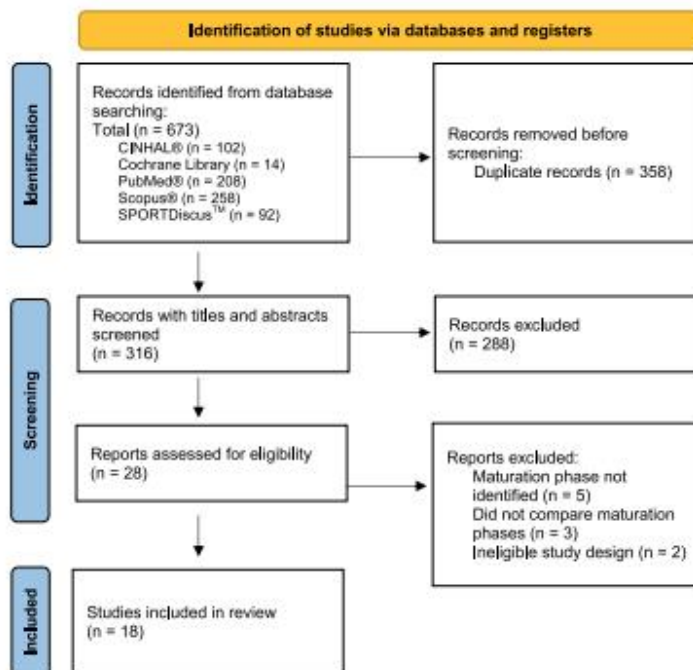


Fig. 1. PRISMA flow diagram of the search strategy and study selection process.

Powers, 2012), two (11.1 %) assessed a single-leg drop landing (Kim and Lim, 2014; Nasserri et al., 2021), and one study each (5.5 %) examined a drop and cut (Sayer et al., 2019), standing vertical jump (Swartz et al., 2005), and horizontal leap (Wild et al., 2016) task. Most studies (61.1 %,  $n = 11$ ) were cross-sectional (Colyer et al., 2021; Hass et al., 2005; Hewett et al., 2004, 2006; Kim & Lim, 2014; Nasserri et al., 2021; Sigward, Pollard, & Powers, 2012; Swartz et al., 2005; Westbrook et al., 2020), followed by longitudinal prospective cohort (33.3 %,  $n = 6$ ) (Chia et al., 2021; Ford et al., 2010a, 2010b; Quatman et al., 2006; Sayer et al., 2019; Wild et al., 2016), and interventional (5.6 %,  $n = 1$ ) (Otsuki et al., 2021).

### 3.5. Narrative synthesis

A summary of the proposed links between the commonly reported biomechanical metrics (knee abduction angle, knee abduction moment, knee flexion, and GRFs) and pubertal maturation is presented in Fig. 2.

#### 3.5.1. Knee abduction angle

Amongst the four DVJ studies regarding knee abduction angle, Hewett et al. (Hewett et al., 2004), Ford et al. (Ford et al., 2010b), and Westbrook et al. (Westbrook et al., 2020) reported significantly greater peak knee abduction angles with maturation in females and significantly greater angles in females than males following the onset of puberty, with *large*, *small*, and *medium* effect sizes observed, respectively. Hass et al. (Hass et al., 2005), who had a lower methodological quality study, in contrast observed similar knee abduction ranges of motion between pre-pubertal and post-pubertal females.

Two studies incorporating a cutting task reported *small* but significantly greater maximum knee valgus angles with maturation in females (Chia et al., 2021; Westbrook et al., 2020), no significant differences

were observed in males (Chia et al., 2023). Furthermore, a third study by Sigward et al. (Sigward, Pollard, Havens, & Powers, 2012) observed significantly greater peak knee valgus angles in females than males regardless of maturation phase; however, smaller angles were observed in the more mature participants regardless of sex.

During a single-leg landing task, Kim (Kim & Lim, 2014) reported that pubertal females demonstrated an increased peak knee abduction angle compared to pre-pubertal participants with a *large* effect size. Conversely, Swartz et al. (Swartz et al., 2005) detected significantly lesser knee valgus angle at both initial contact (*medium* effect size) and at peak vertical GRF (*small* effect size) with maturation regardless of sex in a vertical jump task.

#### 3.5.2. Knee abduction moment

When completing a DVJ task, four studies found that pubertal and post-pubertal females generally demonstrated greater knee abduction moments than pre-pubertal females and males (Ford et al., 2010b; Otsuki et al., 2021; Sigward, Pollard, & Powers, 2012; Westbrook et al., 2020), although the effect sizes were *small* and *medium*. Otsuki et al. (Otsuki et al., 2021) reported increases in peak knee abduction moments over a six-month period in early pubertal females. Similarly, Ford et al. (Ford et al., 2010b) observed larger knee abduction moments during DVJ tasks in pubertal females with maturation with *medium* effect sizes. Ford et al. (Ford et al., 2010b) also found greater knee abduction moments in females than males post-puberty, but no sex differences were observed pre-puberty.

Similar changes in knee abduction moments to those observed in the DVJ tasks were observed in three studies during cutting or horizontal jump tasks (Kim & Lim, 2014; Westbrook et al., 2020; Wild et al., 2016) with *small* effect sizes. Females post-puberty demonstrated greater peak abduction moments than females during pre- and mid-puberty

**Table 1**  
Qualitative synthesis of studies (n = 17) reporting on changes in biomechanics associated with ACL injury during different maturational phases.

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturation phases and identification method	Biomechanical variables	Results	Effect sizes (Hedges's g) <sup>a</sup>
<b>Qualitative synthesis of studies (n = 9) reporting on biomechanics in DVJ tasks</b>								
Ford et al. (2010a)	United States of America	Longitudinal prospective cohort 8 stars: good	265 142 pubertal (age, 12.3 ± 0.8 y; height, 155.9 ± 6.8 cm; mass, 47.8 ± 10.2 kg), 120 post-pubertal (age, 14.4 ± 1.4 y; height, 164.4 ± 5.8 cm; mass, 59.0 ± 8.5 kg)	50 37 pubertal (age, 13.0 ± 1.1 y; height, 165.2 ± 10.2 cm; mass, 54.5 ± 10.2 kg), 13 post-pubertal (age, 15.1 ± 1.1 y; height, 180.8 ± 7.9 cm; mass, 70.1 ± 8.4 kg)	Pubertal, post-pubertal Modified PMOS	Ankle, knee and hip: Stiffness, flexion angle at initial contact, peak angle, and peak moment	All athletes ↑ active knee stiffness over a year (p < 0.05). Only M had ↑ ankle and hip active stiffness (p < 0.05). ↑ peak ankle (31.2 N m MD) and hip (42.2 N m MD) moments, but not knee moments, in post-pubertal M but not post-pubertal F (p < 0.05). F had a ↑ knee to hip moment ratio than M (p < 0.05).	Females Knee flexion angle at initial contact (g -0.127 trivial) Peak knee flexion angle (g -0.223 small) Peak knee flexion moment (g 0.842 large) Males Knee flexion angle at initial contact = 0.419 small) Peak knee flexion angle (g 0.021 trivial) Peak knee flexion moment (g 1.362 large)
Ford, Shapiro, Myer, Van Don Bogaert, & Hewitt (2010b)	United States of America	Longitudinal prospective cohort 8 stars: good	315 total (female or male unspecified) 182 pubertal 133 post-pubertal Female: pubertal (age, 12.3 ± 0.8 y; height, 155.9 ± 6.8 cm; mass, 47.8 ± 10.2 kg), post-pubertal (age, 14.4 ± 1.4 y; height, 164.4 ± 5.8 cm; mass, 59.0 ± 8.5 kg) Male: pubertal (age, 13.0 ± 1.1 y; height, 165.2 ± 10.2 cm; mass, 54.5 ± 10.2 kg) post-pubertal (age, 15.1 ± 1.1 y; height, 180.8 ± 7.9 cm; mass, 70.1 ± 8.4 kg)		Pubertal, post-pubertal Modified PMOS	Stature change, knee abduction angle, knee abduction moment	No sex differences in peak knee abduction angle or moment during DVJ between pubertal M and F (p > 0.05). Pubertal F ↑ peak abduction angle from the first to second year (1.6° MD; p = 0.001), M had no change (p = 0.90). Following puberty, peak abduction angle and moment ↑ in F relative to M (angle: F -9.3 ± 5.7°, M -3.6 ± 4.6°, p = 0.001; moment: F -21.9 ± 13.5 Nm, M -13.0 ± 12.0 Nm, p = 0.017).	Females Knee abduction moment (g -0.501 medium) Knee abduction angle (g -0.271 small) Males Knee abduction moment (g 0.621 medium) Knee abduction angle (g 1.088 large)
Hass et al. (2005)	United States of America	Cross-sectional 5 stars: satisfactory	32 16 pre-pubertal (age, 9.0 ± 1.0 y; height, 134.5 ± 9.1 cm; mass, 33.1 ± 9.2 kg), 16 post-pubertal (age, 20.2 ± 1.2 y; height, 162.6 ± 6.1 cm; mass, 58.5 ± 7.2 kg)		Pre-pubertal, post-pubertal Pre-onset of menarche, at least 6 y past menarche	Knee flexion angle at touchdown, landing phase duration, knee flexion and knee abduction ROM, peak magnitude of posterior GRF, magnitude and timing of peak vertical GRF, peak knee anterior-posterior and medial-lateral joint forces, and peak knee extensor and abduction-adduction moment	Significant maturation level x landing sequence interactions for post-pubertal who had ↓ knee flexion (4.5° MD; p = 0.005) at initial contact, ↑ mediolateral knee joint forces [pre-pubertal: 0.63 + 0.21 N/(kg·√LH) <sup>-1</sup> , post-pubertal: 0.55 + 0.21 N/(kg·√LH)-1] 1.18 MD; p < 0.001), and ↓ knee extensor moments [pre-pubertal: 0.0124 + 0.001 Nm/(kg·BH·√LH) <sup>-1</sup> , post-pubertal: 0.0079 ± 0.001 N	Females Knee flexion angle at initial contact (g -5.000 large) Peak vertical GRF (g -5.348 large) Peak knee abduction moment (g 0.200 small)

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Table 1 (continued)

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturational phase and identification method	Kinematic variables	Results	Effect sizes (Cohen's $d$ ) <sup>a</sup>
Hewson et al., 2014	United States of America	Cross-sectional 7 stars: good	100 14 pre-pubertal (age, 11.5 ± 0.7 y; height, 148.7 ± 5.9 cm; mass, 38.9 ± 5.9 kg), 28 early-pubertal (age, 12.6 ± 1.1 y; height, 158.5 ± 6.1 cm; mass, 46.8 ± 5.5 kg), 38 late/post-pubertal (age, 15.5 ± 1.5 y; height, 168.3 ± 6.5 cm; mass, 63.4 ± 10.0 kg)	81 27 pre-pubertal (age, 12.0 ± 0.6 y; height, 151.2 ± 6.7 cm; mass, 41.9 ± 8.3 kg), 24 early-pubertal (age, 14.2 ± 1.4 y; height, 169.7 ± 9.9 cm; mass, 58.4 ± 11.4 kg), 30 late-post-pubertal (age, 15.8 ± 1.7 y; height, 179.2 ± 8.4 cm; mass, 78.8 ± 10.9 kg)	Pre-pubertal, early-pubertal, late/post-pubertal Modified PMOS, Tanner stages	Medial knee motion, valgus angle at initial contact and maximum angle, hamstring and quadriceps peak torque	<p> <math>m</math>:0g, RH, <math>\sqrt{LFD} \pm 1</math>            01:00:45 MD; <math>p = 0.006</math> compared to pre-pubertal.            *RH, leading height; RH, body height            † loaded with <math>\gamma</math> axial medial knee motion and (<math>p &lt; 0.01</math>) † maximum knee valgus angle (11° MD; <math>p &lt; 0.01</math>) vs M following onset of maturation. † also had <math>\gamma</math> flexor torque (<math>p &lt; 0.01</math>) vs M and significantly different maximum valgus angles between the dominant and non-dominant limbs after maturation.         </p>	<p>           Females            Pre vs early-pubertal            Knee valgus angle at initial contact (g 0.632 median)            Peak knee valgus angle (g 1.697 large)            Early vs late-pubertal            Knee valgus angle at initial contact (g 4.098 large)            Peak knee valgus angle (g 2.223 large)            Pre vs late-pubertal            Knee valgus angle at initial contact (g 4.525 large)            Peak knee valgus angle (g 1.997 large)            Males            Values were not provided.         </p>
Hewson, Myers, Ford, and Gasterby-Smith (2016)	United States of America	Cross-sectional 6 stars: satisfactory	87 6 for maturational groups and participant descriptors not reported	188 6 for maturational groups and participant descriptors not reported	Tanner stages 1, 2, 3, 4 and 5 Tanner stages	vGRF upon contact and take-off, vertical jump height	<p>           F had no change in vertical jump height whereas M <math>\uparrow</math> 12.5% on average between pubertal stages (<math>p = 0.003</math>). The ratio of deep landing force to drop take-off and maximum landing force to maximum take-off force (<math>m</math>:M as they matured (<math>p &lt; 0.05</math>) but did not change in F between pubertal stages.         </p>	Data unavailable—
Onishi, Shimai, Hirose, and Fukabayashi (2021)	Japan	Interventional 8 stars: good	124 17 (10f) and 18 (8f) early-pubertal (age, 12.8 ± 0.7 y; height, 151.1 ± 5.4 cm; mass, 41.0 ± 4.0 kg), 22 (10f) and 28 (9f) late-pubertal (age, 13.9 ± 1.0 y; height, 161.2 ± 5.8 cm; mass, 52.2 ± 6.2 kg), 36 (17f) and 33 (8f) post-pubertal (age, 16.0 ± 0.7 y;		Early-pubertal, late-pubertal, post-pubertal Self-administered rating scale for pubertal development, Tanner stages	Medial knee displacement, knee flexion ROM, peak knee abduction moment	<p>           After six months of training, medial knee displacement significantly <math>\uparrow</math> in early-pubertal control (<math>p = 0.02</math>) and did not change in early-pubertal training (<math>p = 0.37</math>). Knee flexion ROM significantly <math>\downarrow</math> in early-pubertal control (<math>p = 0.01</math>) and did not change in early-pubertal training (<math>p = 0.20</math>). The probability of high knee         </p>	Data unavailable—

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Table 1 (continued)

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturation phases and identification method	Biomechanical variables	Results	Effect sizes (Hedges's $g^a$ )
			height, 161.5 ± 5.7 cm; mass, 55.0 ± 5.3 kg)				abduction moment ↑ in early-pubertal control ( $p < 0.001$ ), but not in early-pubertal training ( $p = 0.13$ ). The probability of high knee abduction moment also ↓ in post-pubertal training ( $p < 0.001$ ) but did not change in post-pubertal control ( $p = 0.58$ ).	
Quatman et al. (2006)	United States of America	Longitudinal prospective cohort 7 stars: good	16 All pubertal first year (age, 12.6 ± 1.0 y; height, 162.0 ± 7.9 cm; mass, 47.5 ± 6.0 kg) and post-pubertal second year (age, 13.6 ± 1.0 y; height, 165.7 ± 8.4 cm; mass, 53.2 ± 6.2 kg)	17 All pubertal first year (age, 13.8 ± 0.6 y; height, 173.0 ± 9.2 cm; mass, 62.6 ± 7.6 kg) and post-pubertal second year (age, 14.8 ± 1.4 y; height, 177.0 ± 7.9 cm; mass, 67.9 ± 5.5 kg)	Pubertal, post-pubertal Modified PMOS, Tanner stages	Vertical jump height, maximum GRF, GRF loading rate	M ↑ vertical jump height with maturation (3.2 cm MD; $p < 0.001$ ); F did not. M significantly ↓ their maximal GRF (0.3BW MD; $p = 0.005$ ); F did not. Take-off force ↓ in females (0.1BW MD; $p = 0.003$ ), but not in M. Both M and F ↓ loading rates with maturation ( $p < 0.001$ ). F had higher loading rates than M at both stages of maturation ( $p = 0.037$ ).	Females Peak vertical ground reaction force (g 0.509 medium) Males Peak vertical ground reaction force (g -0.442 small)
Sigward, Pollard, & Powers (2012)	United States of America	Cross-sectional 7 stars: good	60 15 pre-pubertal (age, 10.2 ± 0.8 y; height, 144.9 ± 7.2 cm; mass, 37.3 ± 6.4 kg) 15 pubertal (age, 12.5 ± 0.7 y; height, 156.9 ± 6.8 cm; mass, 47.8 ± 8.9 kg), 14 post-pubertal (age, 15.7 ± 1.1 y; height, 166.3 ± 6.7 cm; mass, 59.7 ± 6.8 kg), 15 young adult (age, 19.3 ± 1.1 y; height, 166.1 ± 5.7 cm; mass, 64.9 ± 6.9 kg)	59 16 pre-pubertal (age, 11.4 ± 1.0 y; height, 146.9 ± 8.9 cm; mass, 37.9 ± 5.6 kg) 15 pubertal (age, 13.3 ± 1.2 y; height, 160.6 ± 9.7 cm; mass, 52.4 ± 7.8 kg), 14 post-pubertal (age, 15.6 ± 1.1 y; height, 176.4 ± 7.5 cm; mass, 69.7 ± 10.2 kg), 15 young adult (age, 19.8 ± 1.4 y; height, 181.5 ± 7.2 cm; mass, 78.0 ± 6.6 kg)	Pre-pubertal, pubertal, post-pubertal, young adult Modified PMOS, Tanner stages	Internal knee adductor moment, sagittal plane knee/hip moment and energy absorption ratios	When averaged across maturation levels, F had ↑ internal knee adductor moments (0.06 ± 0.02 Nm/kg <sup>2</sup> ; $p < 0.005$ ), knee/hip extensor moment ratios (2.0 ± 0.1 vs. 1.4 ± 0.1 Nm/kg <sup>2</sup> ; $p < 0.001$ ), and knee/hip energy absorption ratios (2.9 ± 0.1 vs. 1.96 ± 0.1 Nm/kg <sup>2</sup> ; $p < 0.001$ ) vs M.	Data unavailable
Westbrook et al. (2020)	United States of America	Cross-sectional 7 stars: good	138 17 pre-pubertal (age, 10.3 ± 0.6 y; height, 137.0 ± 6.8 cm; mass, 34.2 ± 4.5 kg), 32 pubertal (age, 11.9 ± 0.8 y; height, 151.1 ± 5.7 cm; mass, 43.3 ± 6.0 kg), 90 post-pubertal (age, 14.6 ± 1.6 y; height, 162.6		Pre-pubertal, early pubertal, post-pubertal Prediction of percentage of adult stature (Khamis-Roche method)	DVJ Knee abduction, knee flexion, normalised knee moments	Post-pubertal had significantly ( $p < 0.001$ ) ↑ peak abduction angles and moments than pubertal and pre-pubertal (5.4° and 3.4°, 10.1 Nm and 14.2 Nm MD). Post-pubertal and pubertal had ↑ peak knee flexion moments vs pre-pubertal (54.2 Nm and 36.3 Nm MD),	Females Peak knee abduction angle pre vs pub (g 0.322 small) pre vs post (g 0.325 small) pub vs post (g 0.679 medium) Peak knee abduction moment normalised pre vs pub (g 0.277

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Table 1 (continued)

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturation phases and identification method	Biomechanical variables	Results	Effect sizes (Hedges's g) <sup>a</sup>
			± 5.6 cm; mass, 56.2 ± 8.8 kg)				as did post-pubertal vs pubertal (17.9 Nm MD).	small) pre vs post (g -0.295 small) pub vs post (g -0.448 medium) Peak knee flexion angle pre vs pub (g 0.300 small) pre vs post (g 0.380 small) pub vs post (g 0.054) Peak knee flexion moment normalised pre vs pub (g 0.448 small) pre vs post (g 0.636 medium) pub vs post (g 0.257 small)
Qualitative synthesis of studies (n = 3) reporting on biomechanics in cutting tasks								
Chia et al. (2021)	United States of America	Longitudinal prospective cohort 8 stars: good	172 69 pre-pubertal (age, 11.8 ± 0.5 y; height, 148.3 ± 6.3 cm; mass, 38.1 ± 5.8 kg), 164 mid-pubertal (age, 12.8 ± 0.9 y; height, 158.4 ± 5.8 cm; mass, 49.5 ± 8.2 kg), 131 post-pubertal (age, 14.6 ± 1.2 y; height, 163.4 ± 5.5 cm; mass, 57.5 ± 8.5 kg) (monitored across 2-3 phases)		Pre-pubertal, mid-pubertal, post-pubertal Modified PMOS, Tanner stages	45° unanticipated cutting task Trunk: total ROM in all planes, peak trunk flexion, lateral flexion, rotation angles Knee: total ROM in all planes, knee flexion angle at initial contact, peak knee flexion and abduction angles Hip: total ROM in all planes, hip flexion angle at initial contact, peak hip flexion and adduction angle	With maturation, ↓ sagittal plane hip (1.8–2.6° MD, p < 0.03) and knee ROM (2.7–2.9° MD, p < 0.01). ↓ peak hip (2.9–3.2° MD, p < 0.02) and knee flexion angles (2.7–2.9° MD, p < 0.01), indicating ↑ quadriceps dominance. Peak knee abduction angles ↑ (0.9–1.4° MD, p < 0.02), suggesting ↑ ligament dominance. Trunk frontal (2.5–5.7° MD, p ≤ 0.03) and sagittal plane ROM ↓ (2.0° MD, p ≤ 0.01), but trunk transverse-plane ROM ↑ (2.8–3.6° MD, p ≤ 0.02). ↓ peak trunk flexion (3.8–7.8° MD, p ≤ 0.01), hip flexion (2.9–3.3° MD, p ≤ 0.02), and knee flexion angles (2.0–3.0° MD, p ≤ 0.03) at initial contact; more upright cutting posture.	Peak knee flexion pre vs pub (g -0.492 small) pre vs post (g -0.395 small) pub vs post (g -0.061 trivial) Peak knee abduction Pre vs pub (g 0.116 trivial) pre vs post (g 0.364 small) pub vs post (g 0.219 small) Initial contact knee flexion Pre vs pub (g -0.245 small) pre vs post (g -0.387 small) pub vs post (g -0.127 trivial)
Chia et al. (2023)	United States of America	Longitudinal prospective cohort 8 stars: good	42 20 pre-pubertal (age, 12.3 ± 0.5 y; height, 158.0 ± 7.9 cm; mass, 48.1 ± 9.4 kg), 38 mid-pubertal (age, 13.6 ± 1.0 y; height, 168.7 ± 1.0 cm; mass, 56.2 ± 8.9 kg), 30 post-pubertal		Pre-pubertal, mid-pubertal, post-pubertal Modified PMOS, Tanner stages	45° unanticipated cutting task Trunk: total ROM in all planes, peak trunk flexion, right lateral flexion, right rotation angles Knee: total ROM in all planes, knee flexion angle at initial contact, peak	With maturation, hip sagittal-plane RoM ↓ (5.57° MD, p ≤ 0.027). ↓ hip flexion at IC and peak hip flexion from pre to mid (6.25° MD, p ≤ 0.018; 5.95° MD, p ≤ 0.046). ↑ trunk contralateral rotation from pre to	Peak knee flexion pre vs mid (g 0.082 trivial) pre vs post (g 0.091 trivial) mid vs post (g 0.005 trivial) Peak knee abduction Pre vs mid (g 0.163 trivial)

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Table 1 (continued)

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturation phases and identification method	Biomechanical variables	Results	Effect sizes (Hedges's $g$ ) <sup>†</sup>
				(age, 15.0 ± 1.2 y; height, 178.3 ± 7.1 cm; mass, 68.4 ± 9.3 kg) (monitored across 2–3 phases)		knee flexion and abduction angles Hip: total ROM in all planes, hip flexion angle at initial contact, peak hip flexion and adduction angle	post (7.58° MD, $p \leq 5 0.027$ ). No sig diffs in knee variables.	pre vs post ( $g$ 0.171 trivial) mid vs post ( $g$ -0.003 trivial) Initial contact knee flexion Pre vs mid ( $g$ -0.149 small) pre vs post ( $g$ 0.233 small) mid vs post ( $g$ 0.091 trivial) Data unavailable
Colyer et al. (2021)	United Kingdom	Cross-sectional 7 stars: good	35 (age, 15.0 ± 1.0 y; height, 166.1 ± 7.1 cm; mass, 58.0 ± 6.6 kg)		91.2%–100% adult stature Percentage of predicted adult stature	90° unanticipated cutting task Peak external knee abduction moment, peak resultant GRF, knee abduction angle, knee internal rotation, hip internal rotation, and hip abduction angle at initial contact	Significant bilateral asymmetries observed with ↓ peak external knee abduction moments, ↓ GRF, and ↓ knee flexion (from 0 to 18% and 30–39% of contact) during the non-dominant vs dominant cuts (ES = 0.36, 0.63 and 0.50, respectively). Maturation did not affect asymmetries; however, ↓ hip abduction (e.g., 21–51% of contact for dominant cuts) with maturation.	Data unavailable
Sigward, Pullard, Havens, & Powers (2012)	United States of America	Cross-sectional 8 stars: good	80 15 pre-pubertal (age, 10.2 ± 0.8 y; height, 144.9 ± 7.2 cm; mass, 37.3 ± 6.4 kg) 15 pubertal (age, 12.5 ± 0.7 y; height, 156.9 ± 6.8 cm; mass, 47.8 ± 8.9 kg), 14 post-pubertal (age, 15.7 ± 1.1 y; height, 166.3 ± 6.7 cm; mass, 59.7 ± 6.8 kg), 15 young adult (age, 19.3 ± 1.1 y; height, 166.1 ± 5.7 cm; mass, 64.9 ± 6.9 kg)	76 16 pre-pubertal (age, 11.4 ± 1.0 y; height, 146.9 ± 8.9 cm; mass, 37.9 ± 5.6 kg) 15 pubertal (age, 13.3 ± 1.2 y; height, 160.6 ± 9.7 cm; mass, 52.4 ± 7.8 kg), 14 post-pubertal (age, 15.6 ± 1.1 y; height, 176.4 ± 7.5 cm; mass, 69.7 ± 10.2 kg), 15 young adult (age, 19.8 ± 1.4 y; height, 181.5.1 ± 7.2 cm; mass, 78.0 ± 6.6 kg)	Pre-pubertal, pubertal, post-pubertal, young adult Modified PMOS, Tanner stages	45° unanticipated cutting task Peak knee valgus angle, knee adductor moments and GRFs in all planes	No sex × maturation interactions for any variable. On average, F had ↓ knee abduction and adductor moments than M. Pre-pubertal had ↓ knee adductor moments and GRFs than all other groups ( $p = 0.01$ ).	Data unavailable
Westbrook et al. (2020)	United States of America	Cross-sectional 7 stars: good	138 17 pre-pubertal (age, 10.3 ± 0.6 y; height, 137.0 ± 6.8 cm; mass, 34.2 ± 4.5 kg), 32 pubertal (age, 11.9 ± 0.8 y; height, 151.1 ± 5.7 cm; mass, 43.3 ± 6.0 kg), 90 post-pubertal (age, 14.6 ± 1.6 y; height, 162.6 ± 5.6 cm; mass, 56.2 ± 8.8 kg)		Pre-pubertal, early pubertal, post-pubertal Prediction of percentage of adult stature (Khamis-Roche method)	90° cutting task Knee abduction, knee flexion, normalised knee moments	Post-pubertal had significantly ( $p < 0.001$ ) ↑ peak abduction angles and moments than pubertal and pre-pubertal (3.1° and 2.6°, 12.3 Nm and 10.7 Nm MD). Post-pubertal and pubertal had ↑ peak knee flexion moments vs pre-pubertal (73.4 Nm and 33.1 MD), as did post-pubertal vs pubertal (40.3 Nm MD).	Females Peak knee abduction angle pre vs pub ( $g$ 0.095 trivial) pre vs post ( $g$ 0.482 small) pub vs post ( $g$ 0.597 medium) Peak knee abduction moment normalised pre vs pub ( $g$ 0.595 medium) pre vs post ( $g$ 0.249 small) pub vs post ( $g$ )

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Table 1 (continued)

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturation phases and identification method	Biomechanical variables	Results	Effect sizes (Hedges's $g$ ) <sup>a</sup>
								–0.413 small) Peak knee flexion angle pre vs pub (g –0.499 small) pre vs post (g –0.330 small) pub vs post (g 0.330 small) Peak knee flexion moment normalised pre vs pub (g 0.478 small) pre vs post (g 0.552 medium) pub vs post (g 0.201 small)
Qualitative synthesis of studies (n = 5) reporting on biomechanics in other tasks								
Kim & Lim (2014)	Korea	Cross-sectional 7 stars: good	22 11 pre-pubertal (age, 11.6 ± 2.2 y; height, 135.4 ± 9.0 cm; mass, 29.9 ± 5.8 kg), 11 post-pubertal (age, 19.1 ± 3.2 y; height, 153.4 ± 5.0 cm; mass, 47.3 ± 5.6 kg)		Pre-pubertal, post-pubertal Pre- or post-menarcheal onset	Single legged drop landing Max knee flexion angle, max knee abduction angle, max knee internal rotation angle, max knee abduction moment, and hamstring-quadriceps activation ratio	Post-menarche ↓ maximum knee flexion angle (5.56 MD, $p = 0.019$ ) and ↑ maximum knee abduction angle (3.26 MD, $p = 0.039$ ), maximum internal tibial rotation angle (5.73 MD, $p = 0.043$ ), maximum knee abduction moment (0.18 MD, $p = 0.049$ ), and hamstring-quadriceps muscle activity ratio ( $p = 0.033$ ) compared to pre-menarche.	Peak knee flexion angle (g –3.791 large) Peak knee abduction angle (g 32.438 large) Peak knee abduction moment (g 1.791 large)
Nasseri et al. (2021)	Australia	Cross-sectional 8 stars: good	62 19 pre-pubertal (age, 9.8 ± 1.1 y; height, 140.1 ± 0.1 cm; mass, 30.9 ± 4.5 kg), 19 early/mid-pubertal (age, 11.0 ± 1.3 y; height, 150.0 ± 5.7 cm; mass, 37.4 ± 5.6 kg), 24 late/post pubertal (age, 19.9 ± 4.1 y; height, 160.0 ± 0.1 cm; mass, 59.8 ± 9.3 kg)		Pre-pubertal, early/mid-pubertal, late/post-pubertal Tanner stages	Single legged drop landing ACL force, plane loading for all planes, stance percentage	Compared to pre- and early-/mid-pubertal, late-/post-pubertal had significantly ↑ ACL force with MDs of 471 and 356 N during the first 30% and 48%–85% of stance, and 343 and 274 N during the first 24% and 59%–81% of stance, respectively, which overlapped peaks in ACL force. At peak ACL force, contributions from sagittal and transverse plane loading mechanisms to ACL force were ↓ in late-/post-pubertal than pre- and early-/mid-pubertal (ES: 0.44 to 0.77). No differences between pre- and early-/mid-pubertal in ACL force or contributors.	ACL force pre vs early/mid (g 3.994 large) early/mid vs post (g 6.063 large) pre vs post (g 11.905 large)

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Table 1 (continued)

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturation phases and identification method	Biomechanical variables	Results	Effect sizes (Hodges's $g$ ) <sup>a</sup>
Sayer et al. (2019)	Australia	Cross-sectional 8 stars: good	93 31 pre-pubertal (age, 9.4 ± 1.2 y; height, 1.4 ± 0.1 m; mass, 30.0 ± 5.7 kg), 31 early/mid-pubertal (age, 11.2 ± 1.4 y; height, 1.5 ± 0.1 m; mass, 38.4 ± 7.6 kg), 31 late/post-pubertal (age, 19.8 ± 4.0 y; height, 1.7 ± 0.1 m; mass, 60.8 ± 8.8 kg)		Pre-pubertal, early/mid-pubertal, late/post-pubertal Modified Tanner stages	Single legged drop lateral jump Triplanar knee moments and hip moments at the time of peak knee moments	Late/post-pubertal had ↑ peak KFM (0.17 N m/m and 0.45 N m/m), KADM (0.17 N m/m and 0.45 N m/m), and KIRM (3.53 N m/m and 5.07 N m/m) than the early/mid and pre-pubertal group ( $p < 0.05$ ). *KFM, knee flexion moment; KAM, knee abduction moment; KabM, knee abduction moment.	Peak knee abduction moment pre vs early/mid ( $g$ 0.731 medium) pre vs late/post ( $g$ 1.541 large) early/mid vs late/post ( $g$ 0.926 large)
Swartz, Decoster, Russell, and Croce (2005)	United States of America	Cross-sectional 7 stars: good	29 15 pre-pubertal (age, 9.2 ± 1.0 y; height, 136.6 ± 9.5 cm; mass, 32.9 ± 7.9 kg), 14 post-pubertal (age, 24.2 ± 2.3 y; height, 163.5 ± 6.2 cm; mass, 62.4 ± 9.1 kg)	29 15 pre-pubertal (age, 9.4 ± 1.1 y; height, 136.6 ± 12.2 cm; mass, 34.8 ± 7.9 kg), 14 post-pubertal (age, 23.6 ± 3.2 y; height, 178.3 ± 5.6 cm; mass, 83.3 ± 11.5 kg)	Pre-pubertal, post-pubertal Tanner stages	Standing vertical jump Knee flexion, hip flexion, knee valgus at initial contact and at peak vGRF, peak vGRF, time to peak vGRF, and impulse	Significant main effects for developmental stage. Both M and F had ↓ knee valgus (5.83 and 1.93 MD) and ↑ hip flexion (9.11 and 9.09 MD) at maximum vGRF, ↑ knee flexion at maximum vGRF (11.76 and 6.5 MD), ↓ maximum vertical force (3.67 and 2.93 MD) and impulse (0.4 and 0.3 MD), and a ↑ time to maximum vertical force (0.2 and 0.1 MD) with maturation. No sex differences among the biomechanical variables.	Female Knee flexion at initial contact pre vs post ( $g$ 0.128) Knee flexion at peak vGRF pre vs post ( $g$ 0.810 large) Knee valgus at initial contact pre vs post ( $g$ -0.528 medium) Knee valgus at peak vGRF pre vs post ( $g$ -0.445 small) Peak vGRF Pre vs post ( $g$ -1.571 large) Male Knee flexion at initial contact pre vs post ( $g$ 0.645 medium) Knee flexion at peak vGRF pre vs post ( $g$ 0.708 medium) Knee valgus at initial contact pre vs post ( $g$ -0.528 medium) Knee valgus at peak vGRF pre vs post ( $g$ -1.209 large) Peak vGRF pre vs post ( $g$ -1.581 large)
WIM, Munro, and Steele (2016)	Australia	Longitudinal prospective cohort 7 stars: good	33 Stage 1 (age, 11.4 ± 0.1 y; height, 149.7 ± 0.8 cm; mass, 40.1 ± 0.8 kg), Stage 2 (age, 11.8 ± 0.1 y; height, 152.7 ± 0.8 cm; mass, 42.2 ± 0.8 kg), Stage 3 (age, 12.1 ± 0.1 y; height, 155.2 ± 0.8 cm; mass, 44.2 ± 0.8 kg), Stage 4 (age,		Tanner stages 2, 3, and 4 Tanner stages and estimated maturity offset calculation	Horizontal leap task Ankle plantar flexion/dorsiflexion and inversion/eversion, knee flexion/extension and abduction/adduction and external/internal rotation, and hip flexion/extension and abduction/adduction and	Throughout maturation, ↓ knee flexion moment (0.59 N m/kg/m MD, $p = 0.028$ ), ↑ hip flexion (0.17 N m/kg/m MD, $p = 0.047$ ), ↑ external knee abduction moments (0.23 N m/kg/m MD, $p = 0.008$ ), and ↓ external hip adduction moments (0.6 N m/kg/m	Knee flexion moment at peak anteroposterior GRF phase 1 vs phase 2 ( $g$ -1.809 large) phase 1 vs phase 3 ( $g$ -2.869 large) phase 1 vs phase 4 ( $g$ -3.001 large) phase 2 vs phase 3 ( $g$ -1.133 large)

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Table 1 (continued)

Author	Country of study	Study design and study quality	Females (n)	Males (n)	Maturation phases and identification method	Biomechanical variables	Results	Effect sizes (Hedges's $g$ ) <sup>a</sup>
			12.5 ± 0.1 y; height, 157.9 ± 0.8 cm; mass, 46.7 ± 0.8 kg) Assessed over all phases			external/internal rotation angles, ROM, and moments for ankle, knee and hip.	MD, $p = 0.003$ during landing.	large) phase 2 vs phase 4 (g -1.593 large) phase 3 vs phase 4 (g -0.690 medium) Knee abduction moment at peak anteroposterior GRF phase 1 vs phase 2 (g 3.802 large) phase 1 vs phase 3 (g 8.229 large) phase 1 vs phase 4 (g 5.023 large) phase 2 vs phase 3 (g 2.4 large) phase 2 vs phase 4 (g 4.197 large) phase 3 vs phase 4 (g 2.399, large)

Notes. Abbreviations: ACL, anterior cruciate ligament; DVJ, drop vertical jump; CUT, cutting task; F, females; M, males; ROM, range of motion; GRF, ground reaction force; PMOS, pubertal maturation observational scale; MD, mean difference; g, Hedge's  $g$ . Data unavailable—, data needed to calculate effect size were not provided in the manuscript.

Effect size inferences were determined using the thresholds 0.2, 0.5, and 0.8 for small, medium, and large effects, respectively (Cohen, 2013; Ellis, 2010).

<sup>a</sup> In the effect size column, a +ve number indicates an increase with maturation, a -ve indicates a decrease with maturation.

(Westbrook et al., 2020). Pubertal females demonstrated greater peak knee abduction moments than pre-pubertal females during single-leg landings (Nasseri et al., 2021). Knee abduction moment in an all-female cohort was also significantly greater in late/post-pubertal and early/mid-pubertal groups compared to the pre-pubertal group during a drop land and cut task (Sayer et al., 2019).

### 3.5.3. Knee flexion angle

During a DVJ task, peak knee flexion angle was generally greater with maturation regardless of sex, and females landed with larger knee flexion angles than males (Ford et al., 2010a), although the effect sizes were trivial. Swartz et al. (Swartz et al., 2005) also detected significantly greater knee flexion angles at peak vertical GRF with maturation regardless of sex during a vertical jump task. Despite having similar magnitudes and timing of knee flexion, post-pubertal females landed with lesser knee flexion at initial contact than pre-pubertal females with a small effect size, but the post-pubertal females demonstrated a larger knee flexion range of motion in a DVJ with a large effect size (Hass et al., 2005). Westbrook et al. (Westbrook et al., 2020) found no differences in knee flexion between maturational groups in both DVJ and cutting tasks (small effect sizes), similarly Chia (Chia et al., 2023) found no significant differences in males. Data from three studies indicated reduced knee flexion range of motion and peak angles during cutting (small effect size) (Sigward, Pollard, & Powers, 2012), double-leg drop landing (Otsuki et al., 2021), and horizontal leap (Wild et al., 2016) tasks in females with maturation.

### 3.5.4. Ground reaction force

Using a DVJ task, three studies examined GRF (Hass et al., 2005; Hewett et al., 2006; Quatman et al., 2006). Quatman et al. (Quatman et al., 2006) and Hewett et al. (Hewett et al., 2006) (satisfactory quality study) found that maturation was linked with significantly smaller landing GRFs in males, but not females, and smaller take-off forces in females, but not males when normalised to body mass (small to medium effect sizes). Partially aligning with these findings, females showed

higher loading rates than males across all maturational stages, but both sexes decreased DVJ landing loading rates with maturation (Quatman et al., 2006). Hewett et al. (Hewett et al., 2006) also found fluctuations in DVJ landing GRF across maturation, with females showing slight decreases in GRF pre-puberty, slight increases during puberty, and larger decreases again post-puberty. Similarly, a satisfactory quality study by Hass et al. (Hass et al., 2005) indicated smaller GRFs, joint forces, and peak forces in post-pubertal than pre-pubertal females during a DVJ task with a large effect size. Significantly larger ACL forces were observed in late-pubertal compared to pre- and early-/mid-pubertal females in a single-leg drop jump task, although the estimation method using computational modelling limits the comparability of this study to the other studies included in this review (Nasseri et al., 2021). Colyer et al. (Colyer et al., 2021) observed no differences in GRFs with maturation during a non-dominant versus dominant limb cutting task. Regardless of sex, lesser peak vertical GRF was observed with maturation during cutting (Sigward, Pollard, Havens, & Powers, 2012) and DVJ (Quatman et al., 2006) tasks.

## 4. Discussion

Understanding the association between maturational development and biomechanical risk factors associated with ACL injury is important for addressing the increasing ACL injury incidence rates in adolescent athletes (Maniar et al., 2022). The purpose of this systematic review was to establish potential associations between maturation and biomechanical factors associated with ACL injury in males and females. Generally, the studies included were of moderate quality. The only biomechanical factors commonly reported in the included studies (reported across at least three studies) were knee abduction angle, knee abduction moment, knee flexion, and vertical GRF, which are factors identified as potentially linked to ACL injury incidence (Hewett et al., 2016; Myer, Ford, Khoury, Succop, & Hewett, 2011; Pappas, Shiyko, Ford, Myer, & Hewett, 2016). These factors had either low or moderate overall quality of evidence ratings as assessed by the modified GRADE

**Table 2**  
Newcastle-Ottawa Scale quality stars awarded for each study.

Study	Selection (max 5 stars)	Comparability (max 2 stars)	Outcome (max 3 stars)	Total (max 10 stars)
Chia et al. (2021)	3	2	3	8
Chia et al. (2023)	4	2	3	8
Colyer et al. (2021)	2	2	3	7
Ford, Myer, et al. (2010a)	3	2	3	8
Ford, Shapiro, et al. (2010b)	3	2	3	8
Hass et al. (2005)	1	2	2	5
Hewett et al. (2004b)	3	2	2	7
Hewett et al. (2006)	2	2	2	6
Kim et al. (2014)	3	2	2	7
Nasseri et al. (2021)	4	2	2	8
Otsuki et al. (2021)	4	2	2	8
Quatman et al. (2006)	3	2	2	7
Sayer et al. (2019)	3	2	3	8
Sigward et al. (2012a)	3	2	2	7
Sigward et al. (2012b)	4	2	2	8
Swartz et al. (2005)	4	1	2	7
Westbrook et al. (2020)	3	2	2	7
Wild et al. (2016)	3	2	2	7

Note: The number of stars reflect study quality: 9–10 stars = “very good”, 7–8 stars = “good”, 5–6 stars = “satisfactory”, and 0–4 stars = “unsatisfactory” quality.

regarding their association with maturation. For these metrics, both males and females tended to exhibit biomechanics suggestive of an increased risk of ACL injury during various landing and cutting tasks with maturation. Moreover, greater knee abduction angles, knee abduction moments, and vertical GRF, and lesser knee flexion angles were observed in females compared to males in the later maturation stages. These findings support that females in the late and post-pubertal maturational development stages tend to portray biomechanics associated with increased risk of ACL injury, which aligns with the rise in ACL injury occurrence observed in this demographic (Maniar et al., 2022).

The increases in knee abduction angle and moment with maturation in females may contribute towards their increased ACL injury susceptibility in the late and post-pubertal maturational stages (Ford et al., 2010b; Hewett et al., 2004; Maniar et al., 2022; Otsuki et al., 2021; Renstrom et al., 2008; Sayer et al., 2019; Shea et al., 2004; Sigward, Pollard, & Powers, 2012; Westbrook et al., 2020; Zbrojkiewicz et al., 2018). Although it should be noted that the effect sizes of these differences varied from *small* to *large* across studies. Larger knee abduction angles and moments during landing, particularly when paired with higher vertical GRF, have been suggested as contributing mechanistic factors for non-contact ACL injury (Della Villa et al., 2020; Hewett, Torg, & Boden, 2009; Sigurðsson, Karlsson, Snyder-Mackler, & Briem, 2021) due to the increased anterior tibial translation and consequent increased ACL load (Fukuda et al., 2003). The reported association between knee abduction moment during landing and tibia and femur length during the growth spurt (Hewett, Myer, Kiefer, & Ford, 2015) highlights the potential influence of rapid limb growth on increasing knee abduction moments (Wild, Steele, & Munro, 2013), substantiating this review's findings of increased moments with maturation. Knee abduction moment is commonly used as a predictor of ACL injury risk during jump

landing injury screening tasks with reports of 73% sensitivity and 78% specificity for ACL injury forecasting in females (Hewett et al., 2005a, 2005b); although, it has recently been argued that knee abduction moment in isolation may not be a standalone ACL injury risk factor as other biomechanical measures may contribute to injury risk (Cronström, Creaby, & Ageberg, 2020).

There is conflicting evidence for changes in knee flexion biomechanics with maturation during dynamic tasks. As females matured, knee flexion range of motion and knee flexion angles decreased (Della Villa et al., 2020; Hewett et al., 2009; Sigurðsson et al., 2021), although, the effect sizes ranged from *trivial* to *large*. In contrast, two studies showed that knee flexion angle upon initial contact and at peak GRF increased (Swartz et al., 2005), (Ford et al., 2010a). The varied outcomes and effect sizes identified between studies may be partially due to the different movement requirements of the tasks assessed. Decreases in knee flexion angle with maturation were generally observed in studies where tasks incorporated a horizontal component whereas those which reported knee flexion angle increases generally assessed tasks which were more vertical in nature. Landing with a more extended knee or ‘stiff knee strategy’ suggests a greater tendency for using the quadriceps to stabilise the knee joint (Chia et al., 2021; Hewett, Ford, Hoogenboom, & Myer, 2010; Pappas et al., 2016). Knee flexion angles less than 22° upon landing may increase the potential for quadriceps dominance and place excess demands on the ACL, increasing the potential for injury (Colby et al., 2000; Larwa, Stoy, Chafetz, Boniello, & Franklin, 2021; Leppänen et al., 2017; McNair, Marshall, & Matheson, 1990). Adopting a more flexed knee position during landing or cutting can improve force absorption and consequently protect internal knee structures (Boden, Torg, Knowles, & Hewett, 2009; Hass et al., 2005).

Furthermore, stiff landings cause tibiofemoral compression, which

**Table 3**  
Summary of findings regarding risk factors associated with ACL injury (knee abduction angle, knee abduction moment, knee flexion angle, ground reaction force) from studies examining the DVJ task.

Risk factor measured	Certainty assessment							Summary of findings		
	Studies (n)	Phase of investigation (study design)	Methodological weakness (risk of bias - from NOS)	Inconsistency	Indirectness	Imprecision	Publication bias	Participants (n)	Results (direction of relationship with maturation)	Overall certainty of evidence (GRADE)
Knee abduction angle	4 <sup>11,28,31,40</sup>	Phase 1 (1) Phase 2 (3)	✓	Unclear	✓(2) X(2)	X(4)	✓(4)	<b>Unspecified</b> 182 pub 133 post <b>Female</b> 31 pre 45 early 32 pub 196 late/post <b>Male</b> 27 pre 24 early 30 late/post	Knee abduction angle increases with maturation.	□□□□ Low
Knee abduction moment	5 <sup>30,31,46,47,49</sup>	Phase 2 (5)	✓	Present	✓(4) X(1)	X(5)	✓(5)	<b>Unspecified</b> 182 pub 133 post <b>Female</b> 53 pre 17 early 62 pub 22 late 185 post <b>Male</b> 32 pre 30 pub 43 post	Knee abduction moment increases with maturation.	□□□□ Low
Knee flexion angle	4 <sup>31,46,47,49</sup>	Phase 2 (4)	✓	Absent	✓(2) X(2)	X(4)	✓(4)	<b>Female</b> 33 pre 17 early 190 pub 22 late 262 post <b>Male</b> 37 pub 13 post	Knee flexion angle increases with maturation.	□□□□ moderate
Ground reaction force	3 <sup>21,47,48</sup>	Phase 2 (3)	X	Absent	✓(1) X(2)	X(3)	✓(3)	<b>Female</b> 87 not specified 16 pre 16 pub 32 post <b>Male</b> 188 not specified 17 pub 17 post	Landing GRF (normalised to body mass) decrease with maturation in males. Take off GRF decrease with maturation in females.	□□□□ Low

Abbreviations: ACL; Anterior cruciate ligament, GRADE; Grading of Recommendations Assessment, Development and Evaluation, NOS; Newcastle-Ottawa Scale, GRF; Ground Reaction Force.

**Table 4**  
Summary of findings regarding risk factors associated with ACL injury (knee abduction angle, knee abduction moment, knee flexion angle, ground reaction force) from studies examining a cutting task.

Risk factor measured	Certainty assessment							Summary of findings		
	Studies (n)	Phase of investigation (study design)	Methodological weakness (risk of bias - from NOS)	Inconsistency	Indirectness	Imprecision	Publication bias	Participants (n)	Results	Overall certainty of evidence (GRADE)
Knee abduction angle	4 <sup>27,29,31,50,51</sup>	Phase 1 (2) Phase 2 (3)	✓	Present	✓(5)	✓(2) X(3)	✓(4) X(1)	<b>Female</b> 35 not specified 101 pre 212 pub 160 post <b>Male</b> 36 pre 53 pub 59 post	Knee abduction angle increases with maturation.	☐☐☐☐ Low
Knee abduction moment	3 <sup>29,31,51</sup>	Phase 1 (1) Phase 2 (2)	✓	Absent	✓(3)	✓(1) X(3)	✓(2) X(1)	<b>Female</b> 35 not specified 32 pre 48 pub 29 post <b>Male</b> 16 pre 15 pub 29 post	Knee abduction moment increases with maturation.	☐☐☐☐ Moderate
Knee flexion angle	3 <sup>27,31,50,51</sup>	Phase 1 (2) Phase 2 (2)	✓	Present	✓(4)	X(4)	✓(2) X(2)	<b>Female</b> 35 not specified 86 pre 197 pub 131 post <b>Male</b> 20 pre 38 pub 30 post	Knee flexion angle decreases with maturation.	☐☐☐☐ Low
Ground reaction force	2 <sup>29,51</sup>	Phase 1 (1) Phase 2 (1)	✓	Absent	✓(2)	✓(1) X(1)	✓(1) X(1)	<b>Female</b> 35 not specified 15 pre 15 pub 29 post <b>Male</b> 16 pre 15 pub 29 post	GRF (normalised to body mass) decrease with maturation.	☐☐☐☐ Low

Abbreviations: ACL; Anterior cruciate ligament, GRADE; Grading of Recommendations Assessment, Development and Evaluation, NOS; Newcastle-Ottawa Scale, GRF; Ground Reaction Force.

**Table 5**  
Summary of findings regarding risk factors associated with ACL injury (knee abduction angle, knee abduction moment, knee flexion angle, ground reaction force) from studies examining other tasks.

Risk factor measured	Certainty assessment						Summary of findings			
	Studies (n)	Phase of investigation (study design)	Methodological weakness (risk of bias - from NOS)	Inconsistency	Indirectness	Imprecision	Publication bias	Participants (n)	Results	Overall certainty of evidence (GRADE)
Knee abduction angle	3 <sup>55,57</sup>	Phase 2 (3)	✓	Present	✓(3)	✓(2) X(1)	✓(3)	<b>Female</b> 33 across 5 stages 26 pre 55 post <b>Male</b> 15 pre 14 post	Knee abduction angle decreases with maturation in males and is unclear in females.	⊠⊠⊠⊠ moderate
Knee abduction moment	3 <sup>54,56,57</sup>	Phase 2 (3)	✓	Unclear	✓(2) X(1)	✓(1) X(2)	✓(3)	<b>Female</b> 33 across 5 stages 42 pre 30 early 41 post <b>Male</b> 15 pre 14 post	Knee abduction moment increases with maturation.	⊠⊠⊠⊠ Low
Knee flexion angle	3 <sup>54-57</sup>	Phase 2 (3)	✓	Absent	✓(2) X(1)	✓(1) X(2)	✓(3)	<b>Female</b> 33 across 5 stages 57 pre 30 early 55 post <b>Male</b> 15 pre 14 post	Knee flexion angle decreases with maturation.	⊠⊠⊠⊠ Low
Ground reaction force	2 <sup>55,56</sup>	Phase 2 (2)	✓	Present	✓(2)	✓(2)	✓(1) x(1)	<b>Female</b> 34 pre 19 pub 38 post <b>Male</b> 15 pre 14 post	Ground reaction forces (normalised to body mass) decrease with maturation.	⊠⊠⊠⊠ Low

Abbreviations: ACL; Anterior cruciate ligament, GRADE; Grading of Recommendations Assessment, Development and Evaluation, NOS; Newcastle-Ottawa Scale, GRF; Ground Reaction Force.

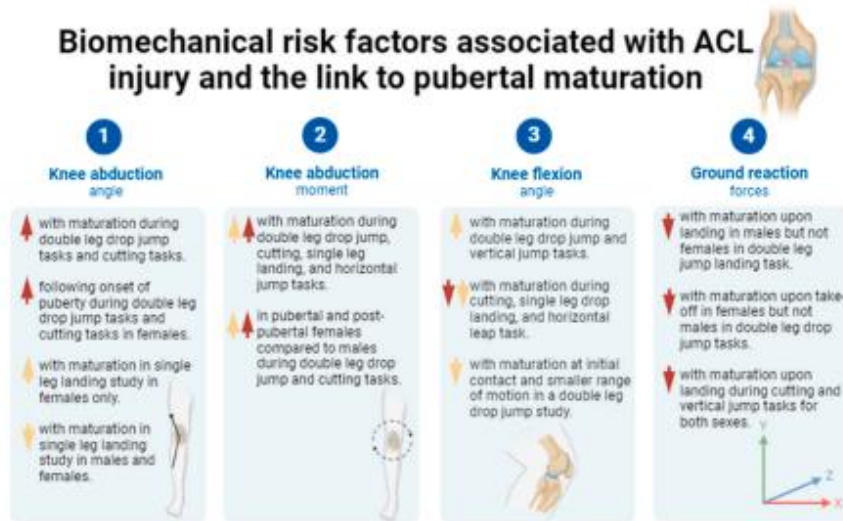


Fig. 2. Summary of the observed links between maturation and changes in biomechanics associated with anterior cruciate ligament (ACL) injury as reported in the literature.

Note: Red arrows indicate low certainty of evidence, yellow arrows indicate moderate certainty of evidence (as determined by GRADE). Two arrows suggest different quality of evidence ratings for the different specified tasks, presented in order of mention. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

loads the ACL (Meyer & Haut, 2008). During a DVJ task, stiff landings have been associated with increased risk of ACL injury in young females (Hewett, Myer, Ford, et al., 2005; Leppänen et al., 2017). Specifically, athletes who went on to sustain ACL injuries displayed lower peak knee flexion angle and higher peak GRF (Hewett, Myer, Ford, et al., 2005; Leppänen et al., 2017). As females mature, GRF during dynamic tasks generally remains the same (Colyer et al., 2021; Hewett et al., 2006; Quatman et al., 2006), or may slightly decrease (Hass et al., 2005; Sigward, Pollard, Havens, & Powers, 2012; Swartz et al., 2005). GRF tends to decrease with maturation in males (Colyer et al., 2021; Hewett et al., 2006; Quatman et al., 2006), suggesting greater improvements than females in force attenuation with maturation. During a DVJ task, the spring-like behaviour observed via the force-time data profile (referred to as stretch-shortening cycle ability) generally improved with maturation, but remained relatively poor in post-pubertal females (Pedley et al., 2021). Stretch-shortening cycle ability is also impacted by an individual's neuromuscular development rate, which is not consistent across maturation (Hewett, Myer, Ford, et al., 2005; Quatman-Yates et al., 2012). Inconsistent development in neuromuscular control may explain individual differences or lack of improvement in force attenuation ability, which is often observed in pubertal females.

The differences in tasks, including the use of double or single limb landing, likely contributed to the conflicting results regarding the link between maturation and biomechanics (Taylor et al., 2017). Over half of the included studies used the DVJ task for identifying potential biomechanical risk factors. Although commonly used as a screening tool for ACL injury risk, biomechanics during a DVJ correlate poorly with cutting biomechanics (Hanzlíková, Richards, Athens, & Hebert-Losier, 2021), which limits comparability and pertinence of results (Kristianslund, Faul, Bahr, Myklebust, & Krosshaug, 2014). Regardless of the link between the task's biomechanical variables and ACL injury risk, observed changes in dynamic tasks across maturation can be viewed more holistically due to previous identification of the higher risk of ACL injuries in post-pubertal females (Prodromos et al., 2007; Waldén et al., 2011). Tasks such as the DVJ involve deceleration and force attenuation,

primarily in the sagittal plane. Single-leg tasks increase the load and task difficulty. Cutting tasks impose a more frontal plane demand and are more sport specific. Implementing both a single-leg landing and incorporating movements that reflect cutting or rotating manoeuvres for assessment of high-risk biomechanics should be considered to improve specificity for ACL injury risk screening (Koga et al., 2010; Westbrook et al., 2020).

Definitions of maturation phases and phases examined also varied between studies, impacting the ability for cross-study inferences and strength of evidence on specific variables. Comprehensive and consistent reporting standards for maturation phase identification and grouping would enhance cross-study inferences (Koopman-Verhoeff, Gredvig-Ardito, Barker, Saletin, & Carskadon, 2020). Tanner stages, as identified using the self-administered pubertal maturation observational scale, were used most often across the included studies. Tanner stages via physical examination from a medical professional are deemed 'gold standard' for maturational phase identification (Rasmussen et al., 2015); however, self-reported Tanner stages are valid for determining maturational status and less intrusive than other validated methods (Leone & Comtois, 2007; Schmitz et al., 2004). Nonetheless, further investigation into the reliability and validity of the pubertal maturation observational scale in different demographics is warranted.

Reporting or controlling for menstrual cycle phase was rarely reported. Given the domination of female participants (65.8%), future research should attempt to control for or report menstrual cycle phase and contraceptive usage status to better understand potential hormonal influence on biomechanics (Balachandrar, Marciniak, Wall, & Balachandrar, 2017; Herzberg et al., 2017). Although more common in females (Joseph et al., 2013), non-contact ACL injury is relatively common in adolescent males (Maniar et al., 2022). The risk of ACL injury throughout maturation in males is relatively unknown and only one of the included studies examined the biomechanics of males alone (Chiu et al., 2023). The small amount of data available suggests significantly different biomechanical movement patterns in males compared to females. Hence, further research into ACL injury risk factors specific to

males should be considered.

This review specifically examined biomechanical risk factors associated with ACL injury; however, it should be noted that ACL injuries are multifactorial in nature and factors such as the demands of the sport or an athlete's position (Bram, Magee, Mehta, Patel, & Ganley, 2021), individual anatomy and morphology (Bayer et al., 2020), cognitive ability (Bertozzi et al., 2023), and the gendered differences regarding coaching, training, and physical activity participation (Parsons, Coen, & Bekker, 2021) will contribute to overall risk of injury.

## 5. Limitations

This systematic review is not without limitations. Firstly, few studies assessed the same metric, used the same task, or considered the same maturation phases, thereby restricting the ability for a meta-analysis to be performed. Studies that did examine the same variables often reported large standard deviations, presented limited or only statistically significant findings, or had small sample sizes; all factors likely to distort the results of a meta-analysis if one had been undertaken. Most studies were of good quality and two were of satisfactory quality in accordance with the NOS, but the strength of the evidence was low-to-moderate based on GRADE ratings. The small quantity of studies assessed for each domain and the variations in effect sizes should be considered when interpreting these results. We chose to include studies of varied study designs (cross-sectional, longitudinal, and interventional) to enhance the breadth of the review and data available for review, despite longitudinal study designs potentially yielding more robust data to establish the potential link between maturation and biomechanical factors associated with ACL injury. Additionally, many of the studies included researchers from the same group based in the USA, which may influence the generalisability of the results of the current review as well as introduce bias through homogeneity of study findings. This overt representation of these researchers and country may mean that many of the participants were from the same or a similar group (as was confirmed or assumed in studies of the same author and year (Ford et al., 2010a; Ford et al., 2010b; Sigward, Pollard, Havens, & Powers, 2012; Sigward, Pollard, & Powers, 2012)), consequently limiting the cultural diversity and global applicability of findings.

## 6. Conclusion

Late and post-pubertal females demonstrate lower-extremity biomechanics associated with increased ACL injury risk. Although the evidence was of low-to-moderate quality and varied between studies, this review demonstrates modified landing and cutting biomechanics occur in response to maturational development, particularly in females. As females mature, there is a tendency for increased knee abduction angles and moments, decreased knee flexion angles and range of motion, and increased GRF during dynamic tasks; variables linked with increased ACL injury risk. Potential changes throughout maturation in males and females in other biomechanical factors require further investigation during multi-planar movement tasks more specific to sport and injury risk, as the DVJ is overtly represented. Future research should explore movement mechanics across maturation, specific to sex, using sport-specific assessment tools and standardised maturation phase identification methods. Despite some contention in the evidence, differences in biomechanics linked with ACL injury risk are evident when comparing sexes and maturation stages. Hence, considering sex and maturation is needed when selecting tasks in injury risk identification processes and developing strategies for ACL injury prevention.

## Key points

- ACL injuries are increasingly common in late-to post-pubertal individuals, particularly females.

- As females mature, knee abduction angles and moments typically increase whereas knee flexion angles generally decrease during dynamic tasks.
- Maturation can influence biomechanics associated with ACL injury during landing and cutting tasks, indicating that late-to post-pubertal females may be at increased risk of ACL injury.
- Few studies examined the same variables and those that did reported large standard deviations, presented limited or only statistically significant findings, or had small sample sizes. The small quantity of studies assessed for each domain, the generally low-to-moderate levels of evidence, and the variations in effect sizes should be considered when interpreting the results.

## Ethical statement

Institutional ethics were not required to be obtained for this systematic review.

## CRedit authorship contribution statement

**Anna J. Butcher:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sarah Ward:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tracey Clissold:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jim Richards:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Kim Hébert-Losier:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ptsp.2024.06.002>.

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## Maximize or Normalize? Examining Single-Leg Drop-Land-Cut Distances in Young Athletes: A Pilot Study

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This study investigated differences in leap distance for a single-leg drop-land-cut (CUT) task based on using either a maximal or normalized (150% leg length) method or the influence of condition order and leg dominance on distance achieved. Twenty-six young court and field sport athletes (61.5% female) completed the single-leg drop-land-cut task on the dominant and nondominant leg under maximal and normalized conditions in a randomized order. Multivariate repeated measures analysis of variance tests with post hoc pairwise comparisons were used to determine the effect of condition (maximal and normalized), leg dominance (dominant and nondominant), and interaction effect on leaping distance. Potential order effects were explored as a between-subjects factor within the analysis of variance. Our findings showed significantly larger leap distances under the maximal condition ( $P < .001$ ,  $\eta_p^2 \geq .417$ ), with the maximal mean being 154.5 (24.7) cm (175.1% [18.6%] leg length) and the normalized mean being 140.7 (19.7) cm (159.0% [5.8%] of leg length). Furthermore, greater distances were achieved during the maximal task when performed following the normalized task ( $P < .001$ , 24.5% further). Practically, the normalized task may be better suited for heterogeneous samples; yet, the maximal task may be more suitable for homogeneous samples or pre-post study designs.

**Keywords:** ACL, puberty, injury screening

### Key Points

- Athletes achieved significantly greater leap distances using a maximal approach compared to a normalized (150% leg length) method during a single-leg drop-land-cut task.
- Performing the maximal task after the normalized one led to greater distances, indicating an order effect in task sequencing.
- The normalized task may be more appropriate for heterogeneous groups, while the maximal task is better suited to homogeneous samples or prepost study designs.


ACL injuries are becoming increasingly common in youth athletes.<sup>1,2</sup> The annual number of ACL injuries reported in young people has risen exponentially. In particular females aged 5–14 years have demonstrated an 10.4% annual growth rate in ACL injury incidence from 1998 to 2018 in Australia.<sup>2</sup> In New Zealand, claims from male and female individuals aged 15–29 years contributed to over 50% of the \$100 million cost of ACL injuries to taxpayers in 2021 alone.<sup>3</sup> Representing 45% of all internal knee injuries,<sup>4</sup> ACL injuries are associated with prolonged recovery periods (eg, return to play at least 9 mo postsurgery<sup>5</sup>), a substantial financial cost of care,<sup>6</sup> impaired functional sporting performance,<sup>7</sup> and an increased risk of early-onset posttraumatic osteoarthritis.<sup>8,9</sup>

The demands of court and field sports require frequent accelerations, decelerations, changes of direction, rotations, and single-leg landings all of which are movements associated with ACL injury incidence.<sup>10,11</sup> Additionally, side-cutting maneuvers are responsible for most noncontact ACL injuries in sports such as

football and handball,<sup>12,13</sup> likely due to the multiplanar nature of the movement that exposes the knee joint to high loads.<sup>14</sup> In response, screening for biomechanical injury risk factors is becoming common practice in team sports particularly in high injury risk populations, such as young female court, and field sport athletes.<sup>15</sup> However, for widespread adoption, the task needs to be suitable for implementation in clinical settings and on the field. A task that involves a single-leg landing followed by an immediate and explosive side-cut may suit these requirements and may better resemble maneuvers associated with ACL injury than what is typically used,<sup>16</sup> such as double-leg drop vertical jumps,<sup>17</sup> single-leg squats,<sup>17</sup> and tuck jumps.<sup>18</sup> Double-leg drop vertical jump tasks have been frequently used to assess ACL injury risk factors in team sport athletes<sup>17,19</sup> despite generally being determined as unsuitable for predicting ACL injury risk.<sup>15,20</sup> Although run and cut maneuvers might be better in the context of screening for risk of ACL injury and commonly assessed in laboratory settings,<sup>20</sup> they are often not practical in clinical environments and can be difficult to standardize in terms of approach speed and angle of cut.

The design of the single-leg drop-land-cut (CUT) task should consider variation in the perception of maximal effort<sup>21</sup> with respect to subjective and anthropometrical factors. Previous research has observed differences in performance and biomechanics between individuals of different maturational groups using both

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a maximal effort method<sup>22</sup> and a normalized cutting distance to 150% of leg length.<sup>23</sup> Although rationales for each of these methods are justifiable, their suitability may depend on the circumstance and purpose of implementation. For example, the maximal condition may be appropriate in a more homogeneous sample of athletes of similar body sizes; however, a normalized condition may be better to compare a more heterogeneous sample as the task is relative to body size. It is currently difficult to select one method over the other as there is a lack of studies directly comparing the 2 methods. Such information would allow practitioners to make an informed decision on test parameters for this task and enable a more appropriate comparison of performance between groups or individuals. This study focused on exploring the differences in performance of 2 conditions of the same task that have previously been used with participants in different pubertal maturation stages to inform development and implementation of injury risk screening tasks in this population. Additionally, if performance from both tasks are assessed, the order of condition of tasks may impact performance as it has been suggested that, in younger populations, some participants can believe they are performing maximally but, once given a target, may achieve further distances.<sup>21</sup> The raw values in centimeters and these values expressed as a percentage of leg length are included to provide perspective of the absolute and relative values. Furthermore, leg dominance can influence biomechanical risk factors<sup>24</sup> and performance<sup>25</sup> during sport-specific tasks that warrant consideration in establishing test parameters, interpreting outcomes, and comparing between groups or individuals. The potential effect of limb dominance on functional performance could impact clinical outcomes for injury risk or recovery screening, particularly considering the influence of perceived task difficulty.<sup>26</sup>

The primary purpose of this pilot study was to determine if differences in leap distance (ie, performance outcome) exist for the CUT task metrics based on using either a maximal or normalized (150% leg length) methodology in young court and field sport athletes. A secondary purpose was to determine whether the order of conditions or leg dominance would influence the distance achieved. It was hypothesized that participants would leap further using the maximal method, on the maximal task when presented second, and when using the dominant leg.

## Methods

Given the exploratory nature of the pilot study and the overall lack of data on the examined tasks in the target population, no formal sample size was conducted a priori. To account for dropout or data loss, a sample size between 20 and 30 participants was targeted based on previous pilot studies stating 12 participants to be appropriate.<sup>27,28</sup> Ultimately, 26 healthy young court or field sport male and female athletes aged between 7 and 20 years volunteered to participate (Table 1), providing an 80% power to detect an effect size  $f$  of 0.24 at a 5% significance level based on the analysis of variance (ANOVA): repeated measures, within-between interaction setting of G\*Power 3.1.9.7. The calculation considered the collection of 4 measurements (dominant and nondominant for maximal and normalized conditions) and 2 groups to account for a potential order effect on leap distances. All participants were right-leg dominant determined by the leg used to kick a ball. The participants had no history of serious back or leg injuries within the 12 months prior to testing. All participants and their parents/legal guardians (if under 16 y) provided informed consent prior to participating in this study, which was approved by the University

**Table 1** Baseline Characteristics of the Participants, Mean (SD)

Characteristic	Males (n = 10)	Females (n = 16)	Total (N = 26)
Age, y	13.9 (3.6)	13.0 (4.4)	13.5 (4.1)
Height, cm	154.5 (33.6)	145.0 (30.0)	155.4 (19.1)
Body mass, kg	49.4 (17.1)	47.1 (16.3)	48.5 (16.2)
BMI, kg/m <sup>2</sup>	18.9 (2.8)	20.1 (5.2)	19.6 (4.0)
Leg length, cm	88.4 (19.4)	85.7 (18.4)	88.6 (12.8)

Abbreviation: BMI, body mass index.

of Waikato Human Research Ethics Committee ([Health] 2022#53) and adhered to the Code of Ethics of the World Medical Association (Declaration of Helsinki Ethical Principles for Medical Research Involving Human Subjects), and the Health Research Council's guidelines relating to research involving children, and United Nations Children's Fund's principles guiding ethical research involving children.<sup>29</sup>

## Equipment

A high-speed video camera with a focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24–200 mm) captured the CUT trials at 120 frames per second (Sony RX10 II, Sony Corporation). The camera was placed 3.5 m in front of the landing area on a tripod with a 1.3-m lens-to-ground distance.

## Procedures

The participants attended a single testing session where they first had their leg length measured until 2 identical measurements were recorded. For leg length, a tape measure was used to record the distance from the anterior superior iliac spine to the medial malleoli on the right (dominant) leg in a supine position.<sup>30</sup> Participants then completed a standardized 5-minute warm-up involving jogging at a self-selected pace on a turf surface for 2 minutes, dynamic stretching (8 reps of each per leg: leg swings, walkouts, lunges, and lateral reaches), and jump-landing drills (15 reps per leg of submaximal vertical hopping, 5 reps of double-leg landing, and 5 reps per leg of single-leg landing).

For the CUT task, participants were required to stand on 1 foot, drop down from a 30-cm box, land on the same foot to a marked distance placed 30 cm in front of the box, and to immediately leap 90° laterally to land on the opposite foot<sup>23</sup> along a marked line on the floor (Figure 1). For instance, participants dropping down and landing on their right foot would leap toward the left to land on their left foot. Participants completed the task in the 2 experimental conditions: (1) normalized distance to 150% of leg length and (2) maximal distance. For the normalized CUT condition, the leg length normalized distance was indicated on the floor using a line of tape. For the maximal distance CUT condition, participants were asked to leap as far as possible, aiming to maximize distance, with no leap distance indicated on the floor. In both conditions, participants were required to maintain balance upon landing and were encouraged to keep their body facing forward. The participants were allowed 2 to 3 practice trials of each condition directly before the test of that same condition for familiarization, following a standardized explanation and demonstration from the primary researcher (A.B.).

Condition order was randomized, as was the use of the dominant or nondominant leg within the condition. For each leg and condition, 3 successful efforts were performed. The individual efforts were separated by 20 seconds of rest for both legs and between legs, whereas individuals rested for 2 minutes between conditions. Participants wore their own footwear that they would usually wear during sporting participation.<sup>31</sup> A pictorial representation of the CUT phases is presented in Figure 1, and a flow chart of the data collection procedure is presented in Figure 2 along with the possible orders of conditions.

( $r^2 = .92$ )<sup>33</sup> and against 3D measures in golf kinematic parameters (intraclass correlation coefficient = .929).<sup>34</sup> A marker was placed in the middle of the toe box (proximal point of the second phalange) of participants' shoes, and leap distance was calculated from the marker on the initial landing foot upon ground contact to the marker on the opposite foot upon the second ground contact. For each participant, the mean leap distance of 3 trials per leg for each condition were used in further analysis. The normalized to leg length units were calculated using the equation: (distance leapt [in centimeters]/leg length [in centimeters]) × 100.

**Data Processing**

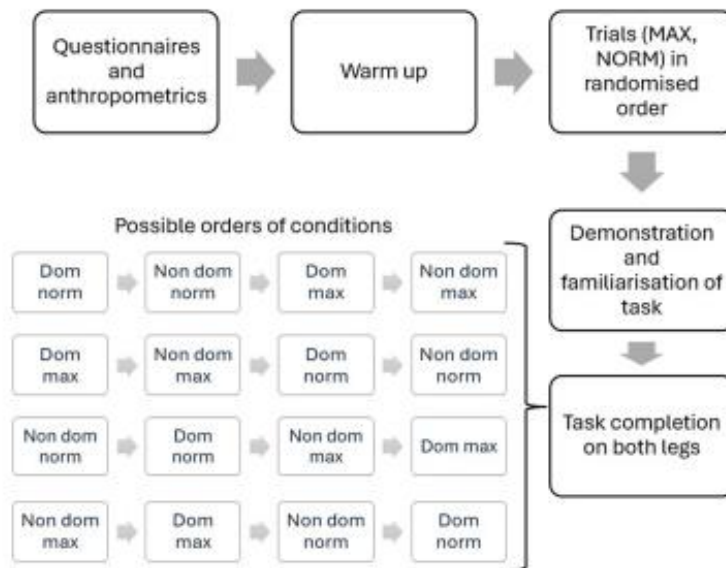
Leap distances were extracted from frontal videos using Silicon Coach (Silicon Coach Pro, version 8), and displacement calibration was performed to a marked 1-m distance along the line where the participants leapt. Silicon Coach Pro has been commonly used to provide accurate data for coaching<sup>32</sup> and has been assessed for displacement agreement against VICON in pelvis measures

**Statistical Analysis**

Using IBM SPSS Statistics (version 29.0.0.0[241]), descriptive statistics were calculated and reported as means, standard deviations, and ranges. Multivariate repeated measures ANOVA tests with post hoc pairwise comparisons were used to determine the within-subject effect of condition (maximal and normalized to leg length), leg dominance (dominant and nondominant), and



**Figure 1** — Image of single-leg drop-land-cut task, cutting to reach 150% of leg length as indicated by a marker on the floor. For the maximal condition, task sequence was similar, but participants leapt as far as possible with only the initial landing marker present.



**Figure 2** — Flow chart of data collection procedure and possible orders of conditions. Note. dom indicates dominant; max, maximal; non dom, nondominant; norm, normalized.

(Ahead of Print)

interaction effect on leaping distance outcomes, both in raw (in centimeters) and normalized to leg length (in percentage) units. Mean differences (MDs) are reported alongside their  $P$  values and 95% CIs. Potential order effects between completing the maximal or normalized condition or the dominant or nondominant leg first were explored as between-subject factors within the ANOVA. Assumption checks for normality of distribution, sphericity of data, and outliers were completed in SPSS using the Shapiro–Wilk test, Mauchly test of sphericity, and visual inspection of studentized residuals for values  $\pm 3$  standard deviations, respectively. Partial eta squared ( $\eta_p^2$ ) effect sizes are used to express the magnitude of differences between conditions using the following interpretations: .01 as a small effect, .06 as a medium effect, and .14 as a large effect.<sup>35</sup> Variances were compared using the modified Levene test by calculating the absolute deviations of each value from the group mean ( $d_{i1} = |x_{i1} - \bar{x}_1|$ ,  $d_{i2} = |x_{i2} - \bar{x}_2|$ ), and the deviations across conditions were compared using paired  $t$  tests. Statistical significance was set to  $P \leq .05$ . Individual measures were plotted on a scatter plot for the 2 conditions to visualize individual performance for the dominant and nondominant legs separately (Figures 3 and 4, respectively).

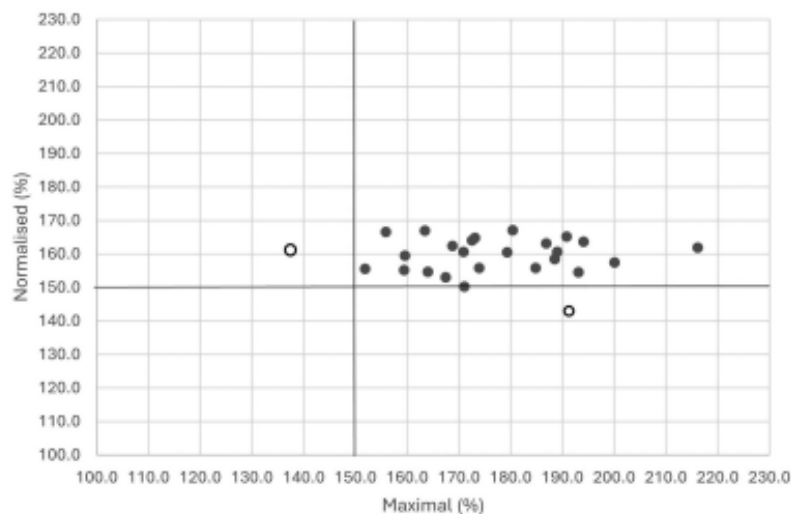
## Results

Repeated measures ANOVA assumptions were met for distance leaped expressed in raw units and normalized to leg length, and no outliers were detected. The results for the repeated measures ANOVA are reported in Table 2. For both measures, there were no significant interaction effects between side and condition ( $P \geq .429$ ,  $P \geq .547$ ; raw and normalized, respectively) or main effects for leg dominance ( $P \geq .247$ ,  $P \geq .282$ ; raw and normalized, respectively). The main effect of condition was statistically significant for distance leapt expressed in both raw and normalized units ( $P < .001$  for both) with large effect size differences ( $\eta_p^2 \geq .417$  and  $\eta_p^2 \geq .432$ , respectively). The distance leapt was 13.9 (7.1,

20.6) cm and 16.1% (8.5%, 23.7%) of leg length greater in the maximal than normalized to leg length CUT condition, with all participants leaping further in the maximal than normalized conditions. Participants leaped an average of 154.5 (24.7) cm (175.1% [18.6%] of leg length) during the maximal task and 140.7 (19.7) cm (159.0% [5.8%] of leg length) during the normalized task. All but 2 participants leaped greater than, or, equal to, the 150% of leg length distance during the maximal trials.

There was no interaction effect between (order and dominance;  $P = .644$ ) and no main effect of order ( $P = .197$ ). There was an interaction effect between order and condition for both the raw ( $F_{1,25} = 5.767$ ,  $P = .024$ ,  $\eta_p^2 = .194$ ) and normalized units ( $F_{1,25} = 6.195$ ,  $P < .001$ ,  $\eta_p^2 = .205$ ). Results from the order of conditions are presented in Table 3. For the raw values, pairwise comparisons revealed no statistically significant differences when considering order within conditions ( $P > .062$ ); however, when considering condition within order, the maximal trial was significantly further than the normalized trial when the normalized task was completed first (MD = 21.1 cm;  $P < .001$ ; 95% CI, 12.3 to 29.8), but the maximal trial was not significantly further than the normalized trial if the maximal trial was completed first (MD = 6.7 cm;  $P = .130$ ; 95% CI, -2.1 to 15.4). For the normalized values pairwise comparisons revealed statistically significant differences when considering order within condition suggesting that within the maximal condition, if normalized was completed first then the maximal trial was further than if the maximal trial was completed first (MD = 14.0%;  $P = .042$ ; 95% CI, 0.5 to 27.5). Furthermore, when considering condition within order, the maximal trial was significantly further than the normalized trial when the normalized task was completed first (MD = 24.5%;  $P < .001$ ; 95% CI, 14.7 to 34.3). However, the maximal trial was not significantly further than the normalized trial if the maximal trial was first (MD = 7.7%;  $P = .117$ ; 95% CI, -2.1 to 17.5).

The modified Levene test revealed a significant difference in variances between the absolute deviations of the maximal and

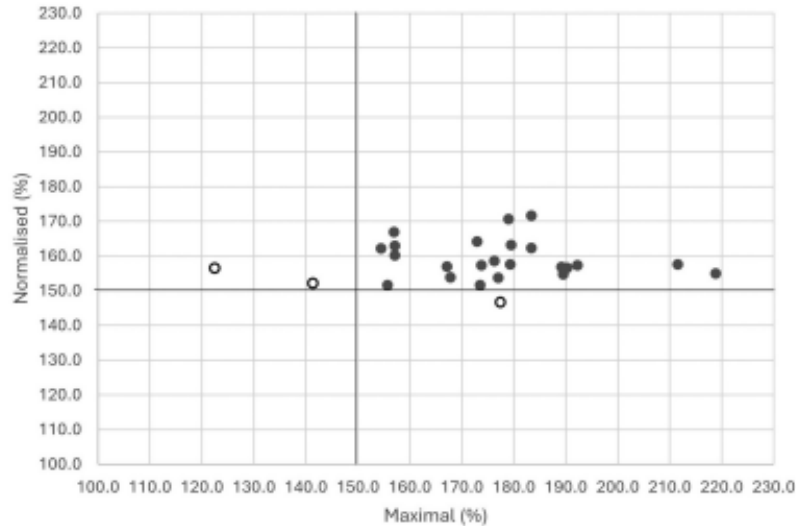


**Figure 3** — Dominant leg cut distance of the maximal compared with normalized (target of 150% leg length) conditions.

normalized conditions for the raw data (maximal mean residual = 20.3 cm; normalized mean residual = 16.4 cm; MD = 4.0 cm;  $P = .048$ ; 95% CI, 0.6 to 7.3) and for the normalized to leg length data (maximal mean residual = 14.1%; normalized mean residual = 4.6%; MD = 9.5%;  $P < .001$ ; 95% CI, 6.4 to 12.5). No significant

differences in variance were observed between order of condition for raw ( $P = .755$ ) or normalized data ( $P = .694$ ).

Regarding the individual measures on the scatter plot, 1 participant for the dominant leg and nondominant leg and 1 participant for the nondominant leg did not achieve a cut distance



**Figure 4** — Nondominant leg cut distance of the maximal compared with normalized (target of 150% leg length) conditions.

**Table 2** Raw and Percentage of Leg Length Leap Distances for Maximal and Normalized to 150% of Leg Length Conditions for the Single-Leg Drop-Land-Cut Task

CUT task	Maximal		Normalized		Effects $P$ , $\eta_p^2$		
	Non-dom	Dom	Non-dom	Dom	Condition	Dominance	Interaction
Raw, cm	153.5 (24.9) (115–197)	155.5 (24.5) (123–206)	140.4 (20.4) (105–181)	140.9 (19.0) (104–170)	$P < .001^*$ , $\eta_p^2 = .417$ (.161 to .580)	$P = .282$ , $\eta_p^2 = .046$ (.000 to .219)	$P = .429$ , $\eta_p^2 = .025$ (.000 to .181)
Normalized, %	174.0 (20.2) (122–219)	176.2 (17.0) (138–216)	158.5 (5.8) (147–172)	159.5 (5.7) (143–167)	$P < .001^*$ , $\eta_p^2 = .432$ (.175 to .591)	$P = .247$ , $\eta_p^2 = .053$ (.000 to .230)	$P = .547$ , $\eta_p^2 = .015$ (.000 to .156)

Abbreviations: Dom, dominant; Non-dom, nondominant. Note: Negative values indicate larger right value. Effect size: small (.01), medium (.06), and large (.14).<sup>35</sup> Data are mean (SD), range (minimum–maximum), and 95% confidence interval (lower to upper).

\*Statistical significance ( $P \leq .05$ ).

**Table 3** Leap Distances by Condition and Order

	Maximal				Normalized			
	First	Second	MD (95% CI)	$P$ , $\eta_p^2$	First	Second	MD (95% CI)	$P$ , $\eta_p^2$
Raw, cm	145.7 (23.8) (115–206)	163.3 (22.1) (130–201)	17.7 (–1.0 to 36.3)	$P = .062$ , $\eta_p^2 = .138$ (.000 to .338)	142.2 (20.6) (104–181)	138.9 (18.6) (111–169)	3.2 (–12.8 to 19.3)	$P = .681$ , $\eta_p^2 = .007$ (.000 to .131)
Normalized, %	168.2 (16.5) (122–200)	182.1 (18.1) (141–219)	14.0 (0.5 to 27.5)	$P = .042^*$ , $\eta_p^2 = .161$ (.003 to .363)	157.6 (4.8) (150–171)	160.3 (6.3) (143–172)	2.7 (–1.2 to 6.6)	$P = .171$ , $\eta_p^2 = .076$ (.000 to .267)

Abbreviation: MD, mean difference. Note: Negative values indicate larger right value. Effect size: small (.01), medium (.06), and large (.14).<sup>35</sup> Data are mean (SD), range (minimum–maximum), and mean difference with 95% confidence interval (lower to upper).

\*Statistical significance ( $P \leq .05$ ).

of 150% leg length during the maximal trial but did during the normalized trial. Also, 1 participant for the dominant leg and the nondominant leg did not achieve a cut distance of 150% leg length during the normalized trial but did during the maximal trial. These observations suggest that for both legs, all participants were able to achieve the 150% leg length target during either or both conditions.

## Discussion

There is currently a lack of standardization of the CUT task. Given the incidence of ACL injury in young athletes,<sup>2</sup> it is important to understand the differences that exist for these tasks when used to explore potential injury risk factors linked to single-leg landings. Our aim was to compare the distances leaped during a CUT task under maximal and normalized conditions (set to 150% leg length) in young court and field sport athletes and to determine the effect of leg dominance and order of tests on outcomes. In agreement with our hypotheses, the distance leapt was significantly further with the maximal condition compared with the normalized condition (MD: 13.9 cm or 16.1% of leg length); however, contrary to our hypothesis, no significant differences were observed between dominant and nondominant legs. The significantly large differences in effect size observed between the normalized and maximal conditions values emphasizes that, although both conditions have their benefits and limitations, the condition selected for assessment warrants consideration as they are fundamentally different.

Additionally, when examining the significant interaction effect between condition and order ( $P = .024$ ), it was observed that if participants completed the normalized condition first, they then leaped significantly further during the respective maximal condition compared with those who completed the maximal condition first ( $P < .001$ ). As the normative value was set, it was not influenced by the maximal condition being performed first. These results highlight the potential variation in perceptions of effort in this population of young athletes as they were able to achieve a further distance once they had jumped to the set distance previously. It is possible that the participants were able to hop further when performing the maximal condition second as they would have practiced the task more times, albeit submaximally, by performing the normalized condition first. In a clinical or research setting, employing a normalized trial prior to a maximal effort trial could lead to a "truer" result for the maximal effort trial. Furthermore, no significant differences were observed between variances of the order of condition, which suggests similarities in this outcome between participants ( $P = .755$  and  $P = .694$ ) for raw and normalized, respectively. Perception of maximal effort and consistency in motor control during the maximal effort trials may be more varied in younger populations. As demonstrated by Lamb et al,<sup>21</sup> some participants can believe that they are performing maximally but, once given a target, may achieve further distances. The maximal condition may be better suited when observing pre- and posttest performance differences within a given individual or when the group has similar physical abilities, perceptions of effort, and anthropometric characteristics. The normalized method may be better when seeking to compare groups with a wider range of abilities, varied perceptions of effort, and differences in anthropometric characteristics. Furthermore, selecting the normalized task may be better if the task goal is completion oriented rather than performance oriented.

The range of individual ability for the maximal condition and how different the distance was from the standardized condition are also noteworthy. Landing distance was more variable under the maximal condition, as demonstrated by the large standard

deviations and significant differences in variance between the maximal and normalized conditions ( $P = .048$  for raw and  $P < .001$  for normalized). These results demonstrate that there were variations in ability and/or effort applied between participants, which should be considered in task selection and result interpretation. It is possible that the presence of a floor tape marker in the normalized condition served as a visual target, which introduces a potential confounding factor when comparing the normalized condition to the maximal condition. A visual target may reduce movement variability by providing participants with an external reference point, which may influence motor planning and execution.<sup>36</sup> In contrast, the lack of a target in the maximal effort condition could inherently allow for more variability. This discrepancy could have contributed to observed differences in movement consistency between conditions. Researchers have suggested that children often adopt different movement patterns from trial-to-trial, possibly in attempt to learn how their bodies produce more force and therefore achieve a better performance outcome but, nonetheless, altering their biomechanics each time.<sup>37</sup> Raffalt et al<sup>37</sup> found higher intrasubject variability in the movement patterns of children compared with adults when assessing reaction force components and angular biomechanics during maximal effort jumping tasks. Previous research has suggested greater variability in jump length in a prepeak height velocity group during a broad jump task<sup>38</sup> and greater jump height variability during a vertical jump task in younger participants, which diminishes with maturation and growth.<sup>39-41</sup> Selection of the normalized condition in our target population of young field and court sport athletes may encourage more consistency in performance and movement patterns leading to a more natural demonstration of how the participant would typically perform the task in a sporting situation. However, the variation in physical ability that exists in youth populations and that is demonstrated by the variance under the maximal condition may influence the level of challenge provided by the normalized test condition.

All participants except for 2 leaped to the 150% of leg length distance during the maximal trials, which seems like an appropriate distance based on the lower end of the maximal distance values (122% nondominant and 138% dominant, Table 2). When set to 150%, all participants were close to the set target (lower end 147% nondominant and 143% dominant). Research has previously suggested that normalizing tasks can be considered good practice in research as it allows standardization in an individualized sense.<sup>42</sup> Practically, setting the same absolute distance or requiring a maximal landing distance may be unsuitable for comparing individuals of different heights, ages, maturation, sexes, and abilities. In a heterogeneous sample, using a CUT task normalized to leg length allows greater standardization and facilitates valid comparisons between individuals. Whether 150% of leg length is the most appropriate has not been established, but it appears reasonable and achievable based on our data set. Setting the distance to 175% might be more reflective of a maximal effort, but it is unlikely that all participants could reach this threshold based on the performance of participants in the current study.

The CUT task has not been used extensively in previous research to explore movement performances based on maturation phases<sup>16</sup>; hence, further research is required as there are no tools unequivocally agreed to be linked with ACL injury incidence. It has been suggested that a larger lateral step distance in a cutting task increases hip and knee extension and ankle plantar flexion torques.<sup>43</sup> Additionally, Havens and Sigward<sup>44</sup> noted greater knee abduction moments during cutting with wider lateral foot plants.

(Ahead of Print)

Therefore, the distance of the cutting task could be an important factor to consider in rendering a task more sensitive and specific for assessing risk of ACL injury. A normalized method for setting distance during a CUT is yet to be explored; however, previous research has used maximal effort methods. Hass et al<sup>22</sup> used a maximal effort CUT task alongside a landing task and a vertical jump task for assessing lower extremity injury risk in prepubertal and postpubertal females. Their study found significant interactions between maturation phase and landing sequence for postpubertal compared with prepubertal participants who demonstrated biomechanics linked with ACL injury incidence. The researchers suggested these results to be a consequence of differences in motor and neuromuscular control strategies (such as reflex and voluntary muscle activation) at different maturational phases, and they emphasized the need to study multiple landing strategies. It is logical to assume that instructing participants to perform a task using a maximal effort would create a relatively consistent challenge level between participants; however, differences in effort perception and neuromuscular ability may influence their ability to produce a maximal or close to maximal effort repeatedly. It is also currently unknown whether performing the maximal version of this or any jump-landing task is injury-risk specific. It is possible that a threshold exists where a normalized distance is challenging enough to elicit biomechanical patterns similar to a maximal effort, but determining this threshold would require further biomechanical research. Typically, athletes are not required to leap laterally as far as possible in a sporting situation as they are usually only required to leap far enough to evade a player or to make a play, indicating that a normalized distance may suffice for assessment of movement competency in the context of ACL injury risk.

Our study is not without limitations. Although the order of tests (normalized or maximal) was randomized, an order effect was observed. Therefore, it is possible that the participants gave different levels of effort across the trials but not necessarily produced a true maximal effort owing to factors, such as fatigue, familiarization, perception of effort, or attention. Perceived difficulty was not collected in this study, limiting our ability to quantify the participants' perceptions of the task demands. Furthermore, the CUT task was anticipated (ie, participants knew which leg to land on and perform the task with), limiting generalization to unanticipated tasks that are more reflective of ACL injury mechanisms.<sup>45</sup> It has been suggested that individuals use different strategies to execute planned versus unplanned movements, specifically, greater implications of overuse injuries are apparent in planned compared with unplanned movements. Future research should examine whether biomechanics are affected based on whether the task is set or involves a reactive component, as well as how biomechanics change with increase in leaping distance. A further limitation is the sample size ( $n=26$ ), which represented a cross-section of the maturation stages for both sexes. With a larger sample size than 26 participants based on detecting differences between CUT tasks, it would have been possible to further explore additional factors, such as the effect of maturation on outcomes or between sex differences. Furthermore, the mean hop distance of the normalized condition was 159% of leg length, exceeding the 150% target. There are several potential underlying factors to this overshooting: the landing distance was too easy, participants had difficulty seeing the target in their peripheral vision while facing forward, the Hawthorne effect<sup>46</sup> and the testing environment incited participants to perform better than the requirement, or the decision to measure the distance based on a marker placed on the toes rather than the midfoot or heel. It is generally common in sports and jump tests involving horizontal

components for individuals to be instructed to "reach" a set landing distance,<sup>47</sup> inferring they must get to or exceed the set target. Reinforcing the importance of landing on the target or redoing trials, which were too far off the target, would likely bring the mean value closer to the target.

Further research is required to determine if 150% leg length is the most appropriate distance for normalization or if perhaps closer to our mean maximal values of 175% would be more suitable and achievable. Furthermore, it would be beneficial to determine if an ideal percentage of leg length exists for the normalized CUT, which best represents that of a high ACL injury risk sporting situation particularly in different maturational groups or in groups with different abilities. Assessing what the average cutting distance is across the course of a game, considering fatigue within different sports, and quantifying this in relation to percentage of leg length may inform the development of screening tools, which are more specific to the demands of the sport.

To conclude, on average, participants leaped significantly further during the CUT task when requiring a maximal effort compared with when normalizing the distance to 150% of leg length, suggesting significantly different performance demands of the conditions. However, a more variable landing distance was observed during the maximal condition, as indicated by larger standard deviations and significant variance in absolute deviations. We recommend that normalizing leaping distance to leg length allows for standardization of the CUT task and facilitates comparisons between individuals deriving from a heterogeneous sample. However, the normalized condition may not elicit a maximal response or sufficiently represent an injury-risk specific situation. Hence, selection of a protocol specific to the study goals is important. A normalized distance based on a percentage of leg length may be better suited when examining individuals presenting with a wide range of heights, maturation stages, sexes, or physical abilities; yet, a maximal distance may be more suitable for a more homogeneous sample or pre-post study designs. Future research should investigate whether lower extremity kinematics and kinetics differ between normalized and maximized CUT tasks and explore the specificity of these maneuvers to biomechanics related to ACL injury risk.

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## Appendix C SESNZ conference presentation for systematic review.

### Biomechanical risk factors associated with anterior cruciate ligament injury and the link to pubertal maturation: A systematic review

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**Introduction.** Anterior cruciate ligament (ACL) injury incidence rate increases following pubertal onset. Research has shown that females have a greater incidence and younger average age of non-contact ACL injury compared to males, peaking between ages 15 to 19. Sex-specific changes have been suggested in lower-extremity mechanics and postural control between maturational groups during landing or cutting tasks. This study aimed to systematically review the literature addressing sex-specific maturation phase as a potentially associated factor for changes in biomechanics associated with ACL injury. **Methods.** Five databases (CINHAL®, Cochrane Library, PubMed®, Scopus®, and SPORTDiscus) were searched. Studies including one or more biomechanical variables linked with ACL injury and exploring participants across two or more maturation phases were considered eligible. Risk of bias and study quality were assessed using a modified version of the Newcastle Ottawa Scale (NOS) and Grading of Recommendations Assessment, Development and Evaluation (GRADE). **Results.** Seventeen included studies examined 312 males (15.6%), 1374 females (68.7%), and 315 individuals of undefined sex (15.7%). Maturation phases included pre-pubertal, early-pubertal, mid-pubertal, late-pubertal, post-pubertal, and young adult. The NOS rankings of methodological quality was considered good for most studies ( $n = 15$ , 88%), and satisfactory for two (12%). Studies most commonly examined knee abduction angle, knee abduction moment, knee flexion, and ground reaction forces and were classified as having a low or medium overall quality of evidence according to the GRADE. Knee abduction angles and moments, and knee flexion angles were generally greater in late and post-pubertal females compared to pre-pubertal females and males across all maturation groups during both landing and cutting tasks. Normalised ground reaction forces were generally greater in less mature participants. **Conclusions.** Late and post-pubertal females demonstrate biomechanics associated with increased ACL injury risk during landing and cutting tasks. Specifically, in response to maturational development, females demonstrated increased knee abduction angles and moments, and decreased knee flexion angles and ranges of motion. Considering sex and maturation is required for selecting appropriate tasks in injury risk identification processes and exercises for ACL injury prevention strategy development.

**Conflict of Interest.** The authors declare no conflict of interest in relation to this work.

## Appendix D SESNZ conference presentation for pilot study.

### Maximise or normalise? Examining drop-land-cut distances in youth athletes

Butcher, A.J.<sup>1,2</sup>, Ward, S., Clissold, T.<sup>3</sup>, Richards, J.<sup>1</sup>, Hébert-Losier, K.<sup>1</sup>

<sup>1</sup>University of Waikato, Hamilton, New Zealand

<sup>2</sup>University of Cumbria, Carlisle, England

<sup>3</sup>Toi Ohomai Institute of Technology, Tauranga, New Zealand

**Introduction.** Court and field sports require frequent single-leg landings and changes of direction, movements associated with non-contact anterior cruciate ligament (ACL) injury. ACL injury risk screening should be sport-specific, reflective of potentially injurious situations, and implementable in clinical settings. This study compared drop-land-cut distances under maximal and normalised conditions in youth athletes, accounting for test order and limb-dominance. **Methods.** Twenty-six court or field sport adolescent athletes ( $13.52 \pm 4.11$  years, 16 females), performed a 30 cm drop landing onto one foot before immediately leaping  $90^\circ$  laterally to land on their contralateral foot. Three drop-land-cuts were performed leaping to a normalised (150% of leg length) distance and three to a maximal-effort distance on both the dominant and non-dominant limbs, the order of which was randomised. Distance data were recorded using 2D video. Repeated measures ANOVA with pairwise t-test comparisons and effect sizes [95% confidence interval] were used to compare leaping distances between conditions, sides, and order of tests. **Results.** Participants leapt significantly further during the maximal effort ( $172.1 \pm 21.2$  cm) than normalised ( $156.2 \pm 10.5$  cm) condition ( $p < 0.001$ , 9.02%,  $15.8 \pm 15.9$  cm). The difference was *large* (Hedge's *g* effect size 1.16 [0.73, 1.62]). No significant differences in leaping distance were found between limbs or based on order of testing. **Conclusions.** Athletes leapt significantly further during the drop-land-cut task when requiring a maximal effort than when normalising the distance to 150% of leg length. However, landing distance was more variable under the maximal condition, as indicates the larger standard deviations. Normalising leaping distance to leg length allows standardisation of the drop-land-cut task and facilitates comparisons between individuals, but it may not elicit a maximal response or sufficiently represent an injury-risk specific situation. Studies should select a protocol specific to the study goals. Future research should investigate whether lower-extremity kinematics and kinetics differ between tasks and the specificity of these manoeuvres to the biomechanics related to ACL injury risk.

**Conflict of Interest.** The authors declare no conflict of interest in relation to this work.

## Appendix E ANZSB conference presentation on systematic review.



### BIOMECHANICAL RISK FACTORS ASSOCIATED WITH ANTERIOR CRUCIATE LIGAMENT INJURY AND THE LINK TO PUBERTAL MATURATION: A SYSTEMATIC REVIEW

<sup>1</sup>Anna Butcher, <sup>2</sup>Sarah Ward, <sup>3</sup>Tracey Clissold, <sup>4</sup>Jim Richards, and <sup>1</sup>Kim Hebert-Losier

<sup>1</sup>Division of Health, Engineering, Computing and Science, *Te Huataki Waiora* School of Health, University of Waikato, Adams Centre for High Performance, Tauranga, NZ

<sup>2</sup>Department of Exercise Sciences, University of Auckland, Auckland, NZ

<sup>3</sup>Faculty of Health, Education and Environment, Toi Ohomai Institute of Technology, Windermere Campus, Tauranga, NZ

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email: [anna.butcher@waikato.ac.nz](mailto:anna.butcher@waikato.ac.nz)

#### INTRODUCTION

Anterior cruciate ligament (ACL) injury incidence rate exponentially increases following pubertal onset<sup>1</sup>. Research has shown that females have a greater incidence and younger average age of non-contact ACL injury compared to males, peaking between ages 15 to 19<sup>2</sup>. Changes with maturation in lower-extremity mechanics and postural control during landing tasks have been suggested as a contributing factor to increased ACL injury risk, particularly in females<sup>3</sup>. Consideration of sex and task differences are required to better understand biomechanical differences associated with ACL injury risk across maturational phases. This study aimed to systematically review the literature to determine whether changes in biomechanics associated with ACL injury occur between different maturation phases and different sexes.

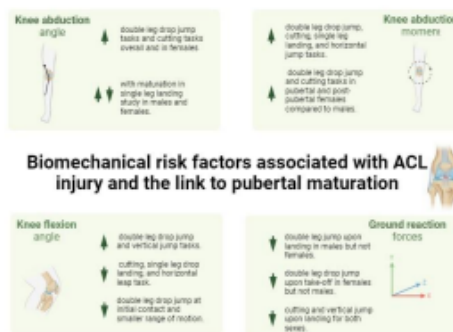
#### METHODS

Five databases (CINHAL®, Cochrane Library, PubMed®, Scopus®, and SPORTDiscus) were searched. Studies including one or more biomechanical variables linked with ACL injury and exploring participants across two or more maturation phases were considered eligible. Risk of bias and study quality were assessed using a modified version of the Newcastle Ottawa Scale (NOS) and Grading of Recommendations Assessment, Development and Evaluation (GRADE).

#### RESULTS AND DISCUSSION

The 18 included studies examined 400 males (19.1%), 1377 females (65.8%), and 315 individuals of undefined sex (15.1%). Maturation phases included pre-pubertal, early-pubertal, mid-pubertal, late-pubertal, post-pubertal, and young adult. The NOS rankings of methodological quality was considered good for most studies ( $n = 16$ , 89%), and satisfactory for two (11%). Nine of the 18 studies used a drop vertical jump task (50%), four used a cutting task (22.2%), two used a single-leg drop landing task (11.1%), one used a drop and cut task (5.5%) and one used a horizontal jump task (5.5%). Studies most often examined knee abduction angle, knee abduction moment, knee flexion, and ground reaction forces and were classified as having a low or medium overall quality of evidence according to the GRADE. Knee abduction angles and moments, and knee flexion angles were generally greater in late and post-pubertal

females compared to pre-pubertal females and males across all maturation groups during both landing and cutting tasks. Normalised ground reaction forces were generally greater in less mature participants.



**Figure 1:** Summary of the observed links between maturation and changes in biomechanics associated with ACL injury as reported in the literature. Note: Arrow indicates and increase or decrease with maturation.

#### CONCLUSIONS

Late and post-pubertal females demonstrate biomechanics associated with increased ACL injury risk during landing and cutting tasks. Specifically, in response to maturational development, females demonstrated increased knee abduction angles and moments, and decreased knee flexion angles and ranges of motion. Our findings highlight sex and maturation need consideration when selecting tasks in injury risk identification processes and exercises for ACL injury prevention strategy development.



#### REFERENCES

1. Renstrom P, et al. *BJSM*. **42(6)**:394-412, 2008.
2. Maniar N, et al. *The Lancet Regional Health—Western Pacific*. **21**, 2022.
3. Ramachandran AK, et al. *Sports Med*. **1-26**, 2024.


**Appendix F** Tauranga public lecture series presentation.





 **University of Waikato - Tauranga** ...  
23 October 2023 · 🌐


 **EVENT ALERT-** Tauranga Public Lecture Series  


Join Dr Kim Hébert-Losier and three of her PhD candidates from The University of Waikato Adams Centre for High Performance Sport for 'Research Cafe', where they will present talks on their latest research.

 Dr Kim Hébert-Losier - How strong are your calves? There's an app for that!

 Anna Butcher - ACL injuries in growing athletes: The link between maturation and biomechanics

 Amy Pearce - How 'hip' are you? Joint replacement outcomes in the Bay of Plenty

 Andrew Fife - To buy or not to buy: The running shoe store dilemma.

## Appendix G Supplementary information for systematic review.

### Supplementary file 1

#### Systematic review search terms

Scopus:

TITLE-ABS-KEY ( ( acl OR "anterior cruciate ligament" ) AND ( matur\* OR pubert\* ) AND ( biomechanic\* OR kinematic\* OR kinetic\* ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) OR LIMIT-TO ( DOCTYPE , "cp" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) )  
Document results= 258

Pubmed:

(ACL or "anterior cruciate ligament") AND (matur\* OR pubert\*) AND (biomechanic\* or kinematic\* or kinetic\*) Filters applied: English

Document results= 208

SportDISCUS:

[https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,sso&db=sph&bquery=\(ACL+or+%26quot%3banterior+cruciate+ligament%26quot%3b\)+AND+\(matur\\*+OR+pubert\\*\)+AND+\(biomechanic\\*+or+kinematic\\*+or+kinetic\\*\)&authtype=sso&custid=s4804380&type=0&searchMode=Standard&site=ehost-live&custid=s4804380](https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,sso&db=sph&bquery=(ACL+or+%26quot%3banterior+cruciate+ligament%26quot%3b)+AND+(matur*+OR+pubert*)+AND+(biomechanic*+or+kinematic*+or+kinetic*)&authtype=sso&custid=s4804380&type=0&searchMode=Standard&site=ehost-live&custid=s4804380)

Document results= 92

Cochrane:

(ACL or "anterior cruciate ligament") AND (matur\* OR pubert\*) AND (biomechanic\* or kinematic\* or kinetic\*) in Title Abstract Keyword

Document results= 13

CINHAL:

[https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,sso&db=ccm&bquery=\(ACL+or+%26quot%3banterior+cruciate+ligament%26quot%3b\)+AND+\(matur\\*+OR+pubert\\*\)+AND+\(biomechanic\\*+or+kinematic\\*+or+kinetic\\*\)&authtype=sso&custid=s4804380&type=0&searchMode=Standard&site=ehost-live&custid=s4804380](https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,sso&db=ccm&bquery=(ACL+or+%26quot%3banterior+cruciate+ligament%26quot%3b)+AND+(matur*+OR+pubert*)+AND+(biomechanic*+or+kinematic*+or+kinetic*)&authtype=sso&custid=s4804380&type=0&searchMode=Standard&site=ehost-live&custid=s4804380)

Document results= 102

## Supplementary file 2

*Author (year). Title*

### NEWCASTLE - OTTAWA QUALITY ASSESSMENT SCALE (adapted for cross sectional studies)

Selection: (Maximum 5 stars)

1) Representativeness of the sample:

- a) Truly representative of the average in the target population. \* (All subjects or random sampling)
- b) Somewhat representative of the average in the target population. \* (Non-random sampling)
- c) Selected group of users.
- d) No description of the sampling strategy.

2) Sample size:

- a) Justified and satisfactory. (Calculated statistical power is stated)\*
- b) Not justified.

3) Non-respondents (Participants excluded from/ did not complete the study):

- a) Comparability between respondents and non-respondents characteristics is established, and the response rate is satisfactory. \*
- b) The response rate is unsatisfactory, or the comparability between respondents and non-respondents is unsatisfactory.
- c) No description of the response rate or the characteristics of the responders and the non-responders.

4) Ascertainment of the exposure. (Maturational status determination):

- a) Validated measurement tool. \*\*
- b) Non-validated measurement tool, but the tool is available or described.\*
- c) No description of the measurement tool.

Comparability: (Maximum 2 stars)

1) The subjects in different outcome groups are comparable, based on the study design or analysis. Confounding factors are controlled.

- a) The study controls for the most important factor (Participant sex) \*
- b) The study controls for any additional factor. (Sport specificity, sporting history, footwear, standardised warm up, technique instructions given, task standardization) \*

Outcome: (Maximum 3 stars)

1) Assessment of the outcome:

a) Independent blind assessment. \*\*

b) Record linkage. \*\*

c) Self report. \*

d) No description.

2) Statistical test:

a) The statistical test used to analyse the data is clearly described and appropriate, and the measurement of the association is presented, including confidence intervals and the probability level. (Includes p values, confidence intervals, standard deviations, smallest worthwhile changes, and numerical values)\*

b) The statistical test is not appropriate, not described or incomplete.

Selection:

Comparability:

Outcome:

Total:



## PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
<b>TITLE</b>			
Title	1	Identify the report as a systematic review.	p.1 l.1
<b>ABSTRACT</b>			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	p.1 l.5
<b>INTRODUCTION</b>			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	p.4 l.12
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	p.4 l.15
<b>METHODS</b>			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	p.5 l.8
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	p.5 l.1
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	p.5 l.3
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	p.5 l.10
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	p.6 l.11 p.7 l.13
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	p.7 l.16
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	p.7 l.16
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	p.6 l.19
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	p.7 l.21
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	p.8 l.1
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	p.8 l.3
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	p.8 l.22
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	p.8 l.1
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	NA
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	NA
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	NA
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	p.7 l.6



## PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
<b>RESULTS</b>			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	p.9 I.2
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	p.9 I.10
Study characteristics	17	Cite each included study and present its characteristics.	p.10-44
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	p.45 I.1
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	p.10-44
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	p.45 I.1
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	NA
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	NA
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	NA
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	NA
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	p.46 I.1
<b>DISCUSSION</b>			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	p.57 & 58
	23b	Discuss any limitations of the evidence included in the review.	p.59 I.17
	23c	Discuss any limitations of the review processes used.	p.60 I.24
	23d	Discuss implications of the results for practice, policy, and future research.	p.61 I.21
<b>OTHER INFORMATION</b>			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	p.4 I.20
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	p.4 I.21
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	p.4 I.21
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	NA
Competing interests	26	Declare any competing interests of review authors.	NA
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	NA



## PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
<b>RESULTS</b>			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	p.9 I.2
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	p.9 I.10
Study characteristics	17	Cite each included study and present its characteristics.	p.10-44
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	p.45 I.1
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	p.10-44
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	p.45 I.1
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	NA
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	NA
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	NA
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	NA
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	p.46 I.1
<b>DISCUSSION</b>			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	p.57 & 58
	23b	Discuss any limitations of the evidence included in the review.	p.59 I.17
	23c	Discuss any limitations of the review processes used.	p.60 I.24
	23d	Discuss implications of the results for practice, policy, and future research.	p.61 I.21
<b>OTHER INFORMATION</b>			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	p.4 I.20
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	p.4 I.21
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	p.4 I.21
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	NA
Competing interests	26	Declare any competing interests of review authors.	NA
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	NA

## Appendix H Ethical approval letter for experimental portion of the research.

The University of Waikato  
Private Bag 3105  
Gate 1, Knighton Road  
Hamilton, New Zealand

Human Research Ethics Committee  
Roger Moltzen  
Telephone: +64021658119  
Email: [humanethics@waikato.ac.nz](mailto:humanethics@waikato.ac.nz)



THE UNIVERSITY OF  
**WAIKATO**  
*Te Whare Wānanga o Waikato*

2 December 2022

Anna Butcher  
Te Huataki Waiora – School of Health  
DHECS  
By email: [ab661@students.waikato.ac.nz](mailto:ab661@students.waikato.ac.nz)

Dear Anna

**HREC(Health)2022#53 : Effects of maturation on biomechanics associated with ACL injury**

Thank you for your responses to the Committee feedback.

We are now pleased to provide formal approval for your project.

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

We wish you all the best with your research.

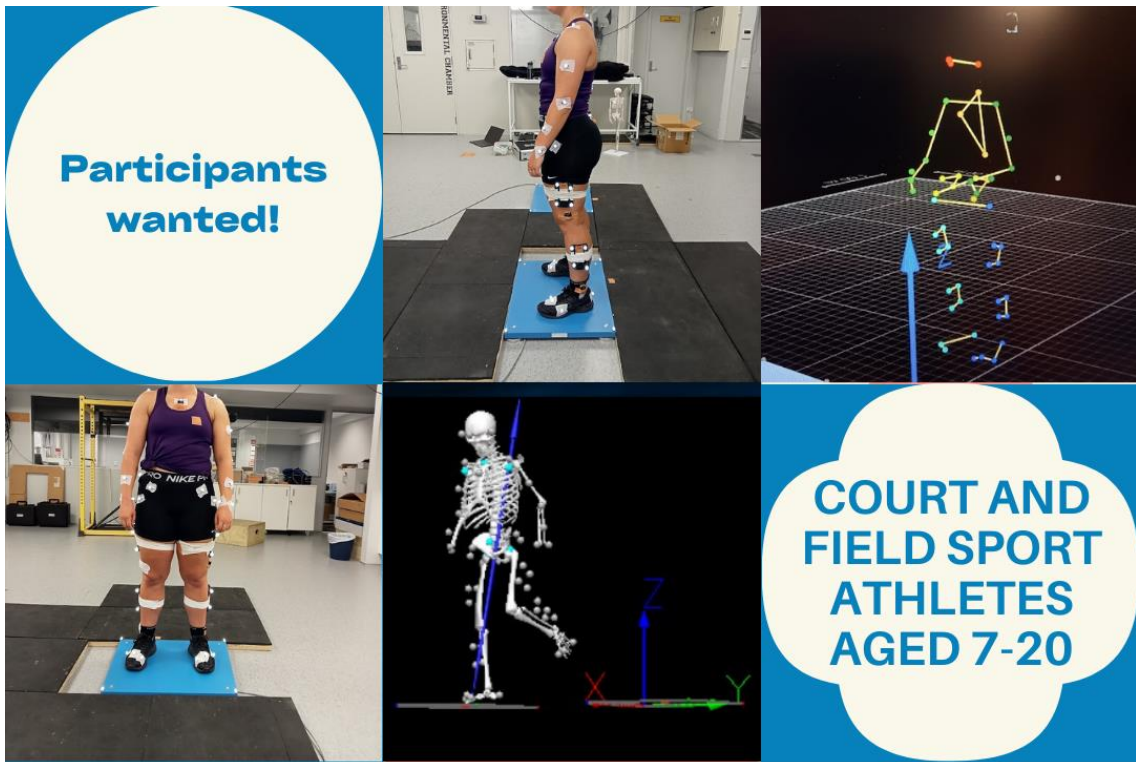
Regards,

A handwritten signature in black ink, appearing to be 'RM'.

---

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

Appendix I Recruitment poster for experimental study.



## Biomechanical research on ACL injury prevention



The University of Waikato are conducting a study on ACL injury risk and prevention using 3D cameras, force plates and more at the Adams centre for high performance sport.

For more information, please contact Anna at [annajbutcher@gmail.com](mailto:annajbutcher@gmail.com) or on 027 305 2434



## Appendix J Information sheet given to participants






# Information Sheet for Participants

**Title** – Effects of maturation and sex on biomechanics pertaining to ACL injury

**Aim** – Investigate the differences in biomechanical and neuromuscular measures pertaining to ACL injury within groups of different defined maturational phases and sex.

**Background** – Anterior cruciate ligament (ACL) injuries are common amongst young athletes and are observed most often between 15-25 years old. Previous research has suggested differences in movement techniques between males and females from 12 years old and further changes throughout maturation. Risk of potential ACL injury can be assessed using tasks involving landing and jumping in different directions and balancing. We want to better understand the movement changes that occur in males and females of different maturational phases and to determine when and how increased risk of ACL injury may be apparent. This information is important for development of effective ACL injury prevention programmes, techniques, or devices.

**Overview** – Should you agree to participate, you will be asked to sign an informed consent form, complete a baseline questionnaire, a menstrual cycle questionnaire (females only) and a maturational phase questionnaire. You will be required to attend a minimum of one and a maximum of two sessions (should you wish to participate in the reliability portion of the study) at the Adams Centre for High Performance Sport. You will be asked to perform four tasks involving dropping from a 30 cm box; 1) onto one foot 2) onto one foot and then hopping as high as you can 3) onto one foot and then hopping sideways onto your other foot 4) turning 90° in the air before landing and then hopping as high as you can. Following this, you will be asked to perform a single leg squat task to test balance, a go/no-go task to test reaction time, and a single leg hop task to test stiffness. Force plates, 3D cameras, 2D cameras, and Inertial measurement units will be used to track your movements and collect data. Each session should last 80 – 90 minutes.

Technology	Description	Picture
Questionnaires	Paper-based or tablet-based recording of participant information, physical activity, maturational phase identification, menstrual cycle related information.	
Cognitive tasks	Paper-based, computer-based, or tablet-based recording of cognitive function	
3D video recordings (Qualisys Track Manager software and cameras)	Monitors 3D biomechanics with use of retro-reflective markers adhered using double-sided tape and topical skin adhesive.	
Force plates (Kistler)	Monitors temporal and kinetic information (i.e., contact time, force applied to ground, shifting of weight during balancing).	
Inertial measurement units (IMU)	Wearable devices that measure acceleration in three planes of motion.	

**What are the potential risks** – The risks associated with participating in this study are no greater than those associated with training or playing in any court or field sport. Although the injury risks are considered minimal, we cannot guarantee your safety. If accidental harm does occur during study participation, the research team will offer immediate first aid and support you in accessing medical attention as required. If

an accidental injury does happen during testing, costs of injury treatment are likely to be covered – at least in part – by Accident Compensation Corporation.

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

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

- Ask any further questions about the study that occurs to you during your participation.
- A summary of findings from the study when it is concluded.
- Have a support person (family, whanau, and/or friend) present during your participation.
- Refuse to answer any particular question, and to withdraw from the study at any time without giving a reason.
- Withdraw any information provided at any point during or up to two weeks after participating in the research activities by contacting the primary investigator.

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

Anna Butcher (**Primary Investigator**)  
The University of Waikato, Adams Centre for High Performance  
52 Miro Street, Mount Maunganui 3116  
[annajbutcher@gmail.com](mailto:annajbutcher@gmail.com)

Kim Hebert-Losier (**Primary Supervisor**)  
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52 Miro Street, Mount Maunganui 3116  
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**Human Research Ethics Committee** – This research project has been approved by the Human Research Ethics Committee (Health) of the University of Waikato under *HREC(Health)#2022-53*.

Any questions about the ethical conduct of this research should be directed to Primary Investigator in a first instance. Any residual concerns may be addressed to the Secretary of the Committee, email [humanethics@waikato.ac.nz](mailto:humanethics@waikato.ac.nz), postal address, University of Waikato, Te Whare Wananga o Waikato, Private Bag 3105, Hamilton 3240.

**Appendix K** Information sheet given to younger participants.


## ***Information Sheet for Participants (Child specific)***





**Title** – Effects of maturation and sex on biomechanics pertaining to ACL injury

**Aim** – Are there differences in movements between different maturational groups and between boys and girls?

**Background** – Anterior cruciate ligament (ACL) knee injuries are common amongst young athletes and often happen between 15-25 years old. The risk of someone getting this injury can be checked using landing, jumping, and balancing tests. We want to better understand the movement changes in boys and girls as they mature to check for when and how risk of injury might be higher. Once we know this, we can develop better injury prevention programmes, techniques, or devices.

**Overview** – If you agree to participate, you will need to sign an informed consent form, complete a baseline questionnaire, a menstrual cycle questionnaire (females only), and a maturational phase questionnaire. You will need to attend a minimum of one and a maximum of two sessions (if you wish to participate in the reliability portion of the study) at the Adams Centre for High Performance Sport. You will be asked to perform four tasks where you will drop from a small 30 cm box; 1) onto one foot 2) onto one foot and then hopping as high as you can 3) onto one foot and then hopping sideways onto your other foot 4) onto one foot after turning 90° in the air. Afterwards, you will do a single leg squat task to test your balance. Force plates and 3D cameras will be used to track your movements and collect data. Each session should last 80 – 90 minutes.

<b>Technology</b>	<b>Description</b>	<b>Picture</b>
Questionnaires	Paper-based or tablet-based recording of participant information, physical activity, maturational phase identification, menstrual cycle related information.	

Cognitive tasks	Paper-based, computer-based, or tablet-based recording of cognitive function	
3D video recordings (Qualisys Track Manager software and cameras)	Monitors 3D biomechanics with use of retro-reflective markers adhered using double-sided tape and topical skin adhesive.	
Force plates (Kistler)	Monitors temporal and kinetic information (i.e., contact time, force applied to ground, shifting of weight during balancing).	
Inertial measurement units (IMU)	Wearable devices that measure acceleration in three planes of motion.	

**What are the potential risks** – The risks associated with participating in this study are no greater than those associated with training or playing in any court or field sport. Although the injury risks are considered minimal, we cannot guarantee your safety. If accidental harm does occur during study participation, the research team will offer immediate first aid and support you in accessing medical attention as required. If an accidental injury does happen during testing, costs of injury treatment are likely to be covered – at least in part – by Accident Compensation Corporation.

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

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

- Ask any questions whenever you like.
- Know what we found out from the study at the end.

- Have a support person (family, whanau, and/or friend) there when you participate.
- Refuse to answer any questions you don't want to and leave the study at any time without giving a reason.
- Take back any information provided at any point during or up to two weeks after your participation by telling the primary investigator.

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

Anna Butcher (**Primary Investigator**)

The University of Waikato, Adams Centre for High Performance  
52 Miro Street, Mount Maunganui 3116

[annajbutcher@gmail.com](mailto:annajbutcher@gmail.com)

Kim Hebert-Losier (**Primary Supervisor**)

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52 Miro Street, Mount Maunganui 3116

[kim.hebert-losier@waikato.ac.nz](mailto:kim.hebert-losier@waikato.ac.nz)

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

Any questions about the ethical conduct of this research should be directed to Primary Investigator in a first instance. Any residual concerns may be addressed to the Secretary of the Committee, email [humanethics@waikato.ac.nz](mailto:humanethics@waikato.ac.nz), postal address, University of Waikato, Te Whare Wananga o Waikato, Private Bag 3105, Hamilton 3240.

## Consent Form for Participants

**Title** – Effects of maturation on biomechanics pertaining to ACL injury

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

I understand that any data, information, or answers will remain confidential in regard to my identity through a coding system. The data will be made publishable, so every effort will be made to ensure confidentiality and anonymity, however, anonymity cannot be guaranteed.

I understand that any video or images taken during the testing sessions may allow me to be identified. I can choose to consent to the use of videos and images in their original form for the use of publications, presentations, reports, marketing/promotion, or educational material. I understand that if I do not provide consent, videos and images may be used in an altered form, where the face will be concealed to de-identify the media if used in publications, presentations, reports, marketing/promotion, or educational material.

***I also understand that:***

- *I am free to withdraw from the study at any time or to decline to answer any particular questions.*
- *I can withdraw any information I have provided up to two weeks after participating in the research activities by contacting the primary investigator.*
- *Any data or answers will remain confidential in regards to my identity through a coding system.*
- *The data might be published, so every effort will be made to ensure confidentiality.*

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

Consent to Participate

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

	Participant:	Proxy (if participant < 16 y):	Researcher:
Signature:	_____	_____	_____
Name:	_____	_____	_____
Date:	_____	_____	_____

Additional Consent (Optional)

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

	Participant:	Proxy (if participant < 16 y):	Researcher:
Signature:	_____	_____	_____

Name:

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Date:

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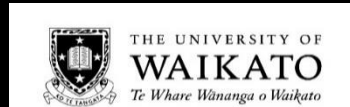
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Appendix M Participant data collection sheets.

**Participant Data Collection Sheet**



Title – Effects of maturation on biomechanics pertaining to ACL injury

TEST DAY, TIME, LOCATION		ID NUMBER	
GENERAL			
NAME			
DATE OF BIRTH (dd /mm/yyyy)			
BIOLOGICAL SEX AT BIRTH (please tick)		<input type="checkbox"/> MALE <input type="checkbox"/> FEMALE	
HEIGHT (cm)		MASS (kg)	
SEATED HEIGHT (cm)		PARENTS HEIGHT (cm)	Mother Father
ETHNICITY			
WHICH LEG WOULD YOU KICK A BALL WITH?			
E-MAIL (for post-study information)			
ARE YOU IN GOOD GENERAL HEALTH?		<input type="checkbox"/> YES <input type="checkbox"/> NO	
DO YOU HAVE ANY CURRENT OR RECENT (less than 3 months) INJURIES?		<input type="checkbox"/> YES <input type="checkbox"/> NO	
If yes, please provide detail			

**Appendix N** Participant physical activity questionnaire.

<b>ID NUMBER</b>	
------------------	--

We are trying to find out about your level of **physical activity**

Remember:

- ✓ There are no right and wrong answers — this is not a test.
- ✓ Please answer all the questions as honestly and accurately as you can — this is very important.
- ✓ Answer all 8 questions.

**QUESTION 1.**

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

- Hardly any physical activity (reading, watching TV, using the computer)
- Mostly sitting, sometimes walk, easy tasks/play
- Light physical activity for about 2 – 4 hours a week, like fishing, talking, dancing
- Moderate exercise 1 – 2 hours a week, like jogging, swimming, gymnastics
- Moderate exercise at least 3 hours a week, like jogging, swimming, gymnastics
- Hard or very hard exercise regularly and several times a week, during which the physical exercise is great, like jogging, rugby, football.

**QUESTION 2.**

During the past **12 months** (year), on how many sports teams did you play? Tick **one** answer only.

*Count any teams run by your school or community groups.*

0 teams

1 team

2 teams

3 teams or more

### **QUESTION 3.**

During the past **7 days**, on how many days were you physically active for a total of **at least 60 minutes per day**? Tick **one** answer only.

*Add up all the time you spent in any kind of physical activity that increased your heart rate and made you breathe hard some of the time.*

0 days

1 day

2 days

3 days

4 days

5 days

6 days

—

7 days

**QUESTION 4.**

During the past **7 days**, on how many days did you do exercises **to strengthen or tone your muscles**, such as push-ups, sit-ups, or weightlifting? Tick **one** answer only.

0 days

1 day

2 days

3 days

4 days

5 days

6 days

7 days

**QUESTION 5.**

On an average **week day**, how many hours do you watch TV? Tick **one** answer only.

I do not watch TV on an average school day

Less than 1 hour per day

1 hour

—

2 hours

3 hours

4 hours

5 hours

More than 5 hours per day

**QUESTION 6.**

On an average **week** day, how many hours do you play video or computer games or use a computer for something that is not school/ work related? Tick **one** answer only.

*Count time spent playing games, watching videos, texting, or using social media on your smartphone, computer, Xbox, PlayStation, iPad, or other tablet.*

I do not play video or computer games or use a computer for something that is not school/ work

Less than 1 hour per day

1 hour

2 hours

3 hours

4 hours

—

5 hours

More than 5 hours per day

### QUESTION 7.

If you go to school, in an average school week, on how many days do you go to physical education (PE) classes?

0 days

1 day

2 days

3 days

4 days

5 days

### QUESTION 8

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

- ✓ Vigorous physical activities require hard physical effort and make you breathe much harder than normal
  
- ✓ Moderate activities take moderate physical effort or make you breathe somewhat harder than normal

- ✓ Walking includes at work, at school, and at home, walking from place to place, and any other walking that you have done for recreation, sport, exercise, or leisure/fun
  
- ✓ Sitting includes time spent sitting at work, at school and at home, while doing some course work and leisure/play time. This may include time spend sitting at a desk, visiting friends, reading, or sitting or lying down to watch TV.

<b>How much time do you usually spend doing this activity?</b>			
<b>Activity</b>	<b>Days per week?</b>	<b>Hours per day?</b>	<b>Minutes per day?</b>
Vigorous			
Moderate			
Walking			
Sitting			



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**Appendix O** The modified pubertal maturation observation scale questionnaire.

**Modified Pubertal Maturation Observational Scale (PMOS)**

<b>ID NUMBER</b>	
------------------	--

Female Characteristic Checklist

- \_\_\_\_\_ The adolescent has grown 3 to 3.5 inches in the past 6 months or is past this growth spurt.
- \_\_\_\_\_ The adolescent has begun breast development.
- \_\_\_\_\_ The adolescent has begun menarche.
- \_\_\_\_\_ The adolescent has evidence of darker underarm hair or shaves.
- \_\_\_\_\_ The adolescent has evidence of darker hair on her legs or shaves.
- \_\_\_\_\_ The adolescent's calves are becoming defined.
- \_\_\_\_\_ The adolescent has evidence of acne.
- \_\_\_\_\_ There was evidence of sweating after physical activities.

Male Characteristic Checklist

- \_\_\_\_\_ The adolescent has evidence of darkening of facial hair or shaves.
- \_\_\_\_\_ The adolescent's voice has gotten deeper or is currently breaking.
- \_\_\_\_\_ The adolescent has grown 3 to 4 inches in the past 6 months or is past the growth spurt.
- \_\_\_\_\_ The adolescent has darker hair on his legs.
- \_\_\_\_\_ The adolescent's biceps are becoming defined.
- \_\_\_\_\_ The adolescent's calves are becoming defined.
- \_\_\_\_\_ The adolescent has evidence of acne.
- \_\_\_\_\_ There was evidence of sweating after physical activities.

\_\_\_\_\_ There is darkened underarm hair.

KEY:

+ characteristic is present

- characteristic is absent

SCORING CRITERIA FOR MALES AND FEMALES

STAGES	NUMBER OF “+”
Prepuberty	1 or less
Mid-pubertal	4 or 5; growth spurt essential
Post-pubertal	at least 6; growth spurt completed

## Appendix P The Tanner stages questionnaire.

Please circle the pubertal stage which most closely represents the participant currently.

Vermont Department of Health  
Health Screening Recommendations for Children & Adolescents

### The Tanner Stages

Because the onset and progression of puberty are so variable, Tanner has proposed a scale, now uniformly accepted, to describe the onset and progression of pubertal changes (Fig. 9-24). Boys and girls are rated on a 5 point scale. Boys are rated for genital development and pubic hair growth, and girls are rated for breast development and pubic hair growth.

Pubic hair growth in females is staged as follows (Fig 9-24, B):

- **Stage I (Preadolescent)** - Vellos hair develops over the pubes in a manner not greater than that over the anterior wall. There is no sexual hair.
- **Stage II** - Sparse, long, pigmented, downy hair, which is straight or only slightly curled, appears. These hairs are seen mainly along the labia. This stage is difficult to quantitate on black and white photographs, particularly when pictures are of fair-haired subjects.
- **Stage III** - Considerably darker, coarser, and curlier sexual hair appears. The hair has now spread sparsely over the junction of the pubes.
- **Stage IV** - The hair distribution is adult in type but decreased in total quantity. There is no spread to the medial surface of the thighs.
- **Stage V** - Hair is adult in quantity and type and appears to have an inverse triangle of the classically feminine type. There is spread to the medial surface of the thighs but not above the base of the inverse triangle.

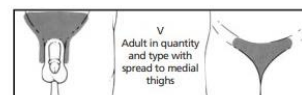
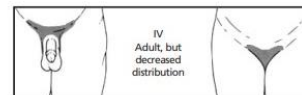
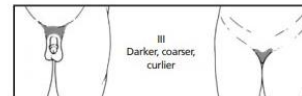
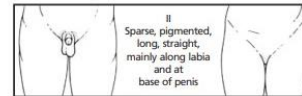
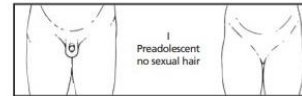


Fig. 9-24, B

The stages in male pubic hair development are as follows (Fig. 9-24, B):

- **Stage I (Preadolescent)** - Vellos hair appears over the pubes with a degree of development similar to that over the abdominal wall. There is no androgen-sensitive pubic hair.
- **Stage II** - There is sparse development of long pigmented downy hair, which is only slightly curled or straight. The hair is seen chiefly at the base of penis. This stage may be difficult to evaluate on a photograph, especially if the subject has fair hair.
- **Stage III** - The pubic hair is considerably darker, coarser, and curlier. The distribution is now spread over the junction of the pubes, and at this point that hair may be recognized easily on black and white photographs.
- **Stage IV** - The hair distribution is now adult in type but still is considerably less than seen in adults. There is no spread to the medial surface of the thighs.
- **Stage V** - Hair distribution is adult in quantity and type and is described in the inverse triangle. There can be spread to the medial surface of the thighs.

VDH 1099

In young women, the Tanner stages for breast development are as follows (Fig. 9-24, C):

- **Stage I (Preadolescent)** - Only the papilla is elevated above the level of the chest wall.
- **Stage II (Breast Budding)** - Elevation of the breasts and papillae may occur as small mounds along with some increased diameter of the areolae.
- **Stage III** - The breasts and areolae continue to enlarge, although they show no separation of contour.
- **Stage IV** - The areolae and papillae elevate above the level of the breasts and form secondary mounds with further development of the overall breast tissue.
- **Stage V** - Mature female breasts have developed. The papillae may extend slightly above the contour of the breasts as the result of the recession of the areolae.

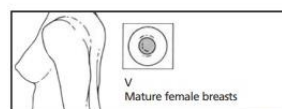
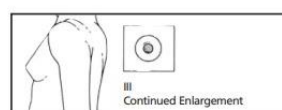
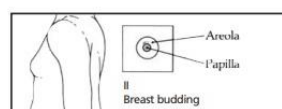
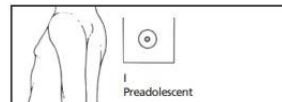


Fig. 9-24, C

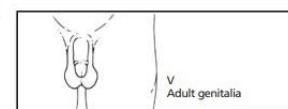
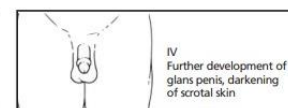
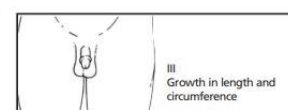
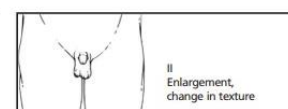
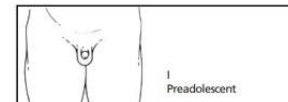


Fig. 9-24, A

The stages for male genitalia development are as follows: (Fig. 9-24, A):

- **Stage I (Preadolescent)** - The testes, scrotal sac, and penis have a size and proportion similar to those seen in early childhood.
- **Stage II** - There is enlargement of the scrotum and testes and a change in the texture of the scrotal skin. The scrotal skin may also be reddened, a finding not obvious when viewed on a black and white photograph.
- **Stage III** - Further growth of the penis has occurred, initially in length, although with some increase in circumference. There also is increased growth of the testes and scrotum.
- **Stage IV** - The penis is significantly enlarged in length and circumference, with further development of the glans penis. The testes and scrotum continue to enlarge, and there is distinct darkening of the scrotal skin. This is difficult to evaluate on a black-and-white photograph.
- **Stage V** - The genitalia are adult with regard to size and shape.

**Appendix Q** Menstrual cycle questionnaire.

**Menstrual cycle questionnaire**

<b>ID NUMBER</b>	
------------------	--

1. Have you begun menstruating? Yes/ No (If the answer is no, you will not need to fill in the remainder of the survey)
2. At what age did you begin menstruation?
3. Do you currently experience menstruation every month?
4. Are you currently using any form of contraceptive? If so, please state which and how long for.
5. Have you used any form of contraception in the past?
6. Do you ever experience unexpected, missed periods or an extended time (>40 days) between periods? Yes/ No
7. If yes, does this happen on a regular basis? If so, please provide details as to how regularly. (If your answer to question 6 was no, skip this question).
8. Have you ever tracked your cycle through the use of an app or diary? Yes/ No
9. Do you have any medical conditions? If so, please specify.
10. Are you currently taking, or have you recently (within the past 6 months) been taking any form of medication? If so, please specify.
11. What was the date of the first day of your most recent period?

**Appendix R** List of LAND metrics and the specific groups which violated the assumption of normality in the two by three-way ANOVA according to the Shapiro-Wilks test.

- Peak knee extension angle (dominant), Female pre-pubertal (Stat = 0.751, df = 9,  $p = 0.006$ ), Male pre-pubertal (Stat = 0.827, df = 14,  $p = 0.011$ )
- Range knee flexion angle (dominant), Male pre-pubertal (Stat = 0.875, df = 14,  $p = 0.050$ )
- Peak knee flexion moment to body mass and height (dominant), Female mid-pubertal (Stat = 0.831, df = 9,  $p = 0.046$ ), Male mid-pubertal (Stat = 0.847, df = 11,  $p = 0.039$ ), Male post-pubertal (Stat = 0.654, df = 11,  $p < 0.001$ )
- Peak knee varus angle (dominant), Male post-pubertal (Stat = 0.817, df = 11,  $p = 0.016$ )
- Range knee valgus angle (dominant), Female pre-pubertal (Stat = 0.778, df = 9,  $p = 0.011$ ), Male post-pubertal (Stat = 0.842, df = 11,  $p = 0.034$ )
- Peak knee varus moment to body mass and height (dominant), Male mid-pubertal (Stat = 0.830, df = 11,  $p = 0.023$ ), Male post-pubertal (Stat = 0.672, df = 11,  $p < 0.001$ )
- Peak knee external rotation moment to body mass and height (dominant), Male post-pubertal (Stat = 0.652, df = 11,  $p < 0.001$ )
- Peak lateral GRF to body mass (dominant), Male pre-pubertal (Stat = 0.872, df = 14,  $p = 0.044$ )
- Peak vGRF to body mass (dominant), Female post-pubertal (Stat = 0.811, df = 10,  $p = 0.020$ )
- Time to PKF (dominant), Male mid-pubertal (Stat = 0.760, df = 11,  $p = 0.003$ ), Female pre-pubertal (Stat = 0.815, df = 9,  $p = 0.030$ )
- Peak knee flexion angle (non-dominant), Female post-pubertal (Stat = 0.842, df = 10,  $p = 0.046$ ), Male pre-pubertal (Stat = 0.843, df = 12,  $p = 0.030$ )
- Peak knee flexion moment to body mass and height (non-dominant), Male mid-pubertal (Stat = 0.826, df = 10,  $p = 0.030$ )
- Range knee valgus angle (non-dominant), Male pre-pubertal (Stat = 0.832, df = 12,  $p = 0.022$ )

- Peak knee valgus moment to body mass and height (non-dominant), Female mid-pubertal (Stat = 0.828, df = 9,  $p = 0.042$ ), Female pre-pubertal (Stat = 0.812, df = 8,  $p = 0.039$ )
- Peak knee varus moment to body mass and height (non-dominant), Male mid-pubertal (Stat = 0.842, df = 10,  $p = 0.046$ )
- Peak knee external rotation moment to body mass and height (non-dominant), Female post-pubertal (Stat = 0.691, df = 10,  $p < 0.001$ )
- Peak breaking GRF to body mass (non-dominant), Male mid-pubertal (Stat = 0.729, df = 10,  $p = 0.002$ )
- Peak medial GRF to body mass (non-dominant), Male mid-pubertal (Stat = 0.819, df = 10,  $p = 0.025$ )
- Time to PKF (non-dominant), Male mid-pubertal (Stat = 0.631, df = 10,  $p < 0.001$ ), Male post-pubertal (Stat = 0.813, df = 11,  $p = 0.014$ )

**Appendix S** List of the LAND metrics which violated the assumption of homogeneity according to Levene's test and consequently were log-transformed.

- Peak knee flexion angle (dominant),  $p = 0.040$
- Peak knee extension angle (dominant),  $p < 0.001$
- Range knee internal rotation angle (dominant),  $p = 0.004$
- Peak knee external rotation moment to body mass and height (dominant),  $p = 0.006$
- Peak propulsion GRF to body mass (dominant),  $p = 0.048$
- Peak medial GRF to body mass (dominant),  $p = 0.013$
- Range knee valgus angle (non-dominant),  $p = 0.030$
- Peak breaking GRF to body mass (non-dominant),  $p = 0.016$
- Peak propulsion GRF to body mass (non-dominant),  $p = 0.003$

**Appendix T** List of CUT metrics and the specific groups which violated the assumption of normality in the two by three-way ANOVA according to the Shapiro-Wilks test.

- Range knee flexion angle (dominant), Female mid-pubertal (Stat = 0.785, df = 9,  $p = 0.014$ )
- Peak knee flexion moment to body mass and height (dominant), Male post-pubertal (Stat = 0.837, df = 10,  $p = 0.041$ )
- Peak knee valgus angle (dominant), Male pre-pubertal (Stat = 0.806, df = 12,  $p = 0.011$ )
- Range knee valgus angle (dominant), Male pre-pubertal (Stat = 0.722, df = 12,  $p = 0.001$ )
- Peak knee internal rotation angle (dominant), Male post-pubertal (Stat = 0.820, df = 10,  $p = 0.025$ )
- Range knee internal rotation angle (dominant), Female pre-pubertal (Stat = 0.829, df = 10,  $p = 0.033$ )
- Peak knee internal rotation moment to body mass and height (dominant), Male post-pubertal (Stat = 0.799, df = 10,  $p = 0.014$ )
- Peak knee external rotation moment to body mass and height (dominant), Female post-pubertal (Stat = 0.798, df = 10,  $p = 0.014$ ), Male post-pubertal (Stat = 0.838, df = 10,  $p = 0.042$ )
- Peak lateral GRF to body mass (dominant), Male mid-pubertal (Stat = 0.727, df = 11,  $p = 0.001$ ), Male post-pubertal (Stat = 0.802, df = 10,  $p = 0.015$ )
- Flight time (dominant), Female pre-pubertal (Stat = 0.816, df = 10,  $p = 0.023$ )
- Time to PKF (dominant), Male post-pubertal (Stat = 0.720, df = 10,  $p = 0.002$ )
- Stance time (dominant), Male post-pubertal (Stat = 0.805, df = 10,  $p = 0.016$ )
- Peak knee flexion moment to body mass and height (non-dominant), Male mid-pubertal (Stat = 0.789, df = 11,  $p = 0.007$ ), Male pre-pubertal (Stat = 0.695, df = 16,  $p < 0.001$ )
- Peak knee extension moment to body mass and height (non-dominant), Male mid-pubertal (Stat = 0.849, df = 11,  $p = 0.042$ )
- Peak knee varus moment to body mass and height (non-dominant), Male mid-pubertal (Stat = 0.849, df = 11,  $p = 0.042$ )

- Range knee internal rotation angle (non-dominant), Female post-pubertal (Stat = 0.835, df = 10,  $p = 0.038$ )
- Peak lateral GRF y to body mass (non-dominant), Male mid-pubertal (Stat = 0.769, df = 11,  $p = 0.004$ ), Male post-pubertal (Stat = 0.868, df = 9,  $p = 0.042$ )
- Peak medial GRF to body mass (non-dominant), Female pre-pubertal (Stat = 0.808, df = 9,  $p = 0.026$ ), Male pre-pubertal (Stat = 0.816, df = 16,  $p = 0.004$ )
- Time to PKF (non-dominant), Male pre-pubertal (Stat = 0.850, df = 16,  $p = 0.014$ )

**Appendix U** List of the CUT metrics which violated the assumption of homogeneity according to Levene's test and consequently were log-transformed.

- Peak knee flexion moment to body mass and height (dominant),  $p = 0.019$
- Peak knee valgus angle (dominant),  $p = 0.042$
- Peak lateral GRF to body mass (dominant),  $p < 0.001$
- Peak propulsion GRF to body mass (dominant),  $p = 0.031$
- Time to PKF (dominant),  $p = 0.043$
- Range knee flexion angle (non-dominant),  $p = 0.033$
- Peak knee extension moment to body mass and height (non-dominant),  $p = 0.022$
- Peak breaking GRF to body mass (non-dominant),  $p = 0.010$
- Peak lateral GRF to body mass (non-dominant),  $p = 0.024$
- Peak propulsion GRF to body mass (non-dominant),  $p = 0.029$
- Peak medial GRF to body mass (non-dominant),  $p = 0.004$
- Time to PKF (non-dominant),  $p = 0.004$
- Stance time (non-dominant),  $p = 0.041$

**Appendix V** List of ROT metrics and the specific groups which violated the assumption of normality in the two by three-way ANOVA according to the Shapiro-Wilks test.

- Peak knee flexion moment (dominant), Male post-pubertal (Stat = 0.821, df = 11,  $p = 0.014$ )
- Peak knee extension moment (dominant), Female pre-pubertal (Stat = 0.817, df = 10,  $p = 0.023$ )
- Range transverse angle (dominant), Female post-pubertal (Stat = 0.841, df = 10,  $p = 0.045$ )
- Peak knee external rotation moment (dominant), Female pre-pubertal (Stat = 0.616, df = 10,  $p < 0.001$ ), Female post-pubertal (Stat = 0.813, df = 10,  $p = 0.021$ ), Male pre-pubertal (Stat = 0.864, df = 13,  $p = 0.044$ )
- Peak anterior GRF (dominant), Male post-pubertal (Stat = 0.834, df = 11,  $p = 0.027$ )
- Peak posterior GRF (dominant) Female mid-pubertal (Stat = 0.813, df = 9,  $p = 0.029$ )
- Peak knee flexion angle (non-dominant), Female post-pubertal (Stat = 0.840, df = 10,  $p = 0.044$ )
- Peak knee flexion moment (non-dominant), Male pre-pubertal (Stat = 0.678, df = 12,  $p < 0.001$ )
- Peak knee valgus moment (non-dominant), Female post-pubertal (Stat = 0.787, df = 10,  $p = 0.010$ ), Female pre-pubertal (Stat = 0.767, df = 8,  $p = 0.012$ )
- Peak knee external rotation angle (non-dominant), Female pre-pubertal (Stat = 0.806, df = 8,  $p = 0.033$ )
- Peak lateral GRF (non-dominant) Male pre-pubertal (Stat = 0.822, df = 12,  $p = 0.017$ )
- Peak medial GRF (non-dominant) Male mid-pubertal (Stat = 0.782, df = 10,  $p = 0.009$ )
- Peak posterior GRF (non-dominant) Male pre-pubertal (Stat = 0.856, df = 12,  $p = 0.043$ )
- Time to PKF (non-dominant) Female pre-pubertal (Stat = 0.774, df = 10,  $p = 0.007$ ), Male pre-pubertal (Stat = 0.798, df = 12,  $p = 0.025$ ), Male mid-pubertal (Stat = 0.816, df = 10,  $p = 0.023$ ), Male post-pubertal (Stat = 0.854, df = 12,  $p = 0.041$ )

- Stance time (non-dominant) Male post-pubertal (Stat = 0.836, df = 12,  $p = 0.025$ )
- Jump height (non-dominant) Male pre-pubertal (Stat = 0.842, df = 12,  $p = 0.029$ )

**Appendix W** List of the ROT metrics which violated the assumption of homogeneity according to Levene's test and consequently were log-transformed.

- Range coronal angle (dominant),  $p = 0.032$
- Peak lateral GRF (dominant),  $p = 0.031$
- Peak vGRF (dominant),  $p = 0.020$
- Peak medial GRF (dominant),  $p = 0.006$
- Jump height (dominant),  $p = 0.037$
- Range coronal angle (non-dominant),  $p = 0.009$
- Peak knee valgus moment (non-dominant),  $p = 0.024$
- Peak knee internal rotation moment (non-dominant),  $p = 0.023$
- Peak lateral GRF (non-dominant),  $p = 0.006$
- Peak vGRF (non-dominant),  $p = 0.037$
- Peak medial GRF (non-dominant),  $p = 0.028$

**Appendix X** List of VERT metrics and the specific groups which violated the assumption of normality in the two by three-way ANOVA according to the Shapiro-Wilks test.

- Range coronal angle (dominant), Female post-pubertal (Stat = 0.741, df = 10,  $p = 0.003$ )
- Peak knee varus moment (dominant), Female pre-pubertal (Stat = 0.857, df = 12,  $p = 0.045$ )
- Range transverse angle (dominant), Female mid-pubertal (Stat = 0.818, df = 9,  $p = 0.033$ )
- Peak knee external rotation moment (dominant), Female pre-pubertal (Stat = 0.822, df = 9,  $p = 0.037$ ), Male pre-pubertal (Stat = 0.790, df = 12,  $p = 0.007$ ), Male mid-pubertal (Stat = 0.735, df = 10,  $p = 0.002$ )
- Peak anterior GRF (dominant), Male post-pubertal (Stat = 0.752, df = 11,  $p = 0.001$ )
- Peak medial GRF (dominant), Female post-pubertal (Stat = 0.818, df = 10,  $p = 0.024$ )
- Peak vGRF (dominant), Female post-pubertal (Stat = 0.771, df = 10,  $p = 0.006$ ), Male post-pubertal (Stat = 0.771, df = 11,  $p = 0.004$ )
- Stance time (dominant), Male post-pubertal (Stat = 0.804, df = 11,  $p = 0.011$ )
- Min knee flexion angle (non-dominant), Female pre-pubertal (Stat = 0.728, df = 9,  $p = 0.003$ ), Female post-pubertal (Stat = 0.829, df = 10,  $p = 0.033$ )
- Peak knee flexion moment (non-dominant), Male pre-pubertal (Stat = 0.844, df = 12,  $p = 0.031$ )
- Peak knee extension moment (non-dominant), Male pre-pubertal (Stat = 0.860, df = 12,  $p = 0.048$ )
- Peak knee varus angle (non-dominant), Female pre-pubertal (Stat = 0.792, df = 9,  $p = 0.017$ )
- Peak knee valgus moment (non-dominant), Female post-pubertal (Stat = 0.746, df = 10,  $p = 0.003$ )
- Peak knee varus moment (non-dominant), Male pre-pubertal (Stat = 0.797, df = 12,  $p = 0.009$ )
- Peak knee internal rotation moment (non-dominant), Male mid-pubertal (Stat = 0.88, df = 10,  $p = 0.042$ )

- Peak knee external rotation moment (non-dominant), Female mid-pubertal (Stat = 0.802, df = 10,  $p = 0.015$ )
- Peak anterior GRF (non-dominant), Female pre-pubertal (Stat = 0.687, df = 9,  $p = 0.001$ )
- Peak medial GRF (non-dominant), Female post-pubertal (Stat = 0.705, df = 10,  $p = 0.001$ ), Female pre-pubertal (Stat = 0.786, df = 9,  $p = 0.014$ ), Male mid-pubertal (Stat = 0.788, df = 11,  $p = 0.007$ )
- Time to PKF (non-dominant), Male mid-pubertal (Stat = 0.832, df = 11,  $p = 0.025$ )
- Stance time (non-dominant), Male mid-pubertal (Stat = 0.790, df = 11,  $p = 0.007$ )

**Appendix Y** List of VERT metrics which violated the assumption of homogeneity according to Levene's test and consequently were log-transformed

- Peak knee valgus moment (dominant),  $p = 0.004$
- Peak knee internal rotation moment (dominant),  $p = 0.048$
- Peak knee external rotation moment (dominant),  $p = 0.004$
- Peak posterior GRF (dominant),  $p = 0.027$
- Peak medial GRF (dominant),  $p = 0.039$
- Jump height (dominant),  $p = 0.009$
- Peak knee flexion moment (non-dominant),  $p = 0.020$
- Peak knee varus moment (non-dominant),  $p = 0.002$

**Appendix Z** LAND task all calculated knee angles (°) and moments (Nm) of the dominant limb according to sex and maturation stage. All variables are presented as mean ± SD.

Sex	M				F				Total				Interaction effect	Main effect Maturation	Main effect Sex
Maturation stage	Pre	Mid	Post	Total M	Pre	Mid	Post	Total F	Pre	Mid	Post	Total	Sex*Maturation		
<b>Max flexion angle (°)</b>	59.098 ± 9.007	64.085 ± 10.894	60.910 ± 16.405	61.175 ± 12.056	58.843 ± 9.601	61.855 ± 6.427	63.843 ± 11.436	61.468 ± 9.398	58.842 ± 9.031	63.081 ± 9.008	62.307 ± 13.988	61.303 ± 10.891	$F(2, 58) = 0.911$ , $p = 0.408$ , partial $\eta^2 = 0.033$ [0.000, 0.109]	$F(2, 58) = 0.622$ , $p = 0.541$ , partial $\eta^2 = 0.023$ [0.000, 0.089]	$F(1, 58) = 0.594$ , $p = 0.444$ , partial $\eta^2 = 0.011$ [0.000, 0.088]
<b>Min flexion angle (°)</b>	11.909 ± 3.350	16.585 ± 4.434*	12.698 ± 7.973	13.579 ± 5.678	10.161 ± 3.182	13.997 ± 2.250	17.377 ± 4.629**	13.971 ± 4.558	11.225 ± 3.350	15.420 ± 3.771	14.926 ± 6.868	13.751 ± 5.182	<b><math>F(2, 58) = 4.490</math></b> , <b><math>p = 0.015</math></b> , partial $\eta^2 = 0.134$ [0.015, 0.254]	<b><math>F(2, 58) = 3.571</math></b> , <b><math>p = 0.034</math></b> , partial $\eta^2 = 0.110$ [0.004, 0.225]	$F(1, 58) = 0.369$ , $p = 0.546$ , partial $\eta^2 = 0.006$ [0.000, 0.077]
<b>Range flexion angle (°)</b>	47.188 ± 7.733	47.499 ± 8.198	48.212 ± 8.943	47.596 ± 8.028	48.283 ± 7.345	47.858 ± 6.062	46.466 ± 9.375	47.496 ± 7.537	47.617 ± 7.433	47.660 ± 7.133	47.380 ± 8.963	47.553 ± 7.756	$F(2, 58) = 0.178$ , $p = 0.838$ , partial $\eta^2 = 0.006$ [0.000, 0.041]	$F(2, 58) = 0.015$ , $p = 0.985$ , partial $\eta^2 = 0.001$ [0.000, 0.000]	$F(1, 58) = 0.002$ , $p = 0.962$ , partial $\eta^2 = 0.000$ [0.000, 0.000]

<b>Max flexion moment (Nm/kg)</b>	0.668 ± 0.160	0.779 ± 0.164	0.731 ± 0.167	0.721 ± 0.165	0.807 ± 0.217 <sup>#</sup>	0.727 ± 0.243 <sup>#</sup>	0.475 ± 0.168	0.663 ± 0.250	0.722 ± 0.193	0.756 ± 0.199	0.609 ± 0.209	0.696 ± 0.207	<b>F(2, 58) = 6.123, p = 0.004, partial η² = 0.174 [0.037, 0.299]</b>	<b>F(2, 58) = 4.146, p = 0.021, partial η² = [0.011, 0.244]</b>	<b>F(1, 58) = 1.467, p = 0.231, partial η² = [0.000, 0.120]</b>
<b>Min flexion moment (Nm/kg)</b>	-2.300 ± 0.361	-2.854 ± 0.397	-2.717 ± 0.641	-2.597 ± 0.521	-2.652 ± 0.435	-2.766 ± 0.511	-2.758 ± 0.431	-2.726 ± 0.445	-2.438 ± 0.421	-2.814 ± 0.442	-2.736 ± 0.538	-2.653 ± 0.490	<b>F(2, 58) = 1.234, p = 0.299, partial η² = 0.041 [0.000, 0.128]</b>	<b>F(2, 58) = 2.991, p = 0.058, partial η² = 0.093 [0.000, 0.205]</b>	<b>F(1, 58) = 0.732, p = 0.396, partial η² = [0.000, 0.094]</b>
<b>Range flexion moment (Nm/kg)</b>	2.968 ± 0.380	3.634 ± 0.475	3.448 ± 0.665	3.318 ± 0.574	3.232 ± 0.448	3.493 ± 0.534	3.232 ± 0.448	3.389 ± 0.526	3.160 ± 0.531	3.570 ± 0.494	3.345 ± 0.569	3.349 ± 0.551	<b>F(2, 58) = 2.984, p = 0.058, partial η² = 0.093 [0.000, 0.204]</b>	<b>F(2, 58) = 2.395, p = 0.100, partial η² = 0.076 [0.000, 0.182]</b>	<b>F(1, 58) = 0.115, p = 0.736, partial η² = [0.000, 0.055]</b>
<b>Max flexion moment (Nm/kg/m)</b>	0.486 ± 0.132	0.459 ± 0.083	0.413 ± 0.096	0.456 ± 0.110	0.564 ± 0.143 <sup>#^</sup>	0.442 ± 0.141 <sup>#</sup>	0.290 ± 0.091	0.427 ± 0.167	0.517 ± 0.139	0.452 ± 0.110	0.355 ± 0.111	0.443 ± 0.137	<b>F(2, 58) = 3.961, p = 0.024, partial η² = 0.120 [0.009, 0.238]</b>	<b>F(2, 58) = 11.876, p &lt; 0.001, partial η² = [0.122, 0.415]</b>	<b>F(1, 58) = 0.490, p = 0.487, partial η² = [0.000, 0.083]</b>

<b>Min flexion moment (Nm/kg/m)</b>	-1.661 ± 0.251	-1.681 ± 0.169	-1.531 ± 0.351	-1.627 ± 0.267	-1.859 ± 0.286	-1.683 ± 0.273	-1.700 ± 0.251	-1.746 ± 0.271	-1.738 ± 0.277	-1.682 ± 0.216	-1.612 ± 0.312	-1.679 ± 0.273	$F(2, 58) = 0.795$ , $p = 0.456$ , partial $\eta^2 = 0.027$ [0.000, 0.102]	$F(2, 58) = 1.549$ , $p = 0.221$ , partial $\eta^2 = 0.051$ [0.000, 0.144]	$F(1, 58) = 3.308$ , $p = 0.074$ , partial $\eta^2 = 0.052$ [0.000, 0.168]
<b>Range flexion moment (Nm/kg/m)</b>	2.147 ± 0.287	2.140 ± 0.191	1.945 ± 0.364	2.083 ± 0.296	2.422 ± 0.397	2.126 ± 0.260	1.991 ± 0.236	2.173 ± 0.345	2.255 ± 0.353 <sup>#</sup>	2.133 ± 0.219	1.967 ± 0.303	2.122 ± 0.319	$F(2, 58) = 1.421$ , $p = 0.250$ , partial $\eta^2 = 0.047$ [0.000, 0.138]	<b><math>F(2, 58) = 6.161</math></b> , $p = 0.004$ , partial $\eta^2 = 0.175$ [0.038, 0.300]	$F(1, 58) = 1.882$ , $p = 0.175$ , partial $\eta^2 = 0.031$ [0.000, 0.132]
<b>Max valgus angle (°)</b>	8.554 ± 5.548	4.939 ± 3.874	4.238 ± 5.728	6.131 ± 5.387	6.610 ± 2.778	5.206 ± 5.053	4.191 ± 5.823	5.294 ± 4.710	7.793 ± 4.683	5.059 ± 4.321	4.216 ± 5.627	5.765 ± 5.080	$F(2, 58) = 0.304$ , $p = 0.739$ , partial $\eta^2 = 0.010$ [0.000, 0.059]	$F(2, 58) = 2.632$ , $p = 0.081$ , partial $\eta^2 = 0.083$ [0.000, 0.191]	$F(1, 58) = 0.207$ , $p = 0.651$ , partial $\eta^2 = 0.004$ [0.000, 0.065]
<b>Min valgus angle (°)</b>	0.006 ± 3.728	-2.609 ± 3.426	-4.003 ± 3.423	-2.018 ± 3.982	-1.181 ± 2.266	-2.657 ± 4.274	-3.352 ± 3.708	-2.431 ± 3.517	-0.458 ± 3.229 <sup>#</sup>	-2.631 ± 3.722	-3.693 ± 3.731	-2.198 ± 3.761	$F(2, 58) = 0.352$ , $p = 0.705$ , partial $\eta^2 = 0.012$ [0.000, 0.065]	<b><math>F(2, 58) = 4.045</math></b> , $p = 0.023$ , partial $\eta^2 = 0.122$ [0.010, 0.240]	$F(1, 58) = 0.045$ , $p = 0.832$ , partial $\eta^2 = 0.001$ [0.000, 0.039]

<b>Range</b>	8.548	7.548 ±	8.241 ±	8.148 ±	7.790 ±	7.863 ±	7.543 ±	7.725 ±	8.251	7.690	7.908	7.963 ±	$F(2, 58) = 0.237,$	$F(2, 58) =$	$F(1, 58) =$
<b>valgus angle</b>	±	2.390	3.659	3.132	1.179	1.779	2.940	2.062	±	±	±	2.705	$p = 0.790,$	$0.146, p =$	$0.291, p =$
<b>(°)</b>	3.352								2.705	2.089	3.273		partial $\eta^2 =$	0.864,	0.592,
													0.008 [0.000,	partial $\eta^2 =$	partial $\eta^2 =$
													0.050]	0.005 [0.000,	0.005
														0.034]	[0.000,
															0.072]
<b>Max valgus</b>	0.680	0.813 ±	0.860 ±	0.776 ±	0.815 ±	0.813 ±	0.581 ±	0.731 ±	0.733	0.813	0.727	0.756 ±	$F(2, 58) = 2.954,$	$F(2, 58) =$	$F(1, 58) =$
<b>moment</b>	±	0.286	0.276	0.291	0.224	0.384	0.189	0.289	±	±	±	0.289	$p = 0.060,$	$0.570, p =$	$0.448, p =$
<b>(Nm/kg)</b>	0.300								0.276	0.324	0.273		partial $\eta^2 =$	0.569,	0.506,
													0.092 [0.000,	partial $\eta^2 =$	partial $\eta^2 =$
													0.203]	0.019 [0.000,	0.008
														0.085]	[0.000,
															0.081]
<b>Min valgus</b>	-0.575	-0.283 ±	-0.255 ±	-0.388	-0.406 ±	-0.340 ±	-0.289 ±	-0.343 ±	-0.510	-0.309	-0.271	-0.369 ±	$F(2, 58) = 1.368,$	<b><math>F(2, 58) =</math></b>	$F(1, 58) =$
<b>moment</b>	±	0.135	0.234	± 0.269	0.302	0.274	0.215	0.259	±	±	±	0.264	$p = 0.263,$	<b>4.845, p =</b>	$0.175, p =$
<b>(Nm/kg)</b>	0.278								0.293	0.205*	0.220*		partial $\eta^2 =$	<b>0.011,</b>	0.677,
													0.045 [0.000,	<b>partial <math>\eta^2 =</math></b>	partial $\eta^2 =$
													0.135]	<b>0.143</b>	0.003
														<b>[0.020,</b>	[0.000,
														<b>0.264]</b>	0.062]
<b>Range</b>	1.255	1.096 ±	1.127 ±	1.167 ±	1.221 ±	1.153 ±	0.870 ±	1.074 ±	1.242	1.122	1.005	1.126 ±	$F(2, 58) = 2.089,$	<b><math>F(2, 58) =</math></b>	$F(1, 58) =$
<b>valgus</b>	±	0.270	0.233	0.285	0.214	0.253	0.138	0.252	±	±	±	0.273	$p = 0.642,$	<b>4.798, p =</b>	$1.473, p =$
<b>moment</b>	0.327								0.283 <sup>#</sup>	0.258	0.230		partial $\eta^2 =$	<b>0.012,</b>	0.230,
<b>(Nm/kg)</b>													0.016 [0.000,	<b>partial <math>\eta^2 =</math></b>	partial $\eta^2 =$
													0.169]	<b>0.142</b>	0.025
														<b>[0.019,</b>	[0.000,
														<b>0.263]</b>	0.120]

<b>Max valgus moment (Nm/kg/m)</b>	0.493 ± 0.221	0.481 ± 0.165	0.485 ± 0.156	0.487 ± 0.181	0.571 ± 0.160	0.492 ± 0.233	0.357 ± 0.113	0.469 ± 0.190	0.524 ± 0.199	0.486 ± 0.193	0.424 ± 0.149	0.479 ± 0.184	$F(2, 58) = 1.805$ , $p = 0.174$ , partial $\eta^2 = 0.059$ [0.000, 0.156]	$F(2, 58) = 2.033$ , $p = 0.140$ , partial $\eta^2 = 0.066$ [0.000, 0.167]	$F(1, 56) = 0.077$ , $p = 0.783$ , partial $\eta^2 = 0.001$ [0.000, 0.048]
<b>Min valgus moment (Nm/kg/m)</b>	-0.417 ± 0.208	-0.168 ± 0.082	-0.152 ± 0.156	-0.260 ± 0.203	-0.288 ± 0.213	-0.214 ± 0.184	-0.180 ± 0.136	-0.226 ± 0.178	-0.366 ± 0.215	-0.189 ± 0.136*	-0.165 ± 0.144*	-0.366 ± 0.215	$F(2, 58) = 1.724$ , $p = 0.187$ , partial $\eta^2 = 0.056$ [0.000, 0.153]	<b><math>F(2, 58) = 7.609</math></b> , $p = 0.001$ , partial $\eta^2 = 0.208$ [0.059, 0.334]	$F(1, 58) = 0.178$ , $p = 0.674$ , partial $\eta^2 = 0.003$ [0.000, 0.062]
<b>Range valgus moment (Nm/kg/m)</b>	0.909 ± 0.241	0.649 ± 0.160	0.637 ± 0.135	0.747 ± 0.227	0.859 ± 0.157	0.707 ± 0.167	0.537 ± 0.084	0.695 ± 0.190	0.890 ± 0.210 <sup>#</sup>	0.675 ± 0.162	0.589 ± 0.122	0.724 ± 0.212	$F(2, 58) = 1.135$ , $p = 0.329$ , partial $\eta^2 = 0.038$ [0.000, 0.122]	<b><math>F(2, 58) = 17.206</math></b> , $p < 0.001$ , partial $\eta^2 = 0.372$ [0.196, 0.489]	$F(1, 58) = 0.512$ , $p = 0.477$ , partial $\eta^2 = 0.009$ [0.000, 0.084]
<b>Max internal rotation angle (°)</b>	9.903 ± 5.815	5.894 ± 5.624	4.789 ± 5.183	7.115 ± 5.878	6.901 ± 5.956	4.729 ± 3.703	8.164 ± 6.669	6.654 ± 5.612	8.728 ± 5.927	5.370 ± 4.772	6.396 ± 6.036	6.913 ± 5.723	$F(2, 58) = 1.825$ , $p = 0.170$ , partial $\eta^2 = 0.059$ [0.000, 0.157]	$F(2, 58) = 1.631$ , $p = 0.205$ , partial $\eta^2 = 0.053$ [0.000, 0.148]	$F(1, 58) = 0.035$ , $p = 0.853$ , partial $\eta^2 = 0.001$ [0.000, 0.035]

<b>Min internal rotation angle (°)</b>	-1.455 ± 6.675	-7.688 ± 5.466	-8.688 ± 5.706	-5.570 ± 6.755	-4.795 ± 6.812	-10.119 ± 6.484	-5.868 ± 6.062	-6.890 ± 6.617	-2.762 ± 6.781 <sup>#</sup>	-8.782 ± 5.913	-7.346 ± 5.907	-6.147 ± 6.674	$F(2, 58) = 1.508,$ $p = 0.230,$ partial $\eta^2 =$ 0.049 [0.000, 0.121]	<b><math>F(2, 58) = 4.853, p = 0.011,</math></b> partial $\eta^2 =$ <b>0.143</b> <b>[0.004,</b> <b>0.200]</b>	$F(1, 58) = 0.392, p = 0.534,$ partial $\eta^2 = 0.007$ [0.000, 0.078]
<b>Range internal rotation angle (°)</b>	11.358 ± 3.007	13.582 ± 4.891	13.478 ± 3.926	12.685 ± 3.969	11.696 ± 3.376	14.849 ± 7.792	14.032 ± 5.028	13.544 ± 5.620	11.490 ± 3.085	14.152 ± 6.211	13.742 ± 4.378	13.061 ± 4.741	$F(2, 58) = 0.001,$ $p = 0.999,$ partial $\eta^2 =$ 0.000 [0.000, 0.000]	$F(2, 58) = 1.207, p = 0.306,$ partial $\eta^2 =$ 0.040 [0.000, 0.126]	$F(1, 58) = 0.034, p = 0.855,$ partial $\eta^2 = 0.001$ [0.000, 0.035]
<b>Max internal rotation moment (Nm/kg)</b>	0.423 ± 0.160	0.547 ± 0.106	0.493 ± 0.173	0.482 ± 0.155	0.506 ± 0.128	0.530 ± 0.189	0.450 ± 0.116	0.494 ± 0.145	0.455 ± 0.151	0.539 ± 0.145	0.473 ± 0.147	0.487 ± 0.150	$F(2, 58) = 1.085,$ $p = 0.345,$ partial $\eta^2 =$ 0.036 [0.000, 0.120]	$F(2, 58) = 1.532, p = 0.225,$ partial $\eta^2 =$ 0.050 [0.000, 0.143]	$F(1, 58) = 0.045, p = 0.833,$ partial $\eta^2 = 0.001$ [0.000, 0.039]
<b>Min internal rotation moment (Nm/kg)</b>	-0.162 ± 0.133	-0.068 ± 0.035	-0.097 ± 0.149	-0.113 ± 0.123	-0.120 ± 0.099	-0.054 ± 0.040	-0.043 ± 0.041	-0.071 ± 0.072	-0.146 ± 0.121	-0.061 ± 0.037*	-0.071 ± 0.112*	-0.095 ± 0.105	$F(2, 58) = 0.203,$ $p = 0.817,$ partial $\eta^2 =$ 0.007 [0.000, 0.045]	<b><math>F(2, 58) = 4.357, p = 0.017,</math></b> partial $\eta^2 =$ <b>0.131</b> <b>[0.014,</b> <b>0.245]</b>	$F(1, 58) = 2.130, p = 0.150,$ partial $\eta^2 = 0.035$ [0.000, 0.139]

<b>Range</b>	0.585	0.615 ±	0.590 ±	0.596 ±	0.627 ±	0.584 ±	0.493 ±	0.565 ±	0.601 ±	0.601	0.544	0.582 ±	$F(2, 58) = 1.211,$	$F(2, 58) =$	$F(1, 58) =$	
<b>internal</b>	±	0.101	0.197	0.156	0.112	0.157	0.105	0.134	0.145	±	±	0.146	$p = 0.305,$	$1.235, p =$	$0.603, p =$	
<b>rotation</b>	0.165												partial $\eta^2 =$	0.298,	0.441,	
<b>moment</b>													0.040 [0.000,	partial $\eta^2 =$	partial $\eta^2 =$	
<b>(Nm/kg)</b>													0.127]	0.041 [0.000,	0.010	
														0.128]	[0.000,	0.089]
<b>Max internal</b>	0.312	0.323 ±	0.277 ±	0.305 ±	0.355 ±	0.322 ±	0.277 ±	0.317 ±	0.329 ±	0.322	0.277	0.310 ±	$F(2, 58) = 0.368,$	$F(2, 58) =$	$F(1, 58) =$	
<b>rotation</b>	±	0.059	0.091	0.096	0.084	0.113	0.068	0.092	0.108	±	±	0.094	$p = 0.693,$	$2.170, p =$	$0.326, p =$	
<b>moment</b>	0.121												partial $\eta^2 =$	0.123,	0.570,	
<b>(Nm/kg/m)</b>													0.013 [0.000,	partial $\eta^2 =$	partial $\eta^2 =$	
													0.067]	0.070 [0.000,	0.006	
														0.172]	[0.000,	0.062]
<b>Min internal</b>	-0.119	-0.041	-0.055	-0.076	-0.085	-0.034	-0.027	-0.048	-0.105	-0.037	-0.042	-0.064 ±	$F(2, 58) = 0.228,$	$F(2, 58) =$	$F(1, 58) =$	
<b>rotation</b>	±	± 0.022	± 0.086	± 0.084	± 0.072	± 0.026	± 0.027	± 0.052	± 0.088	±	±	0.073	$p = 0.791,$	<b>6.525, p =</b>	$1.866, p =$	
<b>moment</b>	0.097												partial $\eta^2 =$	<b>0.003,</b>	0.177,	
<b>(Nm/kg/m)</b>													0.008 [0.000,	partial $\eta^2 =$	partial $\eta^2 =$	
													0.050]	<b>0.184</b>	0.031	
														<b>[0.048,</b>	[0.000,	0.132]
														<b>0.309]</b>		
<b>Range</b>	0.432	0.363 ±	0.333 ±	0.348 ±	0.440 ±	0.355 ±	0.304 ±	0.364 ±	0.435 ±	0.360	0.319	0.374 ±	$F(2, 58) = 0.189,$	$F(2, 58) =$	$F(1, 58) =$	
<b>internal</b>	±	0.058	0.109	0.085	0.079	0.094	0.061	0.096	0.115 <sup>^</sup>	±	±	0.106	$p = 0.828,$	<b>8.058, p &lt;</b>	$0.147, p =$	
<b>rotation</b>	0.136												partial $\eta^2 =$	<b>0.001,</b>	0.703,	
<b>moment</b>													0.0706 [0.000,	partial $\eta^2 =$	partial $\eta^2 =$	
<b>(Nm/kg/m)</b>													0.043]	<b>0.217</b>	0.003	
														<b>[0.065,</b>	[0.000,	0.059]
														<b>0.344]</b>		

Key: **Bold** =  $p < 0.05$ . \* = higher than pre, ^ higher than mid, # higher than post, “ = higher than M total, ‘ = higher than F today, \* = higher than M in same maturation stage, ‘ = higher than F in same maturation stage.

**Appendix AA** LAND task all calculated knee angles (°) and moments (Nm) of the non-dominant limb according to sex and maturation stage. All variables are presented as mean ± SD.

Sex	M				F				Total				Interaction effect sex*maturation	Main effect Maturation	Main effect Sex
Maturation stage	Pre	Mid	Post	Total M	Pre	Mid	Post	Total F	Pre	Mid	Post	Total			
<b>Max flexion angle (°)</b>	58.182 ± 13.769	59.349 ± 9.432	60.570 ± 12.801	59.332 ± 11.934	61.131 ± 10.212	59.355 ± 6.875	61.723 ± 10.099	60.758 ± 8.889	59.361 ± 12.263	59.352 ± 8.093	61.119 ± 11.321	59.974 ± 10.610	$F(2, 54) = 0.087, p =$ $0.917, \text{partial } \eta^2 =$ $0.003 [0.000, 0.018]$	$F(2, 54) =$ $0.154, p =$ $0.858, \text{partial } \eta^2 =$ $0.006 [0.000,$ $0.038]$	$F(1, 54) =$ $0.228, p =$ $0.635,$ $\text{partial } \eta^2 =$ $0.004$ $[0.000,$ $0.071]$
<b>Min flexion angle (°)</b>	10.413 ± 6.161	13.498 ± 3.161	11.596 ± 6.006	11.742 ± 5.364	11.279 ± 2.820	11.844 ± 5.447	15.471 ± 5.160	13.020 ± 4.920	10.759 ± 5.010	12.715 ± 4.348	13.441 ± 5.827	12.317 ± 5.166	$F(2, 54) = 1.475, p =$ $0.238, \text{partial } \eta^2 =$ $0.052 [0.000, 0.149]$	$F(2, 54) =$ $1.439, p =$ $0.246, \text{partial } \eta^2 =$ $0.051 [0.000,$ $0.147]$	$F(1, 54) =$ $0.602, p =$ $0.441,$ $\text{partial } \eta^2 =$ $0.011$ $[0.000,$ $0.094]$
<b>Range flexion angle (°)</b>	47.769 ± 10.846	45.851 ± 8.404	48.975 ± 8.180	47.589 ± 9.101	49.853 ± 9.189	47.511 ± 7.097	46.252 ± 6.594	47.738 ± 7.451	48.602 ± 10.016	46.637 ± 7.644	47.678 ± 7.414	47.657 ± 8.331	$F(2, 54) = 0.487, p =$ $0.617, \text{partial } \eta^2 =$ $0.018 [0.000, 0.083]$	$F(2, 54) =$ $0.295, p =$ $0.746, \text{partial } \eta^2 =$ $0.011 [0.000,$ $0.062]$	$F(1, 54) =$ $0.023, p =$ $0.880,$ $\text{partial } \eta^2 =$ $0.000$ $[0.000,$ $0.031]$

<b>Max flexion moment (Nm/kg)</b>	0.656 ± 0.149	0.665 ± 0.188	0.721 ± 0.135	0.681 ± 0.155	0.722 ± 0.188 <sup>#</sup>	0.761 ± 0.206 <sup>#</sup>	0.501 ± 0.131	0.653 ± 0.207	0.682 ± 0.164	0.711 ± 0.197	0.617 ± 0.172	0.668 ± 0.179	<b>F(2, 54) = 5.608, p = 0.006, partial η<sup>2</sup> = 0.172 [0.032, 0.300]</b>	<b>F(2, 54) = 2.085, p = 0.134, partial η<sup>2</sup> = 0.072 [0.000, 0.179]</b>	<b>F(1, 54) = 0.201, p = 0.656, partial η<sup>2</sup> = 0.004 [0.000, 0.069]</b>
<b>Min flexion moment (Nm/kg)</b>	-2.154 ± 0.492	-2.714 ± 0.336	-2.789 ± 0.508	-2.154 ± 0.531	-2.673 ± 0.630	-2.760 ± 0.491	-2.565 ± 0.505	-2.662 ± 0.526	-2.362 ± 0.596	-2.735 ± 0.405	-2.683 ± 0.507	-2.592 ± 0.528	<b>F(2, 54) = 2.868, p = 0.066, partial η<sup>2</sup> = 0.096 [0.000, 0.211]</b>	<b>F(2, 54) = 2.320, p = 0.108, partial η<sup>2</sup> = 0.079 [0.000, 0.189]</b>	<b>F(1, 54) = 0.780, p = 0.381, partial η<sup>2</sup> = 0.014 [0.000, 0.102]</b>
<b>Range flexion moment (Nm/kg)</b>	2.809 ± 0.536	3.379 ± 0.404 <sup>*</sup>	3.510 ± 0.475 <sup>*</sup>	3.216 ± 0.536	3.395 ± 0.726 <sup>*</sup>	3.521 ± 0.599	3.067 ± 0.509	3.315 ± 0.618	3.044 ± 0.669	3.446 ± 0.496	3.299 ± 0.530	3.261 ± 0.585	<b>F(2, 54) = 4.591, p = 0.014, partial η<sup>2</sup> = 0.145 [0.017, 0.270]</b>	<b>F(2, 57) = 1.976, p = 0.149, partial η<sup>2</sup> = 0.068 [0.000, 0.174]</b>	<b>F(1, 57) = 0.452, p = 0.504, partial η<sup>2</sup> = 0.008 [0.000, 0.087]</b>
<b>Max flexion moment (Nm/kg/m)</b>	0.475 ± 0.114	0.392 ± 0.097	0.405 ± 0.075	0.426 ± 0.101	0.500 ± 0.129 <sup>#</sup>	0.464 ± 0.120 <sup>#</sup>	0.308 ± 0.073	0.417 ± 0.135	0.485 ± 0.117	0.426 ± 0.112	0.359 ± 0.087	0.422 ± 0.117	<b>F(2, 54) = 3.657, p = 0.032, partial η<sup>2</sup> = 0.119 [0.006, 0.240]</b>	<b>F(2, 54) = 8.304, p &lt; 0.001, partial η<sup>2</sup> = 0.235 [0.073, 0.365]</b>	<b>F(1, 54) = 0.000, p = 0.996, partial η<sup>2</sup> = 0.000 [0.000, 0.000]</b>

<b>Min flexion moment (Nm/kg/m)</b>	-1.550 ± 0.313	-1.609 ± 0.182	-1.566 ± 0.291	-1.573 ± 0.265	-1.847 ± 0.395	-1.681 ± 0.263	-1.577 ± 0.293	-1.692 ± 0.325	-1.669 ± 0.369	-1.643 ± 0.221	-1.571 ± 0.284	-1.627 ± 0.297	$F(2, 54) = 1.291, p = 0.283$ , partial $\eta^2 = 0.046$ [0.000, 0.139]	$F(2, 54) = 0.954, p = 0.392$ , partial $\eta^2 = 0.034$ [0.000, 0.119]	$F(1, 54) = 2.761, p = 0.102$ , partial $\eta^2 = 0.049$ [0.000, 0.164]
<b>Range flexion moment (Nm/kg/m)</b>	2.026 ± 0.345	2.000 ± 0.190	1.971 ± 0.273	2.000 ± 0.274	2.347 ± 0.451	2.145 ± 0.318	1.886 ± 0.278	2.109 ± 0.387	2.154 ± 0.412 <sup>#</sup>	2.069 ± 0.262	1.930 ± 0.272	2.049 ± 0.331	$F(2, 54) = 2.124, p = 0.129$ , partial $\eta^2 = 0.073$ [0.000, 0.180]	<b><math>F(2, 54) = 3.425, p = 0.040</math>, partial <math>\eta^2 = 0.113</math> [0.003, 0.232]</b>	$F(1, 54) = 2.420, p = 0.126$ , partial $\eta^2 = 0.043$ [0.000, 0.156]
<b>Max valgus angle (°)</b>	9.012 ± 6.800	4.787 ± 3.923	3.808 ± 3.074	5.997 ± 5.356	7.569 ± 6.676	5.378 ± 4.238	5.286 ± 5.299	5.993 ± 5.323	8.435 ± 6.612	5.067 ± 3.971	4.512 ± 4.235	5.995 ± 5.296	$F(2, 54) = 0.414, p = 0.663$ , partial $\eta^2 = 0.015$ [0.000, 0.076]	$F(2, 54) = 2.991, p = 0.059$ , partial $\eta^2 = 0.100$ [0.000, 0.216]	$F(1, 54) = 0.024, p = 0.878$ , partial $\eta^2 = 0.000$ [0.000, 0.031]
<b>Min valgus angle (°)</b>	0.566 ± 4.049	-2.493 ± 3.256	-3.251 ± 2.440	-1.634 ± 3.664	-1.085 ± 4.967	-3.312 ± 3.912	-2.229 ± 4.612	-2.251 ± 4.418	-0.095 ± 4.390	-2.881 ± 3.504	-2.765 ± 3.581	-1.912 ± 3.997	$F(2, 54) = 0.621, p = 0.541$ , partial $\eta^2 = 0.022$ [0.000, 0.095]	$F(2, 54) = 2.794, p = 0.070$ , partial $\eta^2 = 0.094$ [0.000, 0.209]	$F(1, 54) = 0.226, p = 0.637$ , partial $\eta^2 = 0.004$ [0.000, 0.071]

<b>Range</b>	8.447 ±	7.280 ±	7.059 ±	7.631 ±	8.654 ±	8.690 ±	7.516 ±	8.244 ±	8.530 ±	7.948 ±	7.277 ±	7.907 ±	$F(2, 54) = 0.057, p =$	$F(2, 54) =$	$F(1, 54) =$
<b>valgus angle</b> (°)	3.786	1.586	1.401	2.579	2.391	3.092	1.819	2.440	3.227	2.456	1.589	2.515	0.945, partial $\eta^2 =$ 0.002 [0.000, 0.004]	0.776, $p =$ 0.465, partial $\eta^2 = 0.028$ [0.000, 0.107]	0.945, $p =$ 0.335, partial $\eta^2 =$ 0.017 [0.000, 0.109]
<b>Max valgus</b>	0.722 ±	0.818 ±	0.768 ±	0.767 ±	0.701 ±	0.779 ±	0.600 ±	0.689 ±	0.714 ±	0.800 ±	0.688 ±	0.732 ±	$F(2, 54) = 0.389, p =$	$F(2, 54) =$	$F(1, 54) =$
<b>moment</b> (Nm/kg)	0.360	0.233	0.239	0.281	0.324	0.292	0.262	0.290	0.337	0.256	0.259	0.286	0.680, partial $\eta^2 =$ 0.014 [0.000, 0.073]	0.834, $p =$ 0.440, partial $\eta^2 = 0.030$ [0.000, 0.111]	1.035, $p =$ 0.314, partial $\eta^2 =$ 0.019 [0.000, 0.112]
<b>Min valgus</b>	-0.441	-0.297	-0.202	-0.318	-0.432	-0.320	-0.339	-0.360	-0.437	-0.308	-0.267	-0.337	$F(2, 54) = 0.660, p =$	<b><math>F(2, 54) =</math></b>	$F(1, 54) =$
<b>moment</b> (Nm/kg)	± 0.276	± 0.202	± 0.138	± 0.232	± 0.234	± 0.210	± 0.185	± 0.206	± 0.253	± 0.201	±	± 0.220	0.521, partial $\eta^2 =$ 0.024 [0.000, 0.098]	<b>3.294, <math>p =</math></b> <b>0.045, partial</b> <b><math>\eta^2 = 0.109</math></b> <b>[0.001, 0.227]</b>	0.836, $p =$ 0.365, partial $\eta^2 =$ 0.015 [0.000, 0.105]
<b>Range</b>	1.163 ±	1.115 ±	0.970 ±	1.084 ±	1.133 ±	1.099 ±	0.939 ±	1.050 ±	1.151 ±	1.108 ±	0.955 ±	1.069 ±	$F(2, 54) = 0.066, p =$	$F(2, 54) =$	$F(1, 54) =$
<b>valgus</b>	0.388	0.197	0.140	0.275	0.241	0.292	0.192	0.249	0.329	0.239	0.163	0.262	0.937, partial $\eta^2 =$ 0.002 [0.000, 0.009]	2.510, $p =$ 0.091, partial $\eta^2 = 0.085$ [0.000, 0.197]	0.104, $p =$ 0.748, partial $\eta^2 =$ 0.002 [0.000, 0.056]
<b>moment</b> (Nm/kg)															

<b>Max valgus moment (Nm/kg/m)</b>	0.517 ± 0.233	0.481 ± 0.117	0.431 ± 0.135	0.477 ± 0.171	0.488 ± 0.232	0.471 ± 0.162	0.369 ± 0.158	0.439 ± 0.185	0.505 ± 0.227	0.476 ± 0.136	0.402 ± 0.146	0.460 ± 0.177	$F(2, 54) = 0.115, p = 0.892$ , partial $\eta^2 = 0.004$ [0.000, 0.028]	$F(2, 54) = 1.801, p = 0.175$ , partial $\eta^2 = 0.063$ [0.000, 0.165]	$F(1, 54) = 0.513, p = 0.477$ , partial $\eta^2 = 0.009$ [0.000, 0.090]
<b>Min valgus moment (Nm/kg/m)</b>	-0.322 ± 0.207	-0.180 ± 0.128	-0.113 ± 0.078	-0.209 ± 0.172	-0.304 ± 0.175	-0.198 ± 0.134	-0.214 ± 0.127	-0.236 ± 0.147	-0.315 ± 0.190	-0.189 ± 0.128*	-0.161 ± 0.114*	-0.221 ± 0.160	$F(2, 54) = 0.854, p = 0.432$ , partial $\eta^2 = 0.031$ [0.000, 0.112]	<b><math>F(2, 54) = 5.703, p = 0.006</math>, partial <math>\eta^2 = 0.174</math> [0.033, 0.302]</b>	$F(1, 54) = 0.769, p = 0.384$ , partial $\eta^2 = 0.014$ [0.000, 0.102]
<b>Range valgus moment (Nm/kg/m)</b>	0.838 ± 0.262	0.661 ± 0.113	0.545 ± 0.082	0.687 ± 0.212	0.793 ± 0.192	0.670 ± 0.169	0.584 ± 0.137	0.674 ± 0.181	0.820 ± 0.232 <sup>^#</sup>	0.665 ± 0.139	0.563 ± 0.110	0.681 ± 0.197	$F(2, 54) = 0.143, p = 0.867$ , partial $\eta^2 = 0.005$ [0.000, 0.034]	<b><math>F(2, 54) = 9.495, p &lt; 0.001</math>, partial <math>\eta^2 = 0.260</math> [0.091, 0.389]</b>	$F(1, 54) = 0.012, p = 0.911$ , partial $\eta^2 = 0.000$ [0.000, 0.019]
<b>Max internal rotation angle (°)</b>	9.583 ± 5.867	8.029 ± 5.277	7.520 ± 6.079	8.424 ± 5.661	8.193 ± 5.275	6.063 ± 4.876	7.920 ± 5.579	7.381 ± 5.148	9.027 ± 5.538	7.098 ± 5.051	7.710 ± 5.703	7.955 ± 5.416	$F(2, 54) = 0.249, p = 0.780$ , partial $\eta^2 = 0.009$ [0.000, 0.056]	$F(2, 54) = 0.539, p = 0.586$ , partial $\eta^2 = 0.020$ [0.000, 0.088]	$F(1, 54) = 0.465, p = 0.498$ , partial $\eta^2 = 0.009$ [0.000, 0.087]

<b>Min internal rotation angle (°)</b>	-2.327 ± 5.388	-4.582 ± 5.276	-3.992 ± 5.972	-3.565 ± 5.469	-3.737 ± 5.973	-5.842 ± 6.148	-5.986 ± 5.588	-5.272 ± 5.751	-2.891 ± 5.518	-5.179 ± 5.580	-4.941 ± 5.738	-4.333 ± 5.615	$F(2, 54) = 0.023, p = 0.977, \text{partial } \eta^2 = 0.001 [0.000, 0.000]$	$F(2, 54) = 0.854, p = 0.431, \text{partial } \eta^2 = 0.031 [0.000, 0.112]$	$F(1, 54) = 1.094, p = 0.300, \text{partial } \eta^2 = 0.020 [0.000, 0.115]$
<b>Range internal rotation angle (°)</b>	11.909 ± 4.207	12.611 ± 2.863	11.512 ± 3.894	11.989 ± 3.651	11.930 ± 2.886	11.905 ± 3.884	13.905 ± 3.754	12.653 ± 3.567	11.918 ± 3.649	12.276 ± 3.307	12.276 ± 3.928	12.288 ± 3.598	$F(2, 54) = 0.987, p = 0.379, \text{partial } \eta^2 = 0.035 [0.000, 0.121]$	$F(2, 54) = 0.235, p = 0.792, \text{partial } \eta^2 = 0.009 [0.000, 0.053]$	$F(1, 54) = 0.355, p = 0.554, \text{partial } \eta^2 = 0.007 [0.000, 0.081]$
<b>Max internal rotation moment (Nm/kg)</b>	0.382 ± 0.179	0.425 ± 0.159	0.474 ± 0.145	0.426 ± 0.162	0.480 ± 0.146	0.390 ± 0.164	0.376 ± 0.131	0.412 ± 0.148	0.421 ± 0.170	0.408 ± 0.158	0.428 ± 0.144	0.419 ± 0.155	$F(2, 54) = 2.039, p = 0.140, \text{partial } \eta^2 = 0.070 [0.000, 0.177]$	$F(2, 54) = 0.125, p = 0.883, \text{partial } \eta^2 = 0.005 [0.000, 0.031]$	$F(1, 54) = 0.082, p = 0.776, \text{partial } \eta^2 = 0.002 [0.000, 0.052]$
<b>Min internal rotation moment (Nm/kg)</b>	-0.147 ± 0.114	-0.134 ± 0.092	-0.107 ± 0.079	-0.130 ± 0.095	-0.146 ± 0.079	-0.133 ± 0.097	-0.066 ± 0.069	-0.112 ± 0.087	-0.147 ± 0.099	-0.133 ± 0.091	-0.087 ± 0.076	-0.122 ± 0.091	$F(2, 54) = 0.339, p = 0.714, \text{partial } \eta^2 = 0.012 [0.000, 0.068]$	$F(2, 54) = 2.453, p = 0.096, \text{partial } \eta^2 = 0.083 [0.000, 0.195]$	$F(1, 54) = 0.365, p = 0.548, \text{partial } \eta^2 = 0.007 [0.002, 0.081]$
<b>Range internal</b>	0.529 ± 0.142	0.558 ± 0.155	0.581 ± 0.150	0.555 ± 0.146	0.626 ± 0.112 <sup>#</sup>	0.523 ± 0.145	0.442 ± 0.088	0.524 ± 0.136	0.568 ± 0.137	0.541 ± 0.147	0.515 ± 0.141	0.541 ± 0.141	<b><math>F(2, 54) = 3.804, p = 0.028, \text{partial } \eta^2 = 0.028, \text{partial } \eta^2 = 0.028</math></b>	$F(2, 54) = 1.184, p =$	$F(1, 54) = 0.537, p =$

<b>rotation moment (Nm/kg)</b>													<b>= 0.123 [0.007, 0.245]</b>	0.314, partial $\eta^2 = 0.420$ [0.000, 0.133]	0.467, partial $\eta^2 = 0.010$ [0.000, 0.091]
<b>Max internal rotation moment (Nm/kg/m)</b>	0.275 ± 0.122	0.250 ± 0.092	0.265 ± 0.080	0.264 ± 0.098	0.336 ± 0.110	0.236 ± 0.095	0.230 ± 0.078	0.264 ± 0.102	0.299 ± 0.118	0.243 ± 0.091	0.249 ± 0.079	0.264 ± 0.099	$F(2, 54) = 1.324, p = 0.274$ , partial $\eta^2 = 0.047$ [0.000, 0.141]	$F(2, 54) = 2.436, p = 0.097$ , partial $\eta^2 = 0.083$ [0.000, 0.194]	$F(1, 54) = 0.026, p = 0.872$ , partial $\eta^2 = 0.000$ [0.000, 0.033]
<b>Min internal rotation moment (Nm/kg/m)</b>	-0.108 ± 0.083	-0.079 ± 0.054	-0.060 ± 0.045	-0.083 ± 0.065	-0.101 ± 0.055	-0.083 ± 0.061	-0.043 ± 0.051	-0.073 ± 0.059	-0.105 ± 0.072 <sup>^#</sup>	-0.081 ± 0.056	-0.052 ± 0.047	-0.079 ± 0.062	$F(2, 54) = 0.154, p = 0.857$ , partial $\eta^2 = 0.006$ [0.000, 0.038]	<b><math>F(2, 54) = 3.878, p = 0.027</math>, partial <math>\eta^2 = 0.126</math> [0.008, 0.248]</b>	$F(1, 54) = 0.184, p = 0.670$ , partial $\eta^2 = 0.003$ [0.000, 0.067]
<b>Range internal rotation moment (Nm/kg/m)</b>	0.382 ± 0.099	0.329 ± 0.086	0.326 ± 0.082	0.347 ± 0.091	0.437 ± 0.090	0.319 ± 0.088	0.273 ± 0.054	0.337 ± 0.102	0.404 ± 0.097 <sup>^#</sup>	0.324 ± 0.085	0.301 ± 0.075	0.343 ± 0.095	$F(2, 54) = 2.028, p = 0.141$ , partial $\eta^2 = 0.070$ [0.000, 0.176]	<b><math>F(2, 54) = 9.220, p &lt; 0.001</math>, partial <math>\eta^2 = 0.255</math> [0.087, 0.384]</b>	$F(1, 54) = 0.014, p = 0.906$ , partial $\eta^2 = 0.000$ [0.000, 0.022]

Key: **Bold** =  $p < 0.05$ . \* = higher than pre, ^ higher than mid, # higher than post, “ = higher than M total, ‘ = higher than F today, † = higher than M in same maturation stage, ‡ = higher than F in same maturation stage.

**Appendix AB** CUT task all calculated knee angles (°) and moments (Nm) of the dominant limb according to sex and maturation stage. All variables are presented as mean ± SD.

Sex	M				F				Total				Interaction effect sex*maturation	Main effect Maturation	Main effect Sex
	Pre	Mid	Post	Total M	Pre	Mid	Post	Total F	Pre	Mid	Post	Total			
<b>Maturation group</b>															
<b>Max flexion angle (°)</b>	64.491 ± 7.615	65.076 ± 8.811	62.465 ± 6.685	64.072 ± 7.614	65.710 ± 7.690	63.133 ± 4.390	67.886 ± 7.249	65.661 ± 6.728	65.045 ± 7.494	64.202 ± 7.068	65.175 ± 7.334	64.815 ± 7.199	F(2, 56) = 1.278, p = 0.287, partial η <sup>2</sup> = 0.044 [0.000, 0.134]	F(2, 56) = 0.135, p = 0.874, partial η <sup>2</sup> = 0.005 [0.000, 0.033]	F(1, 56) = 0.709, p = 0.403, partial η <sup>2</sup> = 0.013 [0.000, 0.096]
<b>Min flexion angle (°)</b>	14.251 ± 4.402	18.888 ± 5.397	16.837 ± 7.654	16.580 ± 6.011	15.568 ± 4.859	16.998 ± 3.726	18.244 ± 5.098	16.934 ± 4.603	14.849 ± 4.552	18.037 ± 4.702	17.540 ± 6.371	16.746 ± 5.358	F(2, 56) = 0.625, p = 0.539, partial η <sup>2</sup> = 0.022 [0.000, 0.092]	F(2, 56) = 2.019, p = 0.142, partial η <sup>2</sup> = 0.067 [0.000, 0.175]	F(1, 56) = 0.042, p = 0.839, partial η <sup>2</sup> = 0.001 [0.000, 0.039]
<b>Range flexion angle (°)</b>	50.240 ± 6.946	46.188 ± 5.740	45.628 ± 6.591	47.492 ± 6.603	50.142 ± 6.970	46.135 ± 5.314	49.642 ± 4.731	48.726 ± 5.835	50.195 ± 6.789	46.164 ± 5.407	47.635 ± 5.951	48.069 ± 6.236	F(2, 56) = 0.748, p = 0.478, partial η <sup>2</sup> = 0.026 [0.000, 0.101]	F(2, 56) = 2.303, p = 0.109, partial η <sup>2</sup> = 0.076 [0.000, 0.183]	F(1, 56) = 0.675, p = 0.415, partial η <sup>2</sup> = 0.012 [0.000, 0.095]
<b>Max flexion moment (Nm/kg)</b>	0.580 ± 0.254	0.457 ± 0.189	0.561 ± 0.283	0.533 ± 0.243	0.618 ± 0.221	0.577 ± 0.369	0.618 ± 0.221	0.500 ± 0.280	0.597 ± 0.235	0.511 ± 0.287	0.437 ± 0.247	0.518 ± 0.259	F(2, 56) = 3.072, p = 0.054, partial η <sup>2</sup> = 0.099 [0.000, 0.213]	F(2, 56) = 2.239, p = 0.116, partial η <sup>2</sup> = 0.074 [0.000, 0.180]	F(1, 56) = 0.236, p = 0.629, partial η <sup>2</sup> = 0.004

																	[0.000, 0.070]
<b>Min flexion moment (Nm/kg)</b>	-2.467 ± 0.424	-3.238 ± 0.610	-3.030 ± 0.643	-2.894 ± 0.640	-2.601 ± 0.611	-3.069 ± 0.397	-3.024 ± 0.519	-2.892 ± 0.546	-2.528 ± 0.593 <sup>^</sup> #	-3.162 ± 0.519	-3.027 ± 0.569	-2.893 ± 0.593	F(2, 56) = 0.407, p = 0.668, partial η <sup>2</sup> = 0.014 [0.000, 0.073]	<b>F(2, 56) = 7.678, p = 0.001, partial η<sup>2</sup> = 0.215 [0.061, 0.343]</b>	F(1, 56) = 0.009, p = 0.924, partial η <sup>2</sup> = 0.000 [0.000, 0.014]		
<b>Range flexion moment (Nm/kg)</b>	3.046 ± 0.450	3.695 ± 0.534	3.592 ± 0.716	3.428 ± 0.625	3.220 ± 0.738	3.645 ± 0.392	3.336 ± 0.473	3.392 ± 0.568	3.125 ± 0.589	3.673 ± 0.465*	3.464 ± 0.605	3.411 ± 0.595	F(2, 56) = 0.756, p = 0.474, partial η <sup>2</sup> = 0.026 [0.000, 0.102]	<b>F(2, 56) = 4.819, p = 0.012, partial η<sup>2</sup> = 0.147 [0.020, 0.270]</b>	F(1, 56) = 0.093, p = 0.761, partial η <sup>2</sup> = 0.002 [0.000, 0.053]		
<b>Max flexion moment (Nm/kg/m)</b>	0.429 ± 0.202	0.275 ± 0.125	0.314 ± 0.155	0.343 ± 0.174	0.436 ± 0.137	0.353 ± 0.221	0.193 ± 0.073	0.327 ± 0.181	0.432 ± 0.172 <sup>^</sup> #	0.310 ± 0.175	0.254 ± 0.1333	0.335 ± 0.176	F(2, 56) = 1.983, p = 0.147, partial η <sup>2</sup> = 0.066 [0.000, 0.169]	<b>F(2, 56) = 6.825, p = 0.002, partial η<sup>2</sup> = 0.196 [0.048, 0.323]</b>	F(1, 56) = 0.087, p = 0.769, partial η <sup>2</sup> = 0.002 [0.000, 0.052]		
<b>Min flexion moment (Nm/kg/m)</b>	-1.791 ± 0.243	-1.902 ± 0.264	-1.700 ± 0.366	-1.800 ± 0.294	-1.847 ± 0.315	-1.877 ± 0.263	-1.870 ± 0.337	-1.864 ± 0.318	-1.816 ± 0.303	-1.891 ± 0.257	-1.785 ± 0.353	-1.830 ± 0.305	F(2, 56) = 0.493, p = 0.613, partial η <sup>2</sup> = 0.017 [0.000, 0.081]	F(2, 56) = 0.585, p = 0.560, partial η <sup>2</sup> = 0.020 [0.000, 0.089]	F(1, 56) = 0.722, p = 0.399, partial η <sup>2</sup> = 0.013 [0.000, 0.097]		
<b>Range flexion moment (Nm/kg/m)</b>	2.219 ± 0.319	2.177 ± 0.243	2.015 ± 0.401	2.143 ± 0.319	2.284 ± 0.434	2.230 ± 0.260	2.063 ± 0.318	2.191 ± 0.349	2.249 ± 0.367	2.201 ± 0.245	2.039 ± 0.353	2.166 ± 0.335	F(2, 56) = 0.003, p = 0.997, partial η <sup>2</sup> = 0.000 [0.000, 0.000]	F(2, 56) = 2.265, p = 0.113, partial η <sup>2</sup> = 0.075 [0.000, 0.181]	F(1, 56) = 0.417, p = 0.521, partial η <sup>2</sup> = 0.007		

																	[0.000, 0.082]
<b>Max abduction angle (°)</b>	10.464 ± 6.031	8.917 ± 2.686	7.848 ± 6.692	9.155 ± 5.343	8.841 ± 2.903	9.929 ± 4.128	8.205 ± 6.497	8.959 ± 4.654	9.726 ± 4.832	9.373 ± 3.352	8.026 ± 6.422	9.064 ± 4.993	F(2, 56) = 0.191, p = 0.827, partial η <sup>2</sup> = 0.007 [0.000, 0.044]	F(2, 56) = 1.338, p = 0.271, partial η <sup>2</sup> = 0.046 [0.000, 0.137]	F(1, 56) = 0.004, p = 0.986, partial η <sup>2</sup> = 0.000 [0.000, 0.000]		
<b>Min abduction angle (°)</b>	0.791 ± 3.333	-0.318 ± 2.388	-2.922 ± 4.730	-0.704 ± 3.785	-0.259 ± 3.260	-0.498 ± 2.828	-1.991 ± 4.689	-0.931 ± 3.659	0.314 ± 3.265	-0.399 ± 2.526	-2.457 ± 4.609	-0.704 ± 3.785	F(2, 56) = 0.389, p = 0.679, partial η <sup>2</sup> = 0.014 [0.000, 0.071]	F(2, 56) = 3.135, p = 0.051, partial η <sup>2</sup> = 0.101 [0.000, 0.216]	F(1, 56) = 0.012, p = 0.915, partial η <sup>2</sup> = 0.000 [0.000, 0.019]		
<b>Range abduction angle (°)</b>	9.673 ± 4.723	9.235 ± 3.122	10.770 ± 3.559	9.859 ± 3.832	9.100 ± 2.083	10.427 ± 2.631	10.197 ± 3.037	9.890 ± 2.586	9.412 ± 3.692	9.772 ± 2.901	10.483 ± 3.234	9.874 ± 3.282	F(2, 56) = 0.462, p = 0.632, partial η <sup>2</sup> = 0.016 [0.000, 0.078]	F(2, 56) = 0.558, p = 0.575, partial η <sup>2</sup> = 0.020 [0.000, 0.087]	F(1, 56) = 0.000, p = 0.986, partial η <sup>2</sup> = 0.000 [0.000, 0.000]		
<b>Max abduction moment (Nm/kg)</b>	0.489 ± 0.181	0.588 ± 0.146	0.702 ± 0.348	0.587 ± 0.244	0.554 ± 0.257	0.534 ± 0.280	0.523 ± 0.304	0.537 ± 0.271	0.518 ± 0.216	0.564 ± 0.212	0.613 ± 0.331	0.563 ± 0.256	F(2, 56) = 1.168, p = 0.318, partial η <sup>2</sup> = 0.040 [0.000, 0.128]	F(2, 56) = 0.657, p = 0.522, partial η <sup>2</sup> = 0.023 [0.000, 0.095]	F(1, 56) = 0.727, p = 0.397, partial η <sup>2</sup> = 0.013 [0.000, 0.097]		
<b>Min abduction moment (Nm/kg)</b>	-0.635 ± 0.250	-0.438 ± 0.260	-0.351 ± 0.333	-0.478 ± 0.305	-0.473 ± 0.318	-0.525 ± 0.350	-0.458 ± 0.359	-0.473 ± 0.318	-0.547 ± 0.271	-0.477 ± 0.298	-0.405 ± 0.342	-0.478 ± 0.305	F(2, 56) = 1.638, p = 0.204, partial η <sup>2</sup> = 0.055 [0.000, 0.153]	F(2, 56) = 1.006, p = 0.372, partial η <sup>2</sup> = 0.035 [0.000, 0.118]	F(1, 56) = 0.000, p = 1.000, partial η <sup>2</sup> = 0.000		

																	[0.000, 0.000]
<b>Range</b>	1.124 ±	1.026 ±	1.053 ±	1.070 ±	0.994 ±	1.059 ±	0.982 ±	1.010 ±	1.065 ±	1.041 ±	1.018 ±	1.042 ±	F(2, 56) = 0.447,	F(2, 56) = 0.117,	F(1, 56) =		
<b>abduction moment (Nm/kg)</b>	0.237	0.303	0.358	0.293	0.216	0.240	0.298	0.247	0.232	0.270	0.322	0.272	p = 0.642, partial η <sup>2</sup> = 0.016 [0.000, 0.078]	p = 0.890, partial η <sup>2</sup> = 0.004 [0.000, 0.028]	0.618, p = 0.435, partial η <sup>2</sup> = 0.011 [0.000, 0.092]		
<b>Max</b>	0.360 ±	0.351 ±	0.390 ±	0.366 ±	0.398 ±	0.320 ±	0.319 ±	0.347 ±	0.377 ±	0.337 ±	0.355 ±	0.357 ±	F(2, 56) = 0.614,	F(2, 56) = 0.375,	F(1, 56) =		
<b>abduction moment (Nm/kg/m)</b>	0.141	0.101	0.185	0.141	0.185	0.160	0.187	0.176	0.159	0.128	0.184	0.157	p = 0.545, partial η <sup>2</sup> = 0.021 [0.000, 0.091]	p = 0.689, partial η <sup>2</sup> = 0.013 [0.000, 0.070]	0.271, p = 0.604, partial η <sup>2</sup> = 0.005 [0.000, 0.072]		
<b>Min</b>	-0.464	-0.255	-0.197	-0.314	-0.310	-0.330	-0.290	-0.309	-0.394	-0.288	-0.244	-0.394	F(2, 56) = 2.587,	F(2, 56) = 2.901,	F(1, 56) =		
<b>abduction moment (Nm/kg/m)</b>	± 0.186	± 0.143	± 0.186	± 0.204	± 0.188	± 0.238	± 0.237	± 0.214	± 0.199	± 0.190	± 0.219	± 0.199	p = 0.084, partial η <sup>2</sup> = 0.085 [0.000, 0.195]	p = 0.063, partial η <sup>2</sup> = 0.094 [0.000, 0.207]	0.008, p = 0.928, partial η <sup>2</sup> = 0.000 [0.000, 0.012]		
<b>Range</b>	0.824 ±	0.607 ±	0.588 ±	0.680 ±	0.708	0.650 ±	0.610 ±	0.656 ±	0.772 ±	0.626 ±	0.599 ±	0.669 ±	F(2, 56) = 1.245,	<b>F(2, 56) = 5.311,</b>	F(1, 56) =		
<b>abduction moment (Nm/kg/m)</b>	0.200	0.176	0.185	0.213	±0.141	0.166	0.190	0.166	0.182 <sup>#</sup>	0.168	0.182	0.191	p = 0.296, partial η <sup>2</sup> = 0.043 [0.000, 0.132]	<b>p = 0.008, partial η<sup>2</sup> = 0.159 [0.027, 0.284]</b>	0.137, p = 0.712, partial η <sup>2</sup> = 0.002 [0.000, 0.059]		
<b>Max internal rotation angle (°)</b>	8.397 ±	8.521 ±	7.833 ±	8.267 ±	4.741 ±	8.422 ±	9.114 ±	7.391 ±	6.735 ±	8.477 ±	8.474 ±	7.858 ±	F(2, 56) = 0.752,	F(2, 56) = 0.562,	F(1, 56) =		
	5.523	7.049	7.498	6.474	6.007	6.573	7.725	6.858	5.909	6.659	7.438	6.616	p = 0.476, partial η <sup>2</sup> = 0.026 [0.000, 0.102]	p = 0.573, partial η <sup>2</sup> = 0.020 [0.000, 0.087]	0.230, p = 0.633, partial η <sup>2</sup> = 0.004		

																	[0.000, 0.069]
<b>Min internal rotation angle (°)</b>	-4.965 ± 5.847	-5.810 ± 4.977	-6.324 ± 9.356	-5.659 ± 6.667	-8.599 ± 6.337	-7.398 ± 6.580	-6.377 ± 7.251	-7.460 ± 6.562	-6.617 ± 6.209	-6.525 ± 5.650	-6.351 ± 8.147	-6.501 ± 6.626	F(2, 56) = 0.365, p = 0.696, partial $\eta^2$ = 0.013 [0.000, 0.068]	F(2, 56) = 0.021, p = 0.979, partial $\eta^2$ = 0.001 [0.000, 0.000]	F(1, 56) = 1.027, p = 0.315, partial $\eta^2$ = 0.018 [0.000, 0.109]		
<b>Range internal rotation angle (°)</b>	13.362 ± 4.183	14.332 ± 5.113	14.157 ± 4.738	13.926 ± 4.549	13.340 ± 4.784	15.820 ± 7.969	15.492 ± 2.645	14.852 ± 5.386	13.352 ± 4.356	15.001 ± 6.409	14.824 ± 3.797	14.359 ± 4.938	F(2, 56) = 0.143, p = 0.867, partial $\eta^2$ = 0.005 [0.000, 0.034]	F(2, 56) = 0.716, p = 0.493, partial $\eta^2$ = 0.025 [0.000, 0.099]	F(1, 56) = 0.524, p = 0.472, partial $\eta^2$ = 0.009 [0.000, 0.088]		
<b>Max internal rotation moment (Nm/kg)</b>	0.380 ± 0.138	0.448 ± 0.122	0.430 ± 0.149	0.418 ± 0.135	0.466 ± 0.128	0.372 ± 0.139	0.404 ± 0.149	0.416 ± 0.139	0.419 ± 0.137	0.414 ± 0.132	0.417 ± 0.145	0.417 ± 0.136	F(2, 56) = 1.912, p = 0.157, partial $\eta^2$ = 0.064 [0.000, 0.166]	F(2, 56) = 0.047, p = 0.954, partial $\eta^2$ = 0.002 [0.000, 0.000]	F(1, 56) = 0.023, p = 0.880, partial $\eta^2$ = 0.000 [0.000, 0.030]		
<b>Min internal rotation moment (Nm/kg)</b>	-0.137 ± 0.083	-0.138 ± 0.113	-0.129 ± 0.127	-0.135 ± 0.104	-0.139 ± 0.102	-0.125 ± 0.089	-0.108 ± 0.138	-0.124 ± 0.102	-0.137 ± 0.083	-0.138 ± 0.113	-0.129 ± 0.127	-0.135 ± 0.104	F(2, 56) = 0.065, p = 0.937, partial $\eta^2$ = 0.002 [0.000, 0.008]	F(2, 56) = 0.190, p = 0.828, partial $\eta^2$ = 0.007 [0.000, 0.442]	F(1, 56) = 0.149, p = 0.701, partial $\eta^2$ = 0.003 [0.000, 0.061]		
<b>Range internal rotation</b>	0.517 ± 0.126	0.586 ± 0.134	0.559 ± 0.139	0.553 ± 0.132	0.606 ± 0.105	0.497 ± 0.109	0.512 ± 0.110	0.539 ± 0.115	0.557 ± 0.123	0.546 ± 0.129	0.535 ± 0.129	0.546 ± 0.124	F(2, 56) = 3.031, p = 0.056, partial $\eta^2$ = 0.098 [0.000, 0.212]	F(2, 56) = 0.270, p = 0.765, partial $\eta^2$ = 0.010 [0.000, 0.057]	F(1, 56) = 0.257, p = 0.614, partial $\eta^2$ = 0.005		

<b>moment</b> <b>(Nm/kg)</b>															[0.000, 0.071]
<b>Max internal</b> <b>rotation</b> <b>moment</b> <b>(Nm/kg/m)</b>	0.279 ± 0.105	0.265 ± 0.069	0.240 ± 0.080	0.263 ± 0.086	0.335 ± 0.098	0.225 ± 0.079	0.248 ± 0.089	0.271 ± 0.099	0.305 ± 0.103 <sup>^</sup> #	0.247 ± 0.074	0.244 ± 0.082	0.267 ± 0.091	F(2, 56) = 1.531, p = 0.225, partial η <sup>2</sup> = 0.052 [0.000, 0.148]	<b>F(2, 56) = 3.571,</b> <b>p = 0.035, partial</b> <b>η<sup>2</sup> = 0.113</b> <b>[0.005, 0.231]</b>	F(1, 56) = 0.134, p = 0.716, partial η <sup>2</sup> = 0.002 [0.000, 0.059]
<b>Min internal</b> <b>rotation</b> <b>moment</b> <b>(Nm/kg/m)</b>	-0.099 ± 0.057	-0.081 ± 0.067	-0.073 ± 0.073	-0.085 ± 0.065	-0.099 ± 0.055	-0.077 ± 0.055	-0.067 ± 0.089	-0.082 ± 0.065	-0.099 ± 0.055	-0.079 ± 0.060	-0.071 ± 0.079	-0.083 ± 0.065	F(2, 56) = 0.009, p = 0.991, partial η <sup>2</sup> = 0.000 [0.000, 0.000]	F(2, 56) = 0.991, p = 0.377, partial η <sup>2</sup> = 0.034 [0.000, 0.117]	F(1, 56) = 0.027, p = 0.871, partial η <sup>2</sup> = 0.000 [0.000, 0.032]
<b>Range</b> <b>internal</b> <b>rotation</b> <b>moment</b> <b>(Nm/kg/m)</b>	0.378 ± 0.094	0.346 ± 0.078	0.313 ± 0.076	0.348 ± 0.085	0.302 ± 0.316	0.316 ± 0.071	0.434 ± 0.070	0.353 ± 0.091	0.404 ± 0.090 <sup>^</sup> #	0.326 ± 0.072	0.315 ± 0.072	0.350 ± 0.087	F(2, 56) = 2.171, p = 0.124, partial η <sup>2</sup> = 0.072 [0.000, 0.177]	<b>F(2, 56) = 8.835,</b> <b>p &lt; 0.001, partial</b> <b>η<sup>2</sup> = 0.240 [0.79,</b> <b>0.368]</b>	F(1, 56) = 0.074, p = 0.786, partial η <sup>2</sup> = 0.001 [0.000, 0.049]

Key: **Bold** =  $p < 0.05$ . \* = higher than pre, ^ higher than mid, # higher than post, “ = higher than M total, ‘ = higher than F today, † = higher than M in same maturation stage, ¨ = higher than F in same maturation stage.

**Appendix AC** CUT task all calculated knee angles (°) and moments (Nm) of the non-dominant limb according to sex and maturation stage. All variables are presented as mean ± SD.

Sex	M				F				Total				Interaction effect sex*maturation	Main effect Maturation	Main effect Sex	
	Maturation group	Pre	Mid	Post	Total M	Pre	Mid	Post	Total F	Pre	Mid	Post				Total
	<b>Max flexion angle (°)</b>	60.377 ± 9.717	62.443 ± 7.296	60.835 ± 10.341	61.640 ± 9.717	63.887 ± 9.098	58.826 ± 5.937	66.373 ± 5.995	63.148 ± 7.564	61.640 ± 9.463	60.815 ± 6.802	63.911 ± 9.463	62.027 ± 8.361	F(2, 57) = 1.612, p = 0.209, partial $\eta^2 = 0.054$ [0.000, 0.149]	F(2, 57) = 0.595, p = 0.555, partial $\eta^2 = 0.020$ [0.000, 0.900]	F(1, 57) = 0.706, p = 0.404, partial $\eta^2 = 0.012$ [0.000, 0.095]
	<b>Min flexion angle (°)</b>	12.918 ± 7.233	15.455 ± 5.020	16.061± 8.219	14.433 ± 6.819	14.199 ± 3.041	12.581 ± 3.376	18.164 ± 5.712	15.095 ± 4.781	13.379 ± 6.014	14.162 ± 4.496	17.229 ± 6.800	14.728 ± 5.961	F(2, 57) = 1.007, p = 0.372, partial $\eta^2 = 0.034$ [0.000, 0.117]	F(2, 57) = 2.064, p = 0.136, partial $\eta^2 = 0.068$ [0.000, 0.173]	F(1, 57) = 0.013, p = 0.911, partial $\eta^2 = 0.000$ [0.000, 0.020]
	<b>Range flexion angle (°)</b>	47.698 ± 7.547	46.989 ± 3.727	44.774 ± 10.402	48.052 ± 6.046	49.687 ± 6.046	46.244 ± 5.731	48.208 ± 3.797	48.052 ± 6.046	48.261 ± 7.702	46.654 ± 4.614	46.682 ± 7.434	47.300 ± 6.727	F(2, 57) = 0.690, p = 0.506, partial $\eta^2 = 0.024$ [0.000, 0.096]	F(2, 57) = 0.504, p = 0.607, partial $\eta^2 = 0.017$ [0.000, 0.081]	F(1, 57) = 1.042, p = 0.312, partial $\eta^2 = 0.018$ [0.000, 0.108]
	<b>Max flexion moment (Nm/kg)</b>	0.625 ± 0.178	0.648 ± 0.118	0.742 ± 0.097	0.659 ± 0.149	0.595 ± 0.188	0.662 ± 0.172	0.523 ± 0.156	0.591 ± 0.175	0.614 ± 0.178	0.654 ± 0.141	0.620 ± 0.171	0.629 ± 0.164	F(2, 57) = 2.842, p = 0.067, partial $\eta^2 = 0.091$ [0.000, 0.202]	F(2, 57) = 0.435, p = 0.650, partial $\eta^2 = 0.015$ [0.000, 0.076]	F(1, 57) = 3.682, p = 0.060, partial $\eta^2 = 0.061$

																[0.000, 0.179]
<b>Min flexion moment (Nm/kg)</b>	-2.038 ± 0.599	-2.657 ± 0.387	-2.651 ± 0.962	-2.373 ± 0.700	-2.515 ± 0.537	-2.623 ± 0.358	-2.601 ± 0.454	-2.581 ± 0.441	-2.210 ± 0.612	-2.641 ± 0.365	-2.623 ± 0.701	-2.465 ± 0.603	F(2, 57) = 1.758, p = 0.182, partial $\eta^2$ = 0.058 [0.000, 0.156]	F(2, 57) = 2.966, p = 0.060, partial $\eta^2$ = 0.094 [0.000, 0.206]	F(1, 57) = 0.202, p = 0.655, partial $\eta^2$ = 0.004 [0.000, 0.065]	
<b>Range flexion moment (Nm/kg)</b>	2.692 ± 0.673	3.305 ± 0.448	3.392 ± 0.970	3.045 ± 0.749	3.110 ± 0.664	3.285 ± 0.368	3.125 ± 0.512	3.171 ± 0.448	2.843 ± 0.687	3.296 ± 0.403	3.244 ± 0.738	3.101 ± 0.653	F(2, 57) = 2.249, p = 0.115, partial $\eta^2$ = 0.073 [0.000, 0.178]	F(2, 57) = 2.687, p = 0.077, partial $\eta^2$ = 0.086 [0.000, 0.196]	F(1, 57) = 0.052, p = 0.820, partial $\eta^2$ = 0.001 [0.000, 0.042]	
<b>Max flexion moment (Nm/kg/m)</b>	0.455 ± 0.143	0.381 ± 0.055	0.420 ± 0.059	0.424 ± 0.108	0.417 ± 0.118	0.404 ± 0.099	0.324 ± 0.099	0.380 ± 0.110	0.441 ± 0.133	0.391 ± 0.076	0.367 ± 0.095	0.404 ± 0.119	F(2, 57) = 1.458, p = 0.241, partial $\eta^2$ = 0.049 [0.000, 0.142]	F(2, 57) = 1.995, p = 0.145, partial $\eta^2$ = 0.065 [0.000, 0.170]	F(1, 57) = 1.847, p = 0.179, partial $\eta^2$ = 0.031 [0.000, 0.133]	
<b>Min flexion moment (Nm/kg/m)</b>	-1.479 ± 0.413	-1.567 ± 0.187	-1.497 ± 0.413	-1.511 ± 0.382	-1.770 ± 0.300	-1.601 ± 0.214	-1.609 ± 0.291	-1.658 ± 0.273	-1.584 ± 0.396	-1.583 ± 0.195	-1.559 ± 0.408	-1.576 ± 0.343	F(2, 57) = 0.863, p = 0.428, partial $\eta^2$ = 0.029 [0.000, 0.108]	F(2, 57) = 0.271, p = 0.764, partial $\eta^2$ = 0.009 [0.000, 0.056]	F(1, 57) = 2.433, p = 0.124, partial $\eta^2$ = 0.041 [0.000, 0.149]	
<b>Range flexion moment (Nm/kg/m)</b>	1.936 ± 0.444	1.948 ± 0.199	1.917 ± 0.540	1.935 ± 0.399	2.187 ± 0.362	2.005 ± 0.208	1.933 ± 0.333	2.038 ± 0.317	2.026 ± 0.427	1.974 ± 0.200	1.926 ± 0.423	1.981 ± 0.365	F(2, 57) = 0.877, p = 0.421, partial $\eta^2$ = 0.030 [0.000, 0.109]	F(2, 57) = 1.024, p = 0.366, partial $\eta^2$ = 0.030 [0.000, 0.109]	F(1, 57) = 1.129, p = 0.292, partial $\eta^2$ = 0.019 [0.000, 0.109]	

														$\eta^2 = 0.035$	[0.000,
														[0.000, 0.118]	0.124]
<b>Max</b>	11.056	7.897 ±	6.232 ±	8.960 ±	10.444	8.691 ±	8.009 ±	9.011 ±	10.835	8.254 ±	7.219 ±	8.983 ±	F(2, 57) = 0.194,	F(2, 57) =	F(1, 57) =
<b>abduction</b>	± 6.519	6.642	4.254	6.296	± 5.679	5.567	7.095	6.050	± 6.116	6.036	5.910	6.138	p = 0.824, partial	1.875, p =	0.168, p =
<b>angle (°)</b>													$\eta^2 = 0.007$ [0.000,	0.163, partial	0.683, partial
													0.044]	$\eta^2 = 0.062$	$\eta^2 = 0.003$
														[0.000, 0.164]	[0.000,
															0.062]
<b>Min</b>	0.739 ±	-2.054	-2.158 ±	-0.801	-0.190	-2.171	-3.657	-2.065	0.404 ±	-2.107	-2.990	-1.363	F(2, 57) = 0.149,	<b>F(2, 57) =</b>	F(1, 57) =
<b>abduction</b>	3.602	± 3.798	3.798	± 3.842	± 4.118	± 3.769	± 4.634	± 4.302	3.737 <sup>#</sup>	± 3.685	± 4.175	± 4.069	p = 0.862, partial	<b>3.746, p =</b>	0.703, p =
<b>angle (°)</b>													$\eta^2 = 0.005$ [0.000,	<b>0.030, partial</b>	0.405, partial
													0.035]	<b><math>\eta^2 = 0.116</math></b>	$\eta^2 = 0.012$
														<b>[0.006, 0.234]</b>	[0.000,
															0.094]
<b>Range</b>	10.317	9.951 ±	8.389 ±	9.761 ±	10.634	10.862	11.665	11.076	10.431	10.361	10.209	10.346	F(2, 57) = 0.942,	F(2, 57) =	F(1, 57) =
<b>abduction</b>	±	3.219	3.492	3.800	± 2.960	± 2.959	± 3.370	± 3.031	± 3.831	± 3.059	± 3.720	± 3.515	p = 0.396, partial	0.089, p =	2.701, p =
<b>angle (°)</b>	4.333												$\eta^2 = 0.032$ [0.000,	0.915, partial	0.106, partial
													0.113]	$\eta^2 = 0.003$	$\eta^2 = 0.045$
														[0.000, 0.018]	[0.000,
															0.156]
<b>Max</b>	0.514	0.741 ±	0.568 ±	0.598 ±	0.583 ±	0.601 ±	0.561 ±	0.581 ±	0.538 ±	0.678 ±	0.564 ±	0.590 ±	F(2, 57) = 1.051,	F(2, 57) =	F(1, 57) =
<b>abduction</b>	±	0.193	0.206	0.228	0.216	0.320	0.257	0.258	0.220	0.260	0.229	0.240	p = 0.356, partial	1.612, p =	0.186, p =
<b>moment</b>	0.225												$\eta^2 = 0.036$ [0.000,	0.208, partial	0.668, partial
<b>(Nm/kg)</b>													0.119]	$\eta^2 = 0.054$	$\eta^2 = 0.003$
														[0.000, 0.151]	[0.000,
															0.064]
<b>Min</b>	-0.496	-0.391	-0.243 ±	-0.406	-0.504	-0.340	-0.316	-0.384	-0.499	-0.368	-0.284	-0.396 ±	F(2, 57) = 0.269,	<b>F(2, 57) =</b>	F(1, 57) =
<b>abduction</b>	±	± 0.332	0.181	± 0.289	± 0.222	± 0.301	± 0.153	± 0.238	± 0.255	± 0.311	±	0.266	p = 0.765, partial	<b>3.766, p =</b>	0.021, p =
<b>moment</b>	0.279												$\eta^2 = 0.009$ [0.000,	<b>0.029, partial</b>	0.886, partial
<b>(Nm/kg)</b>													0.056]		$\eta^2 = 0.000$

														$\eta^2 = 0.177$	[0.000,
														<b>[0.007, 0.234]</b>	0.028]
<b>Range</b>	1.010	1.133 ±	0.811 ±	1.003 ±	1.086 ±	0.941 ±	0.877 ±	0.965 ±	1.037 ±	1.046 ±	0.848 ±	0.986 ±	F(2, 57) = 1.206,	<b>F(2, 57) =</b>	F(1, 57) =
<b>abduction</b>	±	0.230	0.271	0.315	0.145	0.341	0.203	0.250	0.293 <sup>#</sup>	0.294 <sup>#</sup>	0.231	0.287	p = 0.307, partial	<b>3.324, p =</b>	0.138, p =
<b>moment</b>	0.352												$\eta^2 = 0.041$ [0.000,	<b>0.043, partial</b>	0.711, partial
<b>(Nm/kg)</b>													0.128]	<b><math>\eta^2 = 0.104</math></b>	$\eta^2 = 0.002$
														<b>[0.007, 0.234]</b>	[0.000,
															0.059]
<b>Max</b>	0.383	0.448 ±	0.321 ±	0.389 ±	0.428 ±	0.362 ±	0.346 ±	0.377 ±	0.399 ±	0.409 ±	0.335 ±	0.384 ±	F(2, 57) = 1.005,	F(2, 57) =	F(1, 57) =
<b>abduction</b>	±	0.115	0.116	0.154	0.181	0.170	0.168	0.167	0.180	0.145	0.137	0.159	p = 0.372, partial	1.266, p =	0.020, p =
<b>moment</b>	0.154												$\eta^2 = 0.034$ [0.000,	0.290, partial	0.888, partial
<b>(Nm/kg/m)</b>													0.117]	$\eta^2 = 0.043$	$\eta^2 = 0.000$
														[0.000, 0.134]	[0.000,
															0.027]
<b>Min</b>	-0.361	-0.236	-0.138 ±	-0.271	-0.361	-0.209	-0.198	-0.254	-0.361	-0.224	-0.171	-0.263 ±	F(2, 57) = 0.302,	<b>F(2, 57) =</b>	F(1, 57) =
<b>abduction</b>	±	± 0.207	0.103	± 0.205	± 0.168	± 0.187	± 0.100	± 0.166	± 0.190	±	±	0.187	p = 0.740, partial	<b>6.756, p =</b>	0.055, p =
<b>moment</b>	0.207									0.193*	0.103*		$\eta^2 = 0.010$ [0.000,	<b>0.002, partial</b>	0.816, partial
<b>(Nm/kg/m)</b>													0.060]	<b><math>\eta^2 = 0.192</math></b>	$\eta^2 = 0.001$
														<b>[0.047, 0.318]</b>	[0.000,
															0.043]
<b>Range</b>	0.744	0.685 ±	0.460 ±	0.660 ±	0.789	0.570	0.544 ±	0.631 ±	0.760 ±	0.633 ±	0.506 ±	0.647 ±	F(2, 57) = 1.499,	<b>F(2, 57) =</b>	F(1, 57) =
<b>abduction</b>	±	0.157	0.155	0.236	±0.127	±0.191	0.135	0.184	0.222 <sup>^#</sup>	0.178 <sup>#</sup>	0.146	0.214	p = 0.232, partial	<b>9.896, p &lt;</b>	0.009, p =
<b>moment</b>	0.264												$\eta^2 = 0.050$ [0.000,	<b>0.001, partial</b>	0.923, partial
<b>(Nm/kg/m)</b>													0.144]	<b><math>\eta^2 = 0.258</math></b>	$\eta^2 = 0.000$
														<b>[0.984, 0.384]</b>	[0.000,
															0.014]
<b>Max internal</b>	12.002	10.512	10.489	11.188	10.668	9.435 ±	9.114 ±	9.071 ±	11.522	10.027	9.701 ±	10.527	F(2, 57) = 0.003,	F(2, 57) =	F(1, 57) =
<b>rotation angle</b>	±	± 7.560	± 5.725	± 7.057	± 4.809	7.732	7.725	6.728	± 6.671	± 7.454	6.164	± 6.734	p = 0.997, partial	0.317, p =	0.507, p =
<b>(°)</b>	7.628												$\eta^2 = 0.000$ [0.000,	0.730, partial	0.479, partial
													0.000]		$\eta^2 = 0.009$

														$\eta^2 = 0.011$	[0.000,
														[0.000, 0.063]	0.085]
<b>Min internal rotation angle (°)</b>	-3.383 ± 6.802	-5.009 ± 6.874	-3.230 ± 4.570	-3.859 ± 6.264	-3.570 ± 3.577	-6.239 ± 6.649	-8.726 ± 7.378	-6.270 ± 6.297	-3.450 ± 5.761	-5.563 ± 6.624	-6.283 ± 6.726	-4.930 ± 6.344	F(2, 57) = 0.961, p = 0.389, partial $\eta^2 = 0.033$ [0.000, 0.114]	F(2, 57) = 0.981, p = 0.381, partial $\eta^2 = 0.033$ [0.000, 0.117]	F(1, 57) = 2.010, p = 0.162, partial $\eta^2 = 0.034$ [0.000, 0.138]
<b>Range internal rotation angle (°)</b>	15.385 ± 4.569	15.520 ± 4.111	13.719 ± 6.344	15.047 ± 4.797	14.238 ± 2.931	15.674 ± 4.308	17.797 ± 3.390	15.971 ± 3.760	14.972 ± 4.028	15.590 ± 4.089	15.984 ± 5.197	14.972 ± 4.028	F(2, 57) = 1.883, p = 0.161, partial $\eta^2 = 0.062$ [0.000, 0.162]	F(2, 57) = 0.285, p = 0.753, partial $\eta^2 = 0.010$ [0.000, 0.059]	F(1, 57) = 0.833, p = 0.365, partial $\eta^2 = 0.014$ [0.000, 0.100]
<b>Max internal rotation moment (Nm/kg)</b>	0.316 ± 0.116	0.422 ± 0.133	0.341 ± 0.139	0.355 ± 0.132	0.422 ± 0.157	0.327 ± 0.150	0.372 ± 0.129	0.374 ± 0.142	0.354 ± 0.139	0.379 ± 0.146	0.358 ± 0.130	0.363 ± 0.137	F(2, 57) = 2.987, p = 0.058, partial $\eta^2 = 0.095$ [0.000, 0.207]	F(2, 57) = 0.088, p = 0.916, partial $\eta^2 = 0.003$ [0.000, 0.018]	F(1, 57) = 0.172, p = 0.860, partial $\eta^2 = 0.003$ [0.000, 0.062]
<b>Min internal rotation moment (Nm/kg)</b>	-0.194 ± 0.101	-0.119 ± 0.092	-0.161 ± 0.121	-0.163 ± 0.105	-0.130 ± 0.073	-0.130 ± 0.087	-0.066 ± 0.060 <sup>a</sup>	-0.107 ± 0.077	-0.171 ± 0.095	-0.124 ± 0.088	-0.108 ± 0.101	-0.138 ± 0.097	F(2, 57) = 1.720, p = 0.188, partial $\eta^2 = 0.057$ [0.000, 0.155]	F(2, 57) = 1.623, p = 0.206, partial $\eta^2 = 0.054$ [0.000, 0.152]	<b>F(1, 57) = 4.443, p = 0.039, partial <math>\eta^2 = 0.072</math> [0.002, 0.195]</b>
<b>Range internal rotation</b>	0.510 ± 0.147	0.541 ± 0.170	0.502 ± 0.199	0.518 ± 0.162	0.552 ± 0.142	0.457 ± 0.104	0.438 ± 0.102	0.481 ± 0.123	0.525 ± 0.144	0.503 ± 0.147	0.466 ± 0.151	0.501 ± 0.146	F(2, 57) = 1.153, p = 0.323, partial $\eta^2 = 0.039$ [0.000, 0.125]	F(2, 57) = 0.877, p = 0.422, partial $\eta^2 = 0.015$	F(1, 57) = 0.857, p = 0.358, partial $\eta^2 = 0.015$

<b>moment (Nm/kg)</b>													$\eta^2 = 0.030$	[0.000, 0.101]	
<b>Max internal rotation moment (Nm/kg/m)</b>	0.229 ± 0.083	0.250 ± 0.080	0.192 ± 0.077	0.227 ± 0.081	0.303 ± 0.120	0.199 ± 0.088	0.231 ± 0.081	0.244 ± 0.103	0.256 ± 0.102	0.227 ± 0.085	0.213 ± 0.079	0.235 ± 0.091	F(2, 57) = 2.796, p = 0.069, partial $\eta^2 = 0.089$ [0.000, 0.200]	F(2, 57) = 2.199, p = 0.120, partial $\eta^2 = 0.072$ [0.000, 0.179]	F(1, 57) = 0.779, p = 0.381, partial $\eta^2 = 0.013$ [0.000, 0.098]
<b>Min internal rotation moment (Nm/kg/m)</b>	-0.140 ± 0.070	-0.070 ± 0.052	-0.091 ± 0.068	-0.107 ± 0.070	-0.091 ± 0.048	-0.080 ± 0.054	-0.041 ± 0.036	-0.069 ± 0.050 <sup>”</sup>	-0.122 ± 0.066	-0.075 ± 0.052	-0.063 ± 0.057 <sup>*</sup>	-0.090 ± 0.064	F(2, 57) = 1.816, p = 0.172, partial $\eta^2 = 0.060$ [0.000, 0.159]	<b>F(2, 57) = 4.449, p = 0.016, partial <math>\eta^2 = 0.135</math> [0.015, 0.256]</b>	<b>F(1, 57) = 4.125, p = 0.047, partial <math>\eta^2 = 0.067</math> [0.000, 0.188]</b>
<b>Range internal rotation moment (Nm/kg/m)</b>	0.369 ± 0.103	0.321 ± 0.096	0.283 ± 0.110	0.334 ± 0.105	0.394 ± 0.106	0.279 ± 0.060	0.271 ± 0.065	0.313 ± 0.095	0.378 ± 0.102 <sup>^#</sup>	0.302 ± 0.083	0.277 ± 0.085	0.324 ± 0.101	F(2, 57) = 0.683, p = 0.509, partial $\eta^2 = 0.023$ [0.000, 0.095]	<b>F(2, 57) = 7.327, p = 0.001, partial <math>\eta^2 = 0.205</math> [0.055, 0.331]</b>	F(1, 57) = 0.171, p = 0.681, partial $\eta^2 = 0.003$ [0.000, 0.062]

Key: **Bold** = p < 0.05. \* = higher than pre, ^ higher than mid, # higher than post, “ = higher than M total, ‘ = higher than F today, \* = higher than M in same maturation stage, ‘ = higher than F in same maturation stage.

**Appendix AD** ROT task all calculated knee angles (°) and moments (Nm) of the dominant limb according to sex and maturation stage. All variables are presented as mean ± SD.

Sex	M				F				Total				Interaction effect sex*maturation	Main effect Maturation	Main effect Sex
	Pre	Mid	Post	Total M	Pre	Mid	Post	Total F	Pre	Mid	Post	Total			
<b>Max flexion angle (°)</b>	59.712 ± 8.921	58.746 ± 12.536	62.715 ± 9.738	60.399 ± 10.165	61.653 ± 9.611	59.791 ± 7.053	65.513 ± 7.371	62.406 ± 8.198	60.556 ± 9.064	59.241 ± 10.048	64.047 ± 8.597	61.323 ± 9.294	F(2, 57) = 0.043, p = 0.958, partial η <sup>2</sup> = 0.002 [0.000, 0.000]	F(2, 57) = 1.426, p = 0.249, partial η <sup>2</sup> = 0.048 [0.000, 0.140]	F(1, 57) = 0.654, p = 0.422, partial η <sup>2</sup> = 0.011 [0.000, 0.092]
<b>Min flexion angle (°)</b>	14.289 ± 4.469	16.066 ± 5.963	14.891 ± 5.578	15.006 ± 5.190	11.900 ± 4.005	14.849 ± 3.127	16.756 ± 5.347	14.490 ± 4.627	13.250 ± 4.350	15.490 ± 4.745	15.779 ± 5.416	14.768 ± 4.906	F(2, 57) = 1.091, p = 0.343, partial η <sup>2</sup> = 0.037 [0.006, 0.122]	F(2, 57) = 2.017, p = 0.142, partial η <sup>2</sup> = 0.066 [0.028, 0.168]	F(1, 57) = 0.221, p = 0.640, partial η <sup>2</sup> = 0.004 [0.000, 0.067]
<b>Range flexion angle (°)</b>	45.424 ± 7.302	42.680 ± 9.632	47.824 ± 7.934	45.424 ± 8.244	49.753 ± 8.976	44.943 ± 7.523	48.757 ± 5.243	47.917 ± 7.430	47.306 ± 8.177	43.752 ± 8.537	48.268 ± 6.639	46.555 ± 7.919	F(2, 57) = 0.258, p = 0.773, partial η <sup>2</sup> = 0.009 [0.000, 0.054]	F(2, 57) = 1.849, p = 0.167, partial η <sup>2</sup> = 0.061 [0.000, 0.161]	F(1, 57) = 1.580, p = 0.214, partial η <sup>2</sup> = 0.027 [0.000, 0.125]

<b>Max flexion moment (Nm/kg)</b>	0.696 ± 0.173	0.886 ± 0.235	0.739 ± 0.098	0.766 ± 0.188	0.738 ± 0.220	0.857 ± 0.262	0.568 ± 0.187	0.716 ± 0.247	0.714 ± 0.191	0.872 ± 0.241*#	0.657 ± 0.168	0.743 ± 0.216	F(2, 57) = 1.606, p = 0.210, partial η <sup>2</sup> = 0.053 [0.000, 0.149]	<b>F(2, 57) = 6.266, p = 0.003, partial η<sup>2</sup> = 0.180 [0.040, 0.306]</b>	F(1, 57) = 1.097, p = 0.299, partial η <sup>2</sup> = 0.019 [0.000, 0.110]
<b>Min flexion moment (Nm/kg)</b>	-2.212 ± 0.245	-2.778 ± 0.569	-2.678 ± 0.652	-2.530 ± 0.552	-2.434 ± 0.470	-2.718 ± 0.419	-2.736 ± 0.488	-2.626 ± 0.467	-2.309 ± 0.369^#	-2.750 ± 0.491	-2.706 ± 0.566	-2.574 ± 0.513	F(2, 57) = 0.445, p = 0.643, partial η <sup>2</sup> = 0.015 [0.000, 0.075]	<b>F(2, 57) = 5.023, p = 0.010, partial η<sup>2</sup> = 0.150 [0.022, 0.273]</b>	F(1, 57) = 0.352, p = 0.555, partial η <sup>2</sup> = 0.006 [0.000, 0.077]
<b>Range flexion moment (Nm/kg)</b>	2.908 ± 0.241	3.664 ± 0.683	3.417 ± 0.668	3.295 ± 0.624	3.172 ± 0.639	3.575 ± 0.478	3.303 ± 0.570	3.343 ± 0.574	3.023 ± 0.466	3.622 ± 0.581*	3.363 ± 0.611	3.317 ± 0.597	F(2, 57) = 0.548, p = 0.581, partial η <sup>2</sup> = 0.019 [0.000, 0.085]	<b>F(2, 57) = 5.612, p = 0.006, partial η<sup>2</sup> = 0.165 [0.030, 0.289]</b>	F(1, 57) = 0.027, p = 0.871, partial η <sup>2</sup> = 0.000 [0.000, 0.032]
<b>Max flexion moment (Nm/kg/m)</b>	0.510 ± 0.149	0.520 ± 0.126	0.418 ± 0.061	0.483 ± 0.125	0.523 ± 0.1439	0.524 ± 0.159	0.351 ± 0.114	0.464 ± 0.160	0.516 ± 0.146#	0.522 ± 0.138#	0.386 ± 0.094	0.474 ± 0.141	F(2, 57) = 0.596, p = 0.554, partial η <sup>2</sup> = 0.020 [0.000, 0.088]	<b>F(2, 57) = 7.453, p = 0.001, partial η<sup>2</sup> = 0.207 [0.057, 0.334]</b>	F(1, 57) = 0.246, p = 0.621, partial η <sup>2</sup> = 0.004 [0.000, 0.069]

<b>Min flexion moment (Nm/kg/m)</b>	-1.606 ± 0.183	-1.626 ± 0.254	-1.508 ± 0.341	-1.580 ± 0.249	-1.737 ± 0.311	-1.659 ± 0.241	-1.689 ± 0.304	-1.696 ± 0.280	-1.663 ± 0.249	-1.641 ± 0.242	-1.594 ± 0.329	-1.633 ± 0.274	F(2, 57) = 0.371, p = 0.692, partial $\eta^2$ = 0.013 [0.000, 0.068]	F(2, 57) = 0.390, p = 0.679, partial $\eta^2$ = 0.013 [0.000, 0.070]	F(1, 57) = 2.730, p = 0.104, partial $\eta^2$ = 0.046 [0.000, 0.157]
<b>Range flexion moment (Nm/kg/m)</b>	2.117 ± 0.241	2.145 ± 0.298	1.925 ± 0.350	2.063 ± 0.303	2.260 ± 0.418	2.183 ± 0.273	2.041 ± 0.360	2.161 ± 0.358	2.179 ± 0.329	2.163 ± 0.279	1.980 ± 0.351	2.108 ± 0.330	F(2, 57) = 0.143, p = 0.867, partial $\eta^2$ = 0.005 [0.000, 0.034]	F(2, 57) = 2.510, p = 0.090, partial $\eta^2$ = 0.081 [0.038, 0.189]	F(1, 57) = 1.434, p = 0.236, partial $\eta^2$ = 0.025 [0.000, 0.121]
<b>Max abduction angle (°)</b>	9.749 ± 4.884	4.558 ± 3.591	4.168 ± 4.958	6.417 ± 5.171	7.355 ± 2.446	6.548 ± 4.570	5.470 ± 5.570	6.455 ± 4.301	8.708 ± 4.115 <sup>^#</sup>	5.501 ± 4.095	4.788 ± 5.167	6.434 ± 4.753	F(2, 57) = 1.478, p = 0.237, partial $\eta^2$ = 0.049 [0.000, 0.143]	<b>F(2, 57) = 4.235, p = 0.019, partial <math>\eta^2</math> = 0.129 [0.012, 0.249]</b>	F(1, 57) = 0.069, p = 0.794, partial $\eta^2$ = 0.001 [0.000, 0.047]
<b>Min abduction angle (°)</b>	1.405 ± 3.978	-2.506 ± 2.980	-2.670 ± 3.478	-1.064 ± 3.966	-0.641 ± 3.469	-1.458 ± 5.018	-2.156 ± 4.557	-1.417 ± 4.260	0.515 ± 3.825 <sup>^#</sup>	-2.010 ± 3.990	-2.425 ± 3.932	-1.226 ± 4.074	F(2, 57) = 0.939, p = 0.397, partial $\eta^2$ = 0.032 [0.000, 0.112]	<b>F(2, 57) = 5.612, p = 0.006, partial <math>\eta^2</math> = 0.165 [0.030, 0.289]</b>	F(1, 57) = 0.026, p = 0.872, partial $\eta^2$ = 0.000 [0.000, 0.031]

<b>Range abduction angle (°)</b>	8.344 ± 3.286	7.064 ± 1.361	6.982 ± 2.329	7.527 ± 2.550	7.995 ± 2.196	8.006 ± 2.534	7.627 ± 1.770	7.872 ± 2.196	8.192 ± 2.898	7.510 ± 2.004	7.289 ± 2.057	7.686 ± 2.381	F(2, 57) = 0.933, p = 0.399, partial η <sup>2</sup> = 0.032 [0.000, 0.112]	F(2, 57) = 1.570, p = 0.217, partial η <sup>2</sup> = 0.052 [0.000, 0.147]	F(1, 57) = 0.172, p = 0.680, partial η <sup>2</sup> = 0.003 [0.000, 0.062]
<b>Max abduction moment (Nm/kg)</b>	0.485 ± 0.234	0.582 ± 0.185	0.607 ± 0.300	0.553 ± 0.244	0.549 ± 0.176	0.513 ± 0.234	0.433 ± 0.228	0.498 ± 0.212	0.513 ± 0.208	0.549 ± 0.206	0.524 ± 0.276	0.528 ± 0.229	F(2, 57) = 1.454, p = 0.242, partial η <sup>2</sup> = 0.049 [0.000, 0.141]	F(2, 57) = 0.107, p = 0.899, partial η <sup>2</sup> = 0.004 [0.000, 0.024]	F(1, 57) = 1.043, p = 0.312, partial η <sup>2</sup> = 0.018 [0.000, 0.108]
<b>Min abduction moment (Nm/kg)</b>	-0.626 ± 0.235	-0.392 ± 0.170	-0.358 ± 0.203	-0.471 ± 0.237	-0.535 ± 0.251	-0.485 ± 0.170	-0.402 ± 0.256	-0.474 ± 0.230	-0.587 ± 0.241	-0.436 ± 0.172*	-0.379 ± 0.232	-0.472 ± 0.225*	F(2, 57) = 1.018, p = 0.368, partial η <sup>2</sup> = 0.035 [0.000, 0.117]	<b>F(2, 57) = 4.851, p = 0.011, partial η<sup>2</sup> = 0.145 [0.020, 0.268]</b>	F(1, 57) = 0.074, p = 0.786, partial η <sup>2</sup> = 0.001 [0.000, 0.048]
<b>Range abduction moment (Nm/kg)</b>	1.111 ± 0.282	0.939 ± 0.167	0.965 ± 0.223	1.013 ± 0.240	1.083 ± 0.284	0.999 ± 0.226	0.835 ± 0.215	0.971 ± 0.258	1.099 ± 0.277 <sup>#</sup>	0.967 ± 0.194	0.903 ± 0.224	0.994 ± 0.248	F(2, 57) = 0.787, p = 0.460, partial η <sup>2</sup> = 0.027 [0.000, 0.103]	<b>F(2, 57) = 3.842, p = 0.027, partial η<sup>2</sup> = 0.119 [0.007, 0.237]</b>	F(1, 57) = 0.298, p = 0.588, partial η <sup>2</sup> = 0.005 [0.000, 0.073]

<b>Max abduction moment (Nm/kg/m)</b>	0.353 ± 0.165	0.344 ± 0.110	0.342 ± 0.169	0.347 ± 0.148	0.391 ± 0.121	0.311 ± 0.135	0.267 ± 0.143	0.324 ± 0.139	0.370 ± 0.145	0.329 ± 0.120	0.306 ± 0.158	0.336 ± 0.143	F(2, 57) = 0.864, p = 0.427, partial η <sup>2</sup> = 0.029 [0.000, 0.108]	F(2, 57) = 1.239, p = 0.297, partial η <sup>2</sup> = 0.042 [0.000, 0.130]	F(1, 57) = 0.403, p = 0.528, partial η <sup>2</sup> = 0.007 [0.000, 0.080]
<b>Min abduction moment (Nm/kg/m)</b>	-0.461 ± 0.191	-0.229 ± 0.093	-0.204 ± 0.119	-0.309 ± 0.186	-0.388 ± 0.197	-0.300 ± 0.121	-0.255 ± 0.184	-0.315 ± 0.175	-0.429 ± 0.193	-0.263 ± 0.110*	-0.228 ± 0.152*	-0.312 ± 0.180	F(2, 57) = 1.297, p = 0.281, partial η <sup>2</sup> = 0.044 [0.000, 0.133]	<b>F(2, 57) = 9.378, p &lt; 0.001, partial η<sup>2</sup> = 0.248 [0.086, 0.374]</b>	F(1, 57) = 0.170, p = 0.628, partial η <sup>2</sup> = 0.003 [0.000, 0.062]
<b>Range abduction moment (Nm/kg/m)</b>	0.814 ± 0.229	0.554 ± 0.101	0.546 ± 0.130	0.651 ± 0.209	0.779 ± 0.220	0.612 ± 0.145	0.522 ± 0.163	0.639 ± 0.205	0.799 ± 0.220 <sup>^#</sup>	0.581 ± 0.124	0.534 ± 0.143	0.645 ± 0.206	F(2, 57) = 0.417, p = 0.661, partial η <sup>2</sup> = 0.014 [0.000, 0.073]	<b>F(2, 57) = 14.021, p &lt; 0.001, partial η<sup>2</sup> = 0.330 [0.155, 0.452]</b>	F(1, 57) = 0.000, p = 0.999, partial η <sup>2</sup> = 0.000 [0.000, 0.000]
<b>Max internal rotation angle (°)</b>	7.634 ± 4.468	2.278 ± 4.498	3.449 ± 6.177	4.705 ± 5.480	4.951 ± 4.770	7.401 ± 7.153	5.891 ± 5.210	6.120 ± 5.720	6.876 ± 4.772	3.545 ± 4.702	5.331 ± 6.797	5.356 ± 5.592	F(2, 57) = 1.644, p = 0.202, partial η <sup>2</sup> = 0.055 [0.000, 0.151]	F(2, 57) = 1.725, p = 0.187, partial η <sup>2</sup> = 0.057 [0.000, 0.155]	F(1, 57) = 1.388, p = 0.244, partial η <sup>2</sup> = 0.024 [0.000, 0.119]

<b>Min internal rotation angle (°)</b>	-2.644 ± 4.021	-8.878 ± 4.390	-7.156 ± 7.287	-5.937 ± 5.883	-4.631 ± 5.409	-8.001 ± 6.585	-3.942 ± 5.665	-5.439 ± 5.937	-3.508 ± 4.669 <sup>^</sup>	-8.463 ± 5.395	-5.626 ± 6.610	-5.708 ± 5.866	F(2, 57) = 1.173, p = 0.317, partial $\eta^2 = 0.040$ [0.000, 0.126]	<b>F(2, 57) = 3.787, p = 0.029, partial <math>\eta^2 = 0.117</math> [0.069, 0.235]</b>	F(1, 57) = 0.242, p = 0.624, partial $\eta^2 = 0.004$ [0.000, 0.070]
<b>Range internal rotation angle (°)</b>	10.342 ± 3.718	11.156 ± 5.001	10.605 ± 3.751	10.667 ± 4.028	10.522 ± 3.348	12.953 ± 6.894	11.343 ± 4.494	11.560 ± 5.620	10.420 ± 3.483	12.007 ± 5.871	10.957 ± 4.033	11.078 ± 4.471	F(2, 57) = 0.163, p = 0.850, partial $\eta^2 = 0.006$ [0.000, 0.038]	F(2, 57) = 0.661, p = 0.520, partial $\eta^2 = 0.023$ [0.000, 0.094]	F(1, 57) = 0.608, p = 0.439, partial $\eta^2 = 0.011$ [0.000, 0.090]
<b>Max internal rotation moment (Nm/kg)</b>	0.419 ± 0.122	0.572 ± 0.096	0.622 ± 0.223	0.529 ± 0.177	0.559 ± 0.140	0.543 ± 0.181	0.570 ± 0.151	0.558 ± 0.152	0.480 ± 0.146	0.558 ± 0.139	0.597 ± 0.189	0.543 ± 0.165	F(2, 57) = 2.435, p = 0.097, partial $\eta^2 = 0.079$ [0.000, 0.186]	F(2, 57) = 2.609, p = 0.082, partial $\eta^2 = 0.084$ [0.000, 0.193]	F(1, 57) = 0.255, p = 0.616, partial $\eta^2 = 0.004$ [0.000, 0.070]
<b>Min internal rotation moment (Nm/kg)</b>	-0.134 ± 0.086	-0.051 ± 0.028	-0.057 ± 0.069	-0.085 ± 0.077	-0.078 ± 0.035	-0.072 ± 0.038	-0.043 ± 0.047	-0.078 ± 0.035	-0.110 ± 0.073	-0.061 ± 0.034*	-0.051 ± 0.058*	-0.075 ± 0.063	F(2, 57) = 2.348, p = 0.105, partial $\eta^2 = 0.076$ [0.000, 0.182]	<b>F(2, 57) = 6.055, p = 0.004, partial <math>\eta^2 = 0.175</math> [0.037, 0.301]</b>	F(1, 57) = 1.092, p = 0.301, partial $\eta^2 = 0.019$ [0.000, 0.109]
<b>Range internal rotation</b>	0.552 ± 0.134	0.623 ± 0.083	0.679 ± 0.204	0.614 ± 0.155	0.653 ± 0.134	0.616 ± 0.162	0.613 ± 0.127	0.628 ± 0.141	0.596 ± 0.144	0.619 ± 0.123	0.648 ± 0.171	0.620 ± 0.147	F(2, 57) = 1.783, p = 0.177, partial	F(2, 57) = 0.484, p =	F(1, 57) = 0.062, p =

<b>moment</b> <b>(Nm/kg)</b>													$\eta^2 = 0.059$ [0.000, 0.158]	0.619, partial $\eta^2 = 0.017$ [0.000, 0.079]	0.805, partial $\eta^2 =$ 0.001 [0.000, 0.045]
<b>Max internal</b> <b>rotation</b> <b>moment</b> <b>(Nm/kg/m)</b>	0.304 ± 0.086	0.338 ± 0.066	0.350 ± 0.121	0.329 ± 0.094	0.401 ± 0.103	0.329 ± 0.103	0.353 ± 0.095	0.362 ± 0.102	0.346 ± 0.104	0.334 ± 0.083	0.351 ± 0.107	0.344 ± 0.098	F(2, 57) = 1.940, p = 0.153, partial $\eta^2 = 0.064$ [0.000, 0.165]	F(2, 57) = 0.236, p = 0.790, partial $\eta^2 = 0.008$ [0.000, 0.051]	F(1, 57) = 1.514, p = 0.224, partial $\eta^2 =$ 0.026 [0.000, 0.123]
<b>Min internal</b> <b>rotation</b> <b>moment</b> <b>(Nm/kg/m)</b>	-0.099 ± 0.068	-0.030 ± 0.016	-0.033 ± 0.039	-0.057 ± 0.058	-0.060 ± 0.037	-0.045 ± 0.025	-0.028 ± 0.033	-0.044 ± 0.034	-0.082 ± 0.059	-0.037 ± 0.021*	-0.030 ± 0.036*	-0.051 ± 0.048	F(2, 57) = 2.200, p = 0.120, partial $\eta^2 = 0.072$ [0.000, 0.176]	<b>F(2, 57) =</b> <b>8.733, p &lt;</b> <b>0.001, partial</b> <b><math>\eta^2 = 0.235</math></b> <b>[0.076, 0.362]</b>	F(1, 57) = 0.794, p = 0.377, partial $\eta^2 =$ 0.014 [0.000, 0.098]
<b>Range internal</b> <b>rotation</b> <b>moment</b> <b>(Nm/kg/m)</b>	0.403 ± 0.105	0.368 ± 0.060	0.382 ± 0.111	0.386 ± 0.095	0.461 ± 0.104	0.374 ± 0.091	0.381 ± 0.085	0.406 ± 0.099	0.428 ± 0.107	0.371 ± 0.074	0.382 ± 0.097	0.395 ± 0.096	F(2, 57) = 0.649, p = 0.526, partial $\eta^2 = 0.022$ [0.000, 0.093]	F(2, 57) = 2.510, p = 0.090, partial $\eta^2 = 0.081$ [0.000, 0.189]	F(1, 57) = 0.743, p = 0.392, partial $\eta^2 =$ 0.013 [0.000, 0.096]

Key: **Bold** = p < 0.05. \* = higher than pre, ^ higher than mid, # higher than post, “ = higher than M total, ‘ = higher than F today, † = higher than M in same maturation stage, ‡ = higher than F in same maturation stage.

**Appendix AE** ROT task all calculated knee angles (°) and moments (Nm) of the non-dominant limb according to sex and maturation stage. All variables are presented as mean ± SD.

Sex	M				F				Total				Interaction effect sex*maturation	Main effect Maturation	Main effect Sex
	Maturation group	Pre	Mid	Post	Total M	Pre	Mid	Post	Total F	Pre	Mid	Post			
<b>Max flexion angle (°)</b>	61.320 ± 7.466	58.157 ± 11.098	61.268 ± 7.218	60.344 ± 8.499	62.967 ± 5.216	55.942 ± 6.609	64.044 ± 5.357	61.024 ± 6.656	61.979 ± 6.556 <sup>^</sup>	57.197 ± 9.071	62.590 ± 6.402 <sup>^</sup>	60.650 ± 7.669	F(2, 54) = 0.595, p = 0.555, partial $\eta^2 = 0.022$ [0.000, 0.088]	<b>F(2, 54) = 3.310, p = 0.044, partial <math>\eta^2 = 0.109</math> [0.002, 0.219]</b>	F(1, 54) = 0.142, p = 0.708, partial $\eta^2 = 0.003$ [0.000, 0.059]
<b>Min flexion angle (°)</b>	13.512 ± 4.392	13.352 ± 4.789	13.832 ± 3.754	13.512 ± 4.392	12.237 ± 3.699	11.761 ± 4.589	16.287 ± 3.844	13.578 ± 4.449	12.906 ± 3.676	12.599 ± 4.636	15.001 ± 4.575	13.542 ± 4.380	F(2, 54) = 1.320, p = 0.276, partial $\eta^2 = 0.047$ [0.000, 0.134]	F(2, 54) = 2.061, p = 0.137, partial $\eta^2 = 0.071$ [0.000, 0.170]	F(1, 54) = 0.005, p = 0.941, partial $\eta^2 = 0.000$ [0.000, 0.003]
<b>Range flexion angle (°)</b>	47.968 ± 5.243	44.804 ± 8.441	47.436 ± 6.341	46.832 ± 6.629	50.730 ± 6.026	44.180 ± 5.908	47.757 ± 3.725	47.446 ± 5.689	49.073 ± 5.587	44.509 ± 7.158	47.589 ± 5.136	47.108 ± 6.180	F(2, 54) = 0.394, p = 0.676, partial $\eta^2 = 0.014$ [0.000, 0.070]	F(2, 54) = 3.111, p = 0.053, partial $\eta^2 = 0.103$ [0.000, 0.212]	F(1, 54) = 0.267, p = 0.608, partial $\eta^2 = 0.005$ [0.000, 0.070]
<b>Max flexion moment (Nm/kg)</b>	0.694 ± 0.226	0.803 ± 0.248	0.690 ± 0.080	0.726 ± 0.199	0.728 ± 0.158	0.846 ± 0.250	0.556 ± 0.176	0.703 ± 0.229	0.707 ± 0.198	0.823 ± 0.243 <sup>#</sup>	0.626 ± 0.148	0.716 ± 0.211	F(2, 54) = 1.279, p = 0.287, partial $\eta^2 = 0.045$ [0.000, 0.132]	<b>F(2, 54) = 5.116, p = 0.009, partial <math>\eta^2 = 0.159</math> [0.024, 0.275]</b>	F(1, 54) = 0.141, p = 0.709, partial $\eta^2 = 0.003$

																[0.000, 0.059]
<b>Min flexion moment (Nm/kg)</b>	-2.304 ± 0.439	-2.564 ± 0.515	-2.837 ± 0.702	-2.569 ± 0.588	-2.615 ± 0.414	-2.719 ± 0.365	-2.538 ± 0.516	-2.622 ± 0.414	-2.429 ± 0.424	-2.637 ± 0.445	-2.695 ± 0.624	-2.587 ± 0.514	F(2, 54) = 1.998, p = 0.145, partial η <sup>2</sup> = 0.069 [0.000, 0.167]	F(2, 54) = 1.125, p = 0.332, partial η <sup>2</sup> = 0.040 [0.000, 0.124]	F(1, 54) = 0.183, p = 0.671, partial η <sup>2</sup> = 0.003 [0.000, 0.064]	
<b>Range flexion moment (Nm/kg)</b>	2.998 ± 0.472	3.367 ± 0.622	3.527 ± 0.724	3.286 ± 0.634	3.343 ± 0.484	3.565 ± 0.440	3.094 ± 0.555	3.325 ± 0.520	3.136 ± 0.496	3.461 ± 0.538	3.321 ± 0.671	3.304 ± 0.581	F(2, 54) = 2.731, p = 0.074, partial η <sup>2</sup> = 0.092 [0.000, 0.198]	F(2, 57) = 1.312, p = 0.278, partial η <sup>2</sup> = 0.046 [0.000, 0.134]	F(1, 57) = 0.063, p = 0.803, partial η <sup>2</sup> = 0.001 [0.000, 0.045]	
<b>Max flexion moment (Nm/kg/m)</b>	0.503 ± 0.190	0.471 ± 0.133	0.387 ± 0.050	0.455 ± 0.143	0.509 ± 0.098	0.515 ± 0.144	0.342 ± 0.106	0.509 ± 0.098	0.505 ± 0.156 <sup>#</sup>	0.492 ± 0.136 <sup>#</sup>	0.366 ± 0.083	0.505 ± 0.156	F(2, 54) = 0.601, p = 0.552, partial η <sup>2</sup> = 0.022 [0.000, 0.088]	<b>F(2, 54) = 7.315, p = 0.002, partial η<sup>2</sup> = 0.213 [0.055, 0.331]</b>	F(1, 54) = 0.003, p = 0.956, partial η <sup>2</sup> = 0.000 [0.000, 0.000]	
<b>Min flexion moment (Nm/kg/m)</b>	-1.653 ± 0.301	-1.508 ± 0.282	-1.587 ± 0.376	-1.587 ± 0.318	-1.834 ± 0.190	-1.662 ± 0.218	-1.562 ± 0.304	-1.676 ± 0.263	-1.725 ± 0.272	-1.581 ± 0.260	-1.576 ± 0.336	-1.627 ± 0.296	F(2, 54) = 0.746, p = 0.479, partial η <sup>2</sup> = 0.027 [0.000, 0.100]	F(2, 54) = 2.052, p = 0.138, partial η <sup>2</sup> = 0.071 [0.000, 0.170]	F(1, 54) = 1.847, p = 0.180, partial η <sup>2</sup> = 0.033 [0.000, 0.133]	
<b>Range flexion moment (Nm/kg/m)</b>	2.156 ± 0.353	1.979 ± 0.324	1.975 ± 0.390	2.042 ± 0.357	2.344 ± 0.272	2.177 ± 0.247	1.905 ± 0.323	2.125 ± 0.330	2.231 ± 0.329 <sup>#</sup>	2.073 ± 0.300	1.941 ± 0.353	2.079 ± 0.345	F(2, 54) = 1.094, p = 0.342, partial η <sup>2</sup> = 0.039 [0.000, 0.122]	<b>F(2, 54) = 4.505, p = 0.016, partial η<sup>2</sup> = 0.166 [0.000, 0.331]</b>	F(1, 54) = 1.523, p = 0.223, partial η <sup>2</sup> = 0.027 [0.000, 0.133]	

														$\eta^2 = 0.143$ [0.016, 0.258]	[0.000, 0.124]
<b>Max abduction angle (°)</b>	10.127 ± 5.427	3.667 ± 5.801	3.241 ± 2.747	5.874 ± 5.713	6.060 ± 3.585	6.452 ± 4.870	5.537 ± 6.211	5.997 ± 4.926	8.500 ± 5.096	4.986 ± 5.423	4.334 ± 4.745	5.929 ± 5.329	F(2, 54) = 2.876, p = 0.065, partial $\eta^2 = 0.096$ [0.000, 0.203]	F(2, 54) = 3.110, p = 0.053, partial $\eta^2 = 0.103$ [0.000, 0.212]	F(1, 54) = 0.069, p = 0.794, partial $\eta^2 = 0.001$ [0.000, 0.047]
<b>Min abduction angle (°)</b>	1.140 ± 4.379	-3.626 ± 3.965	-3.085 ± 2.344	-1.713 ± 4.192	-1.715 ± 3.746	-2.014 ± 5.780	-2.502 ± 6.160	-2.106 ± 5.232	-0.002 ± 4.281	-2.863 ± 4.847	-2.807 ± 4.462	-1.890 ± 4.651	F(2, 54) = 1.272, p = 0.289, partial $\eta^2 = 0.045$ [0.000, 0.132]	F(2, 54) = 1.989, p = 0.147, partial $\eta^2 = 0.069$ [0.000, 0.167]	F(1, 54) = 0.035, p = 0.853, partial $\eta^2 = 0.001$ [0.000, 0.036]
<b>Range abduction angle (°)</b>	8.987 ± 3.808	7.293 ± 2.310	6.326 ± 1.437	7.587 ± 2.905	7.775 ± 1.533	8.467 ± 3.222	8.039 ± 2.617	7.775 ± 1.533	8.503 ± 3.104	7.849 ± 2.765	7.142 ± 2.210	7.819 ± 2.723	F(2, 54) = 0.999, p = 0.375, partial $\eta^2 = 0.036$ [0.000, 0.116]	F(2, 54) = 0.863, p = 0.427, partial $\eta^2 = 0.031$ [0.000, 0.108]	F(1, 54) = 1.036, p = 0.313, partial $\eta^2 = 0.019$ [0.000, 0.107]
<b>Max abduction moment (Nm/kg)</b>	0.438 ± 0.127	0.782 ± 0.210*	0.678 ± 0.254*	0.622 ± 0.245	0.653 ± 0.361	0.609 ± 0.291	0.509 ± 0.286	0.585 ± 0.306	0.524 ± 0.263	0.700 ± 0.260	0.597 ± 0.277	0.605 ± 0.272	<b>F(2, 54) = 3.679, p = 0.032, partial <math>\eta^2 = 0.120</math> [0.006, 0.232]</b>	F(2, 54) = 1.709, p = 0.191, partial $\eta^2 = 0.060$ [0.000, 0.154]	F(1, 54) = 0.407, p = 0.526, partial $\eta^2 = 0.007$ [0.000, 0.080]
<b>Min abduction moment (Nm/kg)</b>	-0.599 ± 0.247	-0.360 ± 0.123	-0.276 ± 0.145	-0.418 ± 0.228	-0.443 ± 0.196	-0.377 ± 0.255	-0.323 ± 0.195	-0.377 ± 0.215	-0.537 ± 0.236	-0.368 ± 0.191*	-0.298 ± 0.168*	-0.400 ± 0.221	F(2, 54) = 2.009, p = 0.144, partial $\eta^2 = 0.069$ [0.000, 0.142]	<b>F(2, 54) = 11.710, p &lt; 0.001, partial <math>\eta^2 = 0.232</math></b>	F(1, 54) = 0.182, p = 0.671, partial $\eta^2 = 0.003$

														$\eta^2 = 0.303$ <b>[0.126, 0.430]</b>	[0.000, 0.076]
<b>Range</b>	1.037 ±	1.141 ±	0.954 ±	1.041 ±	1.096 ±	0.986 ±	0.832 ±	0.962 ±	1.060 ±	1.068 ±	0.896 ±	1.005 ±	F(2, 54) = 1.035,	<b>F(2, 54) =</b>	F(1, 54) =
<b>abduction</b>	0.249	0.223	0.251	0.247	0.268	0.300	0.207	0.272	0.252 <sup>#</sup>	0.267 <sup>#</sup>	0.234	0.259	p = 0.362, partial	<b>3.214, p &lt;</b>	1.254, p =
<b>moment</b>													$\eta^2 = 0.037$ [0.000,	<b>0.048, partial</b>	0.268, partial
<b>(Nm/kg)</b>													0.118]	<b><math>\eta^2 = 0.106</math></b> <b>[0.001, 0.224]</b>	$\eta^2 = 0.023$ [0.000, 0.115]
<b>Max</b>	0.314 ±	0.459 ±	0.380 ±	0.380 ±	0.461 ±	0.368 ±	0.313 ±	0.461 ±	0.373 ±	0.416 ±	0.348 ±	0.378 ±	<b>F(2, 54) = 3.353,</b>	F(2, 54) =	F(1, 54) =
<b>abduction</b>	0.086	0.113*	0.142	0.126	0.256*	0.163	0.174	0.256	0.184	0.143	0.157	0.162	<b>p = 0.042, partial</b>	0.906, p =	0.008, p =
<b>moment</b>													<b><math>\eta^2 = 0.110</math></b>	0.410, partial	0.927, partial
<b>(Nm/kg/m)</b>													<b>[0.002, 0.220]</b>	$\eta^2 = 0.032$ [0.000, 0.110]	$\eta^2 = 0.000$ [0.000, 0.012]
<b>Min abduction</b>	-0.429	-0.214	-0.154	-0.272	-0.315	-0.233	-0.203	-0.246	-0.383	-0.223	-0.177	-0.260	F(2, 54) = 2.009,	<b>F(2, 54) =</b>	F(1, 54) =
<b>moment</b>	± 0.179	± 0.078	± 0.077	± 0.171	± 0.143	± 0.163	± 0.126	± 0.146	± 0.169	±	±	± 0.160	p = 0.144, partial	<b>11.710, p &lt;</b>	0.182, p =
<b>(Nm/kg/m)</b>										0.122*	0.104*		$\eta^2 = 0.069$ [0.000,	<b>0.001, partial</b>	0.671, partial
													0.175]	<b><math>\eta^2 = 0.303</math></b> <b>[0.121, 0.416]</b>	$\eta^2 = 0.003$ [0.000, 0.067]
<b>Range</b>	0.743 ±	0.673 ±	0.534 ±	0.652 ±	0.776 ±	0.600 ±	0.516 ±	0.621 ±	0.756 ±	0.639 ±	0.525 ±	0.638 ±	F(2, 54) = 0.524,	<b>F(2, 54) =</b>	F(1, 54) =
<b>abduction</b>	0.174	0.126	0.136	0.170	0.202	0.174	0.138	0.196	0.181 <sup>^#</sup>	0.151 <sup>#</sup>	0.134	0.181	p = 0.595, partial	<b>10.934, p &lt;</b>	0.216, p =
<b>moment</b>													$\eta^2 = 0.019$ [0.000,	<b>0.001, partial</b>	0.644, partial
<b>(Nm/kg/m)</b>													0.083]	<b><math>\eta^2 = 0.288</math></b> <b>[0.110, 0.403]</b>	$\eta^2 = 0.004$ [0.000, 0.067]
<b>Max internal</b>	11.100	7.107 ±	7.402 ±	8.657 ±	8.668 ±	7.212 ±	7.365 ±	7.700 ±	10.127	7.157 ±	7.384 ±	8.227 ±	F(2, 54) = 0.248,	F(2, 54) =	F(1, 54) =
<b>rotation angle</b>	± 7.440	5.597	6.345	6.630	5.672	6.576	5.557	5.751	± 6.216	5.906	5.833	6.216	p = 0.781, partial	1.117, p =	0.230, p =
<b>(°)</b>													$\eta^2 = 0.009$ [0.000,	0.335, partial	0.633, partial
													0.053]		$\eta^2 = 0.004$

														$\eta^2 = 0.040$	[0.000,
														[0.000, 0.123]	0.068]
<b>Min internal</b>	-1.885	-5.613	-3.688	-3.616	-2.732	-5.111	-7.186	-5.175	-2.224	-5.375	-5.354	-4.317	F(2, 54) = 0.494,	F(2, 54) =	F(1, 54) =
<b>rotation angle</b>	$\pm 7.444$	$\pm 7.431$	$\pm 4.727$	$\pm 6.628$	$\pm 4.524$	$\pm 7.610$	$\pm 6.114$	$\pm 6.298$	$\pm 6.309$	$\pm 7.309$	$\pm 5.586$	$\pm 6.475$	p = 0.613, partial	1.473, p =	0.575, p =
<b>(°)</b>													$\eta^2 = 0.018$ [0.000,	0.238, partial	0.452, partial
													0.080]	$\eta^2 = 0.052$	$\eta^2 = 0.011$
														[0.000, 0.142]	[0.000,
															0.089]
<b>Range internal</b>	12.985	12.719	11.090	12.273	11.401	12.324	14.551	12.875	12.352	12.532	12.738	12.544	F(2, 54) = 2.582,	F(2, 54) =	F(1, 54) =
<b>rotation angle</b>	$\pm 3.772$	$\pm 3.160$	$\pm 3.605$	$\pm 3.535$	$\pm 4.239$	$\pm 3.597$	$\pm 3.821$	$\pm 3.966$	$\pm 3.936$	$\pm 3.284$	$\pm 4.025$	$\pm 3.715$	p = 0.085, partial	0.144, p =	0.163, p =
<b>(°)</b>													$\eta^2 = 0.087$ [0.000,	0.866, partial	0.610, partial
													0.192]	$\eta^2 = 0.005$	$\eta^2 = 0.005$
														[0.000, 0.034]	[0.000,
															0.062]
<b>Max internal</b>	0.476 $\pm$	0.548 $\pm$	0.597 $\pm$	0.538 $\pm$	0.531 $\pm$	0.515 $\pm$	0.488 $\pm$	0.510 $\pm$	0.498 $\pm$	0.533 $\pm$	0.545 $\pm$	0.525 $\pm$	F(2, 54) = 1.381,	F(2, 54) =	F(1, 54) =
<b>rotation</b>	0.120	0.165	0.174	0.157	0.158	0.201	0.116	0.155	0.136	0.178	0.156	0.156	p = 0.260, partial	0.327, p =	0.487, p =
<b>moment</b>													$\eta^2 = 0.049$ [0.000,	0.722, partial	0.488, partial
<b>(Nm/kg)</b>													0.138]	$\eta^2 = 0.012$	$\eta^2 = 0.009$
														[0.000, 0.063]	[0.000,
															0.084]
<b>Min internal</b>	-0.135	-0.065	-0.059	-0.088	-0.086	-0.071	-0.051	-0.068	-0.116	-0.068	-0.055	-0.115	F(2, 54) = 2.011,	<b>F(2, 54) =</b>	F(1, 54) =
<b>rotation</b>	$\pm 0.077$	$\pm 0.026$	$\pm 0.050$	$\pm 0.065$	$\pm 0.055$	$\pm 0.051$	$\pm 0.028$	$\pm 0.046$	$\pm 0.072$	$\pm$	$\pm$	$\pm 0.072$	p = 0.144, partial	<b>6.183, p =</b>	1.557, p =
<b>moment</b>										0.039*	0.040*		$\eta^2 = 0.069$ [0.000,	<b>0.004, partial</b>	0.218, partial
<b>(Nm/kg)</b>													0.144]	<b><math>\eta^2 = 0.186</math></b>	$\eta^2 = 0.028$
														<b>[0.038, 0.304]</b>	[0.000,
															0.125]
<b>Range internal</b>	0.611 $\pm$	0.613 $\pm$	0.656 $\pm$	0.626 $\pm$	0.617 $\pm$	0.587 $\pm$	0.539 $\pm$	0.578 $\pm$	0.613 $\pm$	0.600 $\pm$	0.600 $\pm$	0.605 $\pm$	F(2, 54) = 1.019,	F(2, 54) =	F(1, 54) =
<b>rotation</b>	0.124	0.158	0.155	0.142	0.139	0.160	0.114	0.137	0.126	0.155	0.147	0.141	p = 0.368, partial	0.077, p =	1.492, p =
<b>moment</b>													$\eta^2 = 0.036$ [0.000,	0.926, partial	0.227, partial
<b>(Nm/kg)</b>													0.117]		$\eta^2 = 0.027$

														$\eta^2 = 0.003$	[0.000,
														[0.000, 0.013]	0.123]
<b>Max internal rotation moment (Nm/kg/m)</b>	0.342 ± 0.089	0.321 ± 0.096	0.335 ± 0.100	0.334 ± 0.092	0.376 ± 0.116	0.313 ± 0.114	0.300 ± 0.066	0.326 ± 0.101	0.356 ± 0.099	0.317 ± 0.102	0.318 ± 0.085	0.330 ± 0.095	F(2, 54) = 0.636, p = 0.533, partial $\eta^2 = 0.023$ [0.000, 0.092]	F(2, 54) = 1.215, p = 0.305, partial $\eta^2 = 0.043$ [0.000, 0.129]	F(1, 54) = 0.021, p = 0.885, partial $\eta^2 = 0.000$ [0.000, 0.028]
<b>Min internal rotation moment (Nm/kg/m)</b>	-0.099 ± 0.060	-0.038 ± 0.016	-0.033 ± 0.027	-0.058 ± 0.050	-0.062 ± 0.041	-0.044 ± 0.032	-0.032 ± 0.019	-0.045 ± 0.032	-0.084 ± 0.055	-0.041 ± 0.024*	-0.033 ± 0.023*	-0.052 ± 0.043	F(2, 54) = 2.011, p = 0.144, partial $\eta^2 = 0.069$ [0.000, 0.168]	<b>F(2, 54) = 11.706, p &lt; 0.001, partial <math>\eta^2 = 0.302</math> [0.126, 0.429].</b>	F(1, 54) = 0.183, p = 0.671, partial $\eta^2 = 0.003$ [0.000, 0.064]
<b>Range internal rotation moment (Nm/kg/m)</b>	0.441 ± 0.103	0.360 ± 0.093	0.368 ± 0.089	0.392 ± 0.100	0.437 ± 0.108	0.357 ± 0.090	0.332 ± 0.066	0.371 ± 0.093	0.440 ± 0.102 <sup>^#</sup>	0.358 ± 0.089	0.351 ± 0.079	0.383 ± 0.098	F(2, 54) = 0.209, p = 0.812, partial $\eta^2 = 0.008$ [0.000, 0.047]	<b>F(2, 54) = 5.568, p &lt; 0.006, partial <math>\eta^2 = 0.171</math> [0.030, 0.288].</b>	F(1, 54) = 0.345, p = 0.559, partial $\eta^2 = 0.006$ [0.000, 0.076]

Key: **Bold** = p < 0.05. \* = higher than pre, ^ higher than mid, # higher than post, “ = higher than M total, ‘ = higher than F today, \* = higher than M in same maturation stage, ‘ = higher than F in same maturation stage.

**Appendix AF** VERT task all calculated knee angles (°) and moments (Nm) of the dominant limb according to sex and maturation stage. All variables are presented as mean ± SD.

Sex	M				F				Total				Interaction effect sex*maturation	Main effect Maturation	Main effect Sex
	Maturation group	Pre	Mid	Post	Total M	Pre	Mid	Post	Total F	Pre	Mid	Post			
<b>Max flexion angle (°)</b>	62.514 ± 7.579	61.612 ± 11.135	61.426 ± 9.513	61.865 ± 9.131	62.847 ± 8.829	59.056 ± 6.322	65.034 ± 8.963	62.410 ± 8.251	62.657 ± 7.925	60.401 ± 9.027	63.066 ± 9.231	62.111 ± 8.678	F(2, 56) = 0.615, p = 0.544, partial $\eta^2$ = 0.021 [0.000, 0.091]	F(2, 56) = 0.595, p = 0.555, partial $\eta^2$ = 0.021 [0.000, 0.090]	F(1, 56) = 0.041, p = 0.839, partial $\eta^2$ = 0.001 [0.000, 0.039]
<b>Min flexion angle (°)</b>	12.646 ± 3.951	18.209 ± 6.626*	14.083 ± 6.177	14.789 ± 5.940	11.558 ± 3.089	13.287 ± 3.820	17.834 ± 5.644*	14.355 ± 5.024	12.180 ± 3.564	15.877 ± 5.900	15.788 ± 6.107	14.593 ± 5.505	<b>F(2, 56) = 3.684, p = 0.031, partial <math>\eta^2</math> = 0.116 [0.006, 0.235]</b>	<b>F(2, 56) = 3.698, p = 0.031, partial <math>\eta^2</math> = 0.117 [0.006, 0.235]</b>	F(1, 56) = 0.331, p = 0.568, partial $\eta^2$ = 0.006 [0.000, 0.077]
<b>Range flexion angle (°)</b>	49.868 ± 6.404	43.403 ± 8.631	47.343 ± 9.838	47.075 ± 8.556	51.289 ± 9.903	45.768 ± 6.682	47.200 ± 7.022	48.054 ± 8.014	50.477 ± 7.893	44.524 ± 7.652	47.278 ± 8.476	47.517 ± 8.262	F(2, 56) = 0.123, p = 0.885, partial $\eta^2$ = 0.004 [0.000, 0.029]	F(2, 56) = 2.649, p = 0.080, partial $\eta^2$ = 0.086 [0.000, 0.197]	F(1, 56) = 0.335, p = 0.565, partial $\eta^2$ = 0.006 [0.000, 0.077]
<b>Max flexion moment (Nm/kg)</b>	0.722 ± 0.174	0.729 ± 0.191	0.704 ± 0.121	0.718 ± 0.158	0.822 ± 0.215	0.879 ± 0.308	0.562 ± 0.218	0.748 ± 0.279	0.765 ± 0.194#	0.800 ± 0.258#	0.640 ± 0.182	0.731 ± 0.220	F(2, 56) = 2.995, p = 0.058, partial $\eta^2$ = 0.097 [0.000, 0.210]	<b>F(2, 56) = 4.057, p = 0.023, partial <math>\eta^2</math> = 0.127 [0.010, 0.247]</b>	F(1, 56) = 0.474, p = 0.494, partial $\eta^2$ = 0.008

[0.000,  
0.085]

<b>Min flexion moment (Nm/kg)</b>	-2.409 ± 0.337	-2.903 ± 0.638	-2.765 ± 0.535	-2.680 ± 0.537	-2.644 ± 0.512	-2.654 ± 0.468	-2.811 ± 0.553	-2.707 ± 0.501	-2.510 ± 0.426	-2.785 ± 0.563	-2.786 ± 0.530	-2.692 ± 0.517	F(2, 56) = 1.118, p = 0.334, partial $\eta^2$ = 0.038 [0.000, 0.125]	F(2, 56) = 1.727, p = 0.187, partial $\eta^2$ = 0.058 [0.000, 0.157]	F(1, 56) = 0.007, p = 0.934, partial $\eta^2$ = 0.000 [0.000, 0.010]
<b>Range flexion moment (Nm/kg)</b>	3.131 ± 0.361	3.632 ± 0.655	3.469 ± 0.668	3.398 ± 0.569	3.466 ± 0.709	3.533 ± 0.470	3.374 ± 0.489	3.455 ± 0.546	3.275 ± 0.549	3.585 ± 0.561	3.426 ± 0.540	3.423 ± 0.555	F(2, 56) = 1.042, p = 0.360, partial $\eta^2$ = 0.036 [0.000, 0.121]	F(2, 56) = 1.300, p = 0.281, partial $\eta^2$ = 0.044 [0.000, 0.135]	F(1, 56) = 0.111, p = 0.740, partial $\eta^2$ = 0.001 [0.000, 0.056]
<b>Max flexion moment (Nm/kg/m)</b>	0.523 ± 0.143	0.428 ± 0.108	0.396 ± 0.069	0.450 ± 0.121	0.573 ± 0.136	0.537 ± 0.181	0.346 ± 0.129	0.480 ± 0.177	0.544 ± 0.139 <sup>#</sup>	0.479 ± 0.153 <sup>#</sup>	0.373 ± 0.101	0.464 ± 0.148	F(2, 56) = 1.989, p = 0.146, partial $\eta^2$ = 0.066 [0.000, 0.169]	<b>F(2, 56) = 10.169, p &lt; 0.001, partial <math>\eta^2</math> = 0.266 [0.099, 0.393]</b>	F(1, 56) = 1.199, p = 0.278, partial $\eta^2$ = 0.021 [0.000, 0.115]
<b>Min flexion moment (Nm/kg/m)</b>	-1.734 ± 0.278	-1.701 ± 0.311	-1.551 ± 0.276	-1.659 ± 0.278	-1.848 ± 0.314	-1.616 ± 0.254	-1.735 ± 0.340	-1.733 ± 0.310	-1.782 ± 0.272	-1.661 ± 0.281	-1.635 ± 0.314	-1.692 ± 0.293	F(2, 56) = 1.160, p = 0.321, partial $\eta^2$ = 0.040 [0.000, 0.128]	F(2, 56) = 1.621, p = 0.207, partial $\eta^2$ = 0.055 [0.000, 0.152]	F(1, 56) = 0.930, p = 0.339, partial $\eta^2$ = 0.016 [0.000, 0.105]
<b>Range flexion moment (Nm/kg/m)</b>	2.255 ± 0.291	2.129 ± 0.298	1.947 ± 0.308	2.109 ± 0.319	2.421 ± 0.436	2.152 ± 0.226	2.080 ± 0.291	2.213 ± 0.349	2.326 ± 0.360 <sup>#</sup>	2.140 ± 0.259	2.008 ± 0.301	2.156 ± 0.334	F(2, 56) = 0.277, p = 0.759, partial $\eta^2$ = 0.010 [0.000, 0.058]	<b>F(2, 56) = 5.777, p = 0.005, partial <math>\eta^2</math> = 0.005, partial <math>\eta^2</math> = 0.031</b>	F(1, 56) = 1.812, p = 0.184, partial $\eta^2$ = 0.031

														$\eta^2 = 0.171$	[0.000,
														<b>[0.033, 0.297]</b>	0.134]
<b>Max</b>	7.421 ±	5.369 ±	5.883 ±	6.275 ±	7.292 ±	6.249 ±	4.219 ±	5.859 ±	7.365 ±	5.786 ±	5.127 ±	6.087 ±	F(2, 56) = 0.374, p	F(2, 56) =	F(1, 56) =
<b>abduction</b>	3.837	4.640	5.854	4.794	2.866	4.754	5.592	4.613	3.374	4.584	5.663	4.679	= 0.690, partial $\eta^2$	1.287, p =	0.063, p =
<b>angle (°)</b>													= 0.013 [0.000,	0.284, partial	0.803, partial
													0.069]	$\eta^2 = 0.044$	$\eta^2 = 0.001$
														[0.000, 0.134]	[0.000,
															0.046]
<b>Min abduction</b>	-1.073	-1.979	-2.999	-2.019	-0.134	-1.239	-2.552	-1.353	-0.671	-1.628	-2.796	-1.718	F(2, 56) = 0.019, p	F(2, 56) =	F(1, 56) =
<b>angle (°)</b>	± 4.176	± 3.432	± 4.549	± 4.074	± 2.248	± 5.148	± 4.429	± 4.113	± 3.441	± 4.220	± 4.393	± 4.072	= 0.981, partial $\eta^2$	1.471, p =	0.450, p =
													= 0.001 [0.000,	0.239, partial	0.505, partial
													0.000]	$\eta^2 = 0.050$	$\eta^2 = 0.008$
														[0.000, 0.144]	[0.000,
															0.084]
<b>Range</b>	8.493 ±	7.348 ±	8.882 ±	8.294 ±	7.426 ±	7.488 ±	6.772 ±	7.212 ±	8.036 ±	7.415 ±	7.923 ±	7.805 ±	F(2, 56) = 0.865, p	F(2, 56) =	F(1, 56) =
<b>abduction</b>	2.507	3.099	3.284	2.953	2.058	2.828	1.770	2.315	2.333	2.892	2.981	2.717	= 0.427, partial $\eta^2$	0.210, p =	2.110, p =
<b>angle (°)</b>													= 0.030 [0.000,	0.811, partial	0.152, partial
													0.109]	$\eta^2 = 0.007$	$\eta^2 = 0.036$
														[0.000, 0.048]	[0.000,
															0.143]
<b>Max</b>	0.778 ±	0.647 ±	0.776 ±	0.739 ±	0.768 ±	0.671 ±	0.534 ±	0.653 ±	0.774 ±	0.658 ±	0.666 ±	0.700 ±	F(2, 56) = 1.663, p	F(2, 56) =	F(1, 56) =
<b>abduction</b>	0.340	0.185	0.246	0.268	0.191	0.355	0.139	0.254	0.280	0.271	0.235	0.263	= 0.199, partial $\eta^2$	1.394, p =	1.337, p =
<b>moment</b>													= 0.056 [0.000,	0.257, partial	0.252, partial
<b>(Nm/kg)</b>													0.154]	$\eta^2 = 0.047$	$\eta^2 = 0.023$
														[0.000, 0.140]	[0.000,
															0.119]
<b>Min abduction</b>	-0.481	-0.358	-0.291	-0.378	-0.425	-0.365	-0.289	-0.357	-0.457	-0.361	-0.290	-0.369	F(2, 56) = 0.132, p	F(2, 56) =	F(1, 56) =
<b>moment</b>	± 0.298	± 0.112	± 0.195	± 0.229	± 0.224	± 0.216	± 0.163	± 0.202	± 0.264	± 0.164	± 0.177	± 0.216	= 0.876, partial $\eta^2$	3.126, p =	0.099, p =
<b>(Nm/kg)</b>													= 0.005 [0.000,	0.052, partial	0.755, partial
													0.032]		$\eta^2 = 0.002$

														$\eta^2 = 0.100$	[0.000, 0.054]
														[0.000, 0.215]	
<b>Range</b>	1.260 ±	1.004 ±	1.068 ±	1.117 ±	1.193 ±	1.004 ±	0.823 ±	1.000 ±	1.231 ±	1.004 ±	0.957 ±	1.064 ±	F(2, 56) = 1.275, p	<b>F(2, 56) =</b>	F(1, 56) =
<b>abduction</b>	0.345	0.227	0.209	0.283	0.259	0.277	0.160	0.274	0.305 <sup>^#</sup>	0.245	0.222	0.283	= 0.287, partial $\eta^2$	<b>7.032, p =</b>	2.549, p =
<b>moment</b>													= 0.044 [0.000,	<b>0.002, partial</b>	0.116, partial
<b>(Nm/kg)</b>													0.134]	<b><math>\eta^2 = 0.201</math></b>	$\eta^2 = 0.044$
														<b>[0.051, 0.328]</b>	[0.000, 0.154]
<b>Max</b>	0.561 ±	0.381 ±	0.435 ±	0.464 ±	0.541 ±	0.405 ±	0.329 ±	0.422 ±	0.553 ±	0.392 ±	0.387 ±	0.445 ±	F(2, 56) = 0.767, p	<b>F(2, 56) =</b>	F(1, 56) =
<b>abduction</b>	0.249	0.109	0.136	0.189	0.141	0.210	0.083	0.171	0.205 <sup>^#</sup>	0.160	0.125	0.181	= 0.469, partial $\eta^2$	<b>6.819, p =</b>	0.684, p =
<b>moment</b>													= 0.027 [0.000,	<b>0.002, partial</b>	0.412, partial
<b>(Nm/kg/m)</b>													0.103]	<b><math>\eta^2 = 0.196</math></b>	$\eta^2 = 0.012$
														<b>[0.048, 0.323]</b>	[0.000, 0.095]
<b>Min abduction</b>	-0.345	-0.211	-0.164	-0.241	-0.303	-0.228	-0.182	-0.236	-0.327	-0.219	-0.172	-0.239	F(2, 56) = 0.296, p	<b>F(2, 56) =</b>	F(1, 56) =
<b>moment</b>	± 0.212	± 0.069	± 0.106	± 0.163	± 0.172	± 0.146	± 0.110	± 0.147	± 0.193	±	±	± 0.155	= 0.745, partial $\eta^2$	<b>5.987, p =</b>	0.003, p =
<b>(Nm/kg/m)</b>										0.109*	0.106*		= 0.010 [0.000,	<b>0.004, partial</b>	0.954, partial
													0.060]	<b><math>\eta^2 = 0.176</math></b>	$\eta^2 = 0.000$
														<b>[0.036, 0.302]</b>	[0.000, 0.000]
<b>Range</b>	0.907 ±	0.592 ±	0.599 ±	0.706 ±	0.844	0.618 ±	0.511 ±	0.652 ±	0.890 ±	0.604 ±	0.559 ±	0.681 ±	F(2, 56) = 0.902, p	<b>F(2, 56) =</b>	F(1, 56) =
<b>abduction</b>	0.248	0.131	0.108	0.228	±0.212	0.154	0.116	0.212	0.230 <sup>^#</sup>	0.139	0.118	0.220	= 0.411, partial $\eta^2$	<b>20.604, p &lt;</b>	1.140, p =
<b>moment</b>													= 0.031 [0.000,	<b>0.001, partial</b>	0.343, partial
<b>(Nm/kg/m)</b>													0.112]	<b><math>\eta^2 = 0.424</math></b>	$\eta^2 = 0.016$
														<b>[0.245, 0.536]</b>	[0.000, 0.113]
<b>Max internal</b>	7.605 ±	3.759 ±	5.016 ±	5.560 ±	7.930 ±	6.292 ±	7.494 ±	7.248 ±	7.744 ±	4.959 ±	6.142 ±	6.322 ±	F(2, 56) = 0.282, p	F(2, 56) =	F(1, 56) =
<b>rotation angle</b>	4.205	5.339	6.555	5.532	4.091	5.219	6.107	5.094	4.055	5.296	6.331	5.362	= 0.755, partial $\eta^2$	1.298, p =	1.680, p =
<b>(°)</b>													= 0.010 [0.000,	0.281, partial	0.200, partial
													0.102]		$\eta^2 = 0.029$

															$\eta^2 = 0.044$	[0.000, 0.130]
															[0.000, 0.135]	[0.000, 0.130]
<b>Min internal rotation angle (°)</b>	-4.391 ± 7.167	-8.632 ± 5.780	-6.517 ± 8.393	-6.389 ± 7.259	-4.864 ± 5.367	-7.141 ± 6.183	-6.020 ± 5.524	-6.009 ± 5.559	-4.594 ± 6.311	-7.926 ± 5.855	-6.292 ± 7.074	-6.217 ± 6.498	F(2, 56) = 0.109, p = 0.897, partial $\eta^2 = 0.004$ [0.000, 0.025]	F(2, 56) = 1.198, p = 0.310, partial $\eta^2 = 0.041$ [0.000, 0.130]	F(1, 56) = 0.089, p = 0.767, partial $\eta^2 = 0.002$ [0.000, 0.052]	
<b>Range internal rotation angle (°)</b>	11.997 ± 5.339	12.392 ± 3.520	11.533 ± 3.783	11.949 ± 4.216	12.794 ± 3.163	13.434 ± 7.129	13.515 ± 2.975	13.257 ± 4.591	12.338 ± 4.454	12.885 ± 5.391	12.434 ± 3.508	12.540 ± 4.402	F(2, 56) = 0.314, p = 0.732, partial $\eta^2 = 0.011$ [0.000, 0.063]	F(2, 56) = 0.044, p = 0.573, partial $\eta^2 = 0.002$ [0.000, 0.000]	F(1, 56) = 1.367, p = 0.247, partial $\eta^2 = 0.024$ [0.000, 0.120]	
<b>Max internal rotation moment (Nm/kg)</b>	0.503 ± 0.116	0.562 ± 0.111	0.559 ± 0.221	0.540 ± 0.158	0.509 ± 0.177	0.519 ± 0.152	0.515 ± 0.083	0.514 ± 0.136	0.506 ± 0.141	0.542 ± 0.130	0.539 ± 0.170	0.529 ± 0.148	F(2, 56) = 0.185, p = 0.832, partial $\eta^2 = 0.007$ [0.000, 0.043]	F(2, 56) = 0.314, p = 0.732, partial $\eta^2 = 0.011$ [0.000, 0.063]	F(1, 56) = 0.497, p = 0.484, partial $\eta^2 = 0.009$ [0.000, 0.086]	
<b>Min internal rotation moment (Nm/kg)</b>	-0.131 ± 0.140	-0.088 ± 0.073	-0.053 ± 0.051	-0.091 ± 0.100	-0.086 ± 0.096	-0.052 ± 0.050	-0.038 ± 0.047	-0.058 ± 0.068	-0.112 ± 0.123	-0.071 ± 0.064	-0.046 ± 0.048	-0.076 ± 0.088	F(2, 56) = 0.361, p = 0.699, partial $\eta^2 = 0.013$ [0.000, 0.068]	F(2, 56) = 2.528, p = 0.089, partial $\eta^2 = 0.083$ [0.000, 0.192]	F(1, 56) = 3.218, p = 0.078, partial $\eta^2 = 0.054$ [0.000, 0.171]	
<b>Range internal rotation</b>	0.634 ± 0.131	0.651 ± 0.100	0.612 ± 0.211	0.631 ± 0.153	0.595 ± 0.155	0.570 ± 0.127	0.553 ± 0.095	0.572 ± 0.123	0.617 ± 0.139	0.612 ± 0.118	0.585 ± 0.168	0.604 ± 0.143	F(2, 56) = 0.102, p = 0.903, partial $\eta^2 = 0.004$ [0.000, 0.023]	F(2, 56) = 0.308, p = 0.736, partial $\eta^2 = 0.044$	F(1, 56) = 2.581, p = 0.114, partial $\eta^2 = 0.044$	

<b>moment</b> <b>(Nm/kg)</b>														$\eta^2 = 0.011$	[0.000,
														[0.000, 0.062]	0.155]
<b>Max internal</b>	0.364 ±	0.329 ±	0.314 ±	0.336 ±	0.356 ±	0.315 ±	0.317 ±	0.329 ±	0.361 ±	0.323 ±	0.315 ±	0.333 ±	F(2, 56) = 0.308, p	F(2, 56) =	F(1, 56) =
<b>rotation</b>	0.093	0.054	0.122	0.096	0.122	0.089	0.045	0.088	0.103	0.071	0.093	0.091	= 0.736, partial $\eta^2$	1.000, p =	0.011, p =
<b>moment</b> <b>(Nm/kg/m)</b>													= 0.011 [0.000,	0.374, partial	0.918, partial
													0.062]	$\eta^2 = 0.034$	$\eta^2 = 0.000$
														[0.000, 0.118]	[0.000,
															0.017]
<b>Min internal</b>	-0.093	-0.053	-0.030	-0.059	-0.062	-0.033	-0.024	-0.039	-0.080	-0.043	-0.027	-0.050	F(2, 56) = 0.572, p	<b>F(2, 56) =</b>	F(1, 56) =
<b>rotation</b>	± 0.097	± 0.048	± 0.029	± 0.069	± 0.072	± 0.032	± 0.029	± 0.049	± 0.086	± 0.042	±	± 0.061	= 0.568, partial $\eta^2$	<b>3.754, p =</b>	2.735, p =
<b>moment</b> <b>(Nm/kg/m)</b>											0.028*		= 0.020 [0.000,	<b>0.030, partial</b>	0.104, partial
													0.088]	<b><math>\eta^2 = 0.118</math></b>	$\eta^2 = 0.047$
														<b>[0.007, 0.237]</b>	[0.000,
															0.159]
<b>Range</b>	0.457 ±	0.383 ±	0.344 ±	0.395 ±	0.418 ±	0.348 ±	0.341 ±	0.368 ±	0.441 ±	0.366 ±	0.342 ±	0.383 ±	F(2, 56) = 0.258, p	<b>F(2, 56) =</b>	F(1, 56) =
<b>internal</b>	0.098	0.055	0.116	0.104	0.109	0.076	0.053	0.086	0.102 <sup>^#</sup>	0.066	0.091	0.097	= 0.774, partial $\eta^2$	<b>6.498, p =</b>	1.264, p =
<b>rotation</b>													= 0.009 [0.000,	<b>0.003, partial</b>	0.266, partial
<b>moment</b> <b>(Nm/kg/m)</b>													0.055]	<b><math>\eta^2 = 0.188</math></b>	$\eta^2 = 0.022$
														<b>[0.044, 0.315]</b>	[0.000,
															0.117]

Key: **Bold** =  $p < 0.05$ . \* = higher than pre, ^ higher than mid, # higher than post, “ = higher than M total, ‘ = higher than F today, † = higher than M in same maturation stage, † = higher than F in same maturation stage.

**Appendix AG** VERT task all calculated knee angles (°) and moments (Nm) of the non-dominant limb according to sex and maturation stage. All variables are presented as mean ± SD.

Sex	M				F				Total				Interaction effect sex*maturation	Main effect Maturation	Main effect Sex
	Maturation group	Pre	Mid	Post	Total M	Pre	Mid	Post	Total F	Pre	Mid	Post			
<b>Max flexion angle (°)</b>	57.533	59.430	59.216	58.652	61.853	56.273	63.255	60.560	59.384	57.934	61.235	59.542	F(2, 54) = 1.186,	F(2, 54) =	F(1, 54) =
	± 9.286	± 9.913	± 7.777	± 8.802	± 10.342	± 5.565	± 7.325	± 8.254	± 9.747	± 8.095	± 7.639	± 8.532	p = 0.313, partial η <sup>2</sup> = 0.042 [0.000, 0.129]	0.760, p = 0.473, partial η <sup>2</sup> = 0.027 [0.000, 0.102]	0.609, p = 0.439, partial η <sup>2</sup> = 0.011 [0.000, 0.092]
<b>Min flexion angle (°)</b>	12.393	15.428	13.480	13.681	11.204	11.918	17.214	13.580	11.883	13.765	15.347	13.634	F(2, 54) = 2.608,	F(2, 54) =	F(1, 54) =
	± 5.477	± 6.196	± 5.359	± 5.636	± 2.908	± 4.814	± 4.744	± 4.956	± 4.499	± 5.722	± 5.285	± 5.285	p = 0.083, partial η <sup>2</sup> = 0.088 [0.000, 0.196]	2.485, p = 0.093, partial η <sup>2</sup> = 0.084 [0.000, 0.191]	0.060, p = 0.808, partial η <sup>2</sup> = 0.001 [0.000, 0.045]
<b>Range flexion angle (°)</b>	45.140	44.003	45.736	44.971	50.648	44.354	46.041	46.980	47.501	44.169	45.888	45.908	F(2, 54) = 0.761,	F(2, 54) =	F(1, 54) =
	± 8.764	± 8.193	± 5.296	± 7.442	± 10.376	± 5.996	± 6.266	± 7.921	± 9.649	± 7.041	± 5.649	± 7.671	p = 0.472, partial η <sup>2</sup> = 0.027 [0.000, 0.102]	1.153, p = 0.323, partial η <sup>2</sup> = 0.041 [0.000, 0.127]	1.058, p = 0.308, partial η <sup>2</sup> = 0.019 [0.000, 0.110]

<b>Max flexion moment (Nm/kg)</b>	0.682 ± 0.253	0.728 ± 0.188	0.783 ± 0.194	0.723 ± 0.214	0.774 ± 0.191	0.763 ± 0.205	0.577 ± 0.211	0.700 ± 0.217	0.722 ± 0.228	0.744 ± 0.192	0.680 ± 0.224	0.715 ± 0.214	F(2, 54) = 2.835, p = 0.068, partial η <sup>2</sup> = 0.095 [0.000, 0.204]	F(2, 54) = 0.514, p = 0.601, partial η <sup>2</sup> = 0.019 [0.000, 0.083]	F(1, 54) = 0.235, p = 0.630, partial η <sup>2</sup> = 0.004 [0.000, 0.069]
<b>Min flexion moment (Nm/kg)</b>	-2.261 ± 0.482	-2.483 ± 0.633	-2.633 ± 0.641	-2.447 ± 0.547	-2.555 ± 0.506	-2.706 ± 0.339	-2.542 ± 0.522	-2.599 ± 0.454	-2.387 ± 0.502	-2.588 ± 0.435	-2.587 ± 0.571	-2.518 ± 0.508	F(2, 54) = 0.813, p = 0.449, partial η <sup>2</sup> = 0.029 [0.000, 0.106]	F(2, 54) = 0.869, p = 0.425, partial η <sup>2</sup> = 0.031 [0.000, 0.110]	F(1, 54) = 1.163, p = 0.286, partial η <sup>2</sup> = 0.021 [0.000, 0.114]
<b>Range flexion moment (Nm/kg)</b>	2.944 ± 0.536	3.211 ± 0.633	3.415 ± 0.650	3.175 ± 0.617	3.329 ± 0.587	3.469 ± 0.458	3.119 ± 0.539	3.299 ± 0.532	3.109 ± 0.578	3.333 ± 0.558	3.267 ± 0.600	3.233 ± 0.577	F(2, 54) = 2.023, p = 0.142, partial η <sup>2</sup> = 0.070 [0.000, 0.171]	F(2, 54) = 0.645, p = 0.529, partial η <sup>2</sup> = 0.023 [0.000, 0.094]	F(1, 54) = 0.609, p = 0.438, partial η <sup>2</sup> = 0.011 [0.000, 0.092]
<b>Max flexion moment (Nm/kg/m)</b>	0.497 ± 0.202	0.426 ± 0.095	0.437 ± 0.104	0.456 ± 0.146	0.543 ± 0.126	0.462 ± 0.107	0.358 ± 0.138	0.451 ± 0.143	0.517 ± 0.171 <sup>#</sup>	0.443 ± 0.100	0.398 ± 0.125	0.454 ± 0.143	F(2, 54) = 2.224, p = 0.118, partial η <sup>2</sup> = 0.076 [0.000, 0.180]	<b>F(2, 54) = 3.970, p = 0.025, partial η<sup>2</sup> = 0.128 [0.009, 0.244]</b>	F(1, 54) = 0.018, p = 0.893, partial η <sup>2</sup> = 0.000 [0.000, 0.025]

<b>Min flexion moment (Nm/kg/m)</b>	-1.629 ± 0.345	-1.457 ± 0.256	-1.474 ± 0.366	-1.527 ± 0.326	-1.786 ± 0.313	-1.649 ± 0.154	-1.562 ± 0.292	-1.662 ± 0.271	-1.696 ± 0.333	-1.548 ± 0.230	-1.518 ± 0.326	-1.590 ± 0.307	F(2, 54) = 0.151, p = 0.860, partial $\eta^2$ = 0.006 [0.000, 0.036]	F(2, 54) = 2.304, p = 0.110, partial $\eta^2$ = 0.079 [0.000, 0.183]	F(1, 54) = 3.507, p = 0.067, partial $\eta^2$ = 0.061 [0.000, 0.177]
<b>Range flexion moment (Nm/kg/m)</b>	2.126 ± 0.415	1.883 ± 0.312	1.911 ± 0.367	1.983 ± 0.376	2.329 ± 0.362	2.111 ± 0.188	1.920 ± 0.299	2.329 ± 0.362	2.213 ± 0.397 <sup>^#</sup>	1.991 ± 0.279	1.916 ± 0.326	2.044 ± 0.358	F(2, 54) = 0.624, p = 0.540, partial $\eta^2$ = 0.023 [0.000, 0.092]	<b>F(2, 54) = 4.694, p = 0.013, partial <math>\eta^2</math> = 0.148 [0.018, 0.267]</b>	F(1, 54) = 2.834, p = 0.098, partial $\eta^2$ = 0.050 [0.000, 0.161]
<b>Max abduction angle (°)</b>	7.129 ± 3.326	5.160 ± 6.710	3.470 ± 3.583	5.370 ± 4.806	7.234 ± 3.969	5.285 ± 3.999	5.161 ± 6.581	5.867 ± 4.976	7.174 ± 3.520	5.219 ± 5.443	4.315 ± 5.229	5.602 ± 4.851	F(2, 54) = 0.173, p = 0.841, partial $\eta^2$ = 0.006 [0.000, 0.041]	F(2, 54) = 1.830, p = 0.170, partial $\eta^2$ = 0.063 [0.000, 0.162]	F(1, 54) = 0.256, p = 0.615, partial $\eta^2$ = 0.005 [0.000, 0.071]
<b>Min abduction angle (°)</b>	-0.683 ± 3.510	-2.429 ± 3.847	-2.986 ± 2.951	-1.948 ± 3.498	-0.619 ± 4.703	-3.083 ± 4.999	-2.735 ± 5.299	-2.167 ± 4.703	-0.655 ± 3.953	-2.739 ± 4.315	-2.860 ± 4.177	-2.050 ± 4.203	F(2, 54) = 0.061, p = 0.941, partial $\eta^2$ = 0.002 [0.000, 0.006]	F(2, 54) = 1.737, p = 0.186, partial $\eta^2$ = 0.060 [0.000, 0.158]	F(1, 54) = 0.010, p = 0.919, partial $\eta^2$ = 0.000 [0.000, 0.016]

<b>Range</b>	7.811 ±	7.589 ±	6.456 ±	7.318 ±	7.854 ±	8.367 ±	7.896 ±	8.034 ±	7.811 ±	7.589 ±	6.456 ±	7.318 ±	F(2, 54) = 0.437,	F(2, 54) =	F(1, 54) =
<b>abduction</b>	1.655	3.007	1.762	2.204	2.414	2.944	2.376	2.496	1.655	3.007	1.762	2.204	p = 0.648, partial	0.637, p =	1.488, p =
<b>angle (°)</b>													η <sup>2</sup> = 0.016 [0.000,	0.533, partial	0.228,
													0.076]	η <sup>2</sup> = 0.023	partial η <sup>2</sup> =
														[0.000, 0.093]	0.027
															[0.000,
															0.145]
<b>Max</b>	0.675 ±	0.818 ±	0.643 ±	0.709 ±	0.648 ±	0.635 ±	0.537 ±	0.604 ±	0.663 ±	0.731 ±	0.590 ±	0.660 ±	F(2, 54) = 0.421,	F(2, 54) =	F(1, 54) =
<b>abduction</b>	0.228	0.227	0.221	0.231	0.355	0.313	0.256	0.301	0.281	0.280	0.239	0.269	p = 0.659, partial	1.272, p =	2.311, p =
<b>moment</b>													η <sup>2</sup> = 0.015 [0.000,	0.289, partial	0.134,
<b>(Nm/kg)</b>													0.074]	η <sup>2</sup> = 0.045	partial η <sup>2</sup> =
														[0.000, 0.134]	0.041
															[0.000,
															0.148]
<b>Min abduction</b>	-0.443	-0.322	-0.216	-0.334	-0.412	-0.348	-0.333	-0.363	-0.430	-0.334	-0.275	-0.348	F(2, 54) = 0.584,	F(2, 54) =	F(1, 54) =
<b>moment</b>	± 0.342	± 0.120	± 0.125	± 0.244	± 0.211	± 0.232	± 0.163	± 0.198	± 0.287	± 0.177	± 0.154	± 0.222	p = 0.561, partial	2.515, p =	0.440, p =
<b>(Nm/kg)</b>													η <sup>2</sup> = 0.021 [0.000,	0.090, partial	0.510,
													0.089]	η <sup>2</sup> = 0.085	partial η <sup>2</sup> =
														[0.000, 0.192]	0.008
															[0.000,
															0.083]
<b>Range</b>	1.118 ±	1.139 ±	0.859 ±	1.044 ±	1.060 ±	0.983 ±	0.870 ±	0.967 ±	1.093 ±	1.065 ±	0.865 ±	1.008 ±	F(2, 54) = 0.569,	<b>F(2, 54) =</b>	F(1, 54) =
<b>abduction</b>	0.321	0.226	0.251	0.286	0.215	0.245	0.208	0.229	0.276 <sup>#</sup>	0.243 <sup>#</sup>	0.209	0.261	p = 0.570, partial	<b>4.938, p =</b>	1.125, p =
<b>moment</b>													η <sup>2</sup> = 0.021 [0.000,	<b>0.011, partial</b>	0.293,
<b>(Nm/kg)</b>													0.088]	<b>η<sup>2</sup> = 0.155</b>	partial η <sup>2</sup> =
														<b>[0.021, 0.274]</b>	0.020
															[0.000,
															0.112]
<b>Max</b>	0.487 ±	0.477 ±	0.360 ±	0.443 ±	0.457 ±	0.384 ±	0.331 ±	0.389 ±	0.473 ±	0.433 ±	0.345 ±	0.418 ±	F(2, 54) = 0.239,	F(2, 54) =	F(1, 54) =
<b>abduction</b>	0.155	0.116	0.122	0.142	0.257	0.180	0.156	0.200	0.200	0.153	0.137	0.172	p = 0.788, partial	2.943, p =	1.299, p =

<b>moment</b> (Nm/kg/m)													$\eta^2 = 0.009$ [0.000, 0.052]	0.061, partial $\eta^2 = 0.098$ [0.000, 0.208]	0.259, partial $\eta^2 =$ 0.023 [0.000, 0.118]
<b>Min abduction</b> <b>moment</b> (Nm/kg/m)	-0.321 $\pm 0.251$	-0.191 $\pm 0.075$	-0.121 $\pm 0.071$	-0.218 $\pm 0.181$	-0.292 $\pm 0.158$	-0.215 $\pm 0.147$	-0.210 $\pm 0.116$	-0.238 $\pm 0.140$	-0.309 $\pm 0.211$	-0.202 $\pm 0.112^*$	-0.166 $\pm 0.104^*$	-0.227 $\pm 0.162$	F(2, 54) = 0.744, $p = 0.480$ , partial $\eta^2 = 0.101$ [0.000, 0.101]	<b>F(2, 54) =</b> <b>4.616, p =</b> <b>0.014, partial</b> <b><math>\eta^2 = 0.146</math></b> <b>[0.017, 0.264]</b>	F(1, 54) = 0.595, $p =$ 0.444, partial $\eta^2 =$ 0.011 [0.000, 0.091]
<b>Range</b> <b>abduction</b> <b>moment</b> (Nm/kg/m)	0.806 $\pm$ 0.231	0.668 $\pm$ 0.118	0.481 $\pm$ 0.123	0.661 $\pm$ 0.214	0.750 $\pm$ 0.173	0.600 $\pm$ 0.143	0.541 $\pm$ 0.148	0.627 $\pm$ 0.170	0.781 $\pm$ 0.205 <sup>^#</sup>	0.636 $\pm$ 0.132 <sup>^#</sup>	0.511 $\pm$ 0.136	0.645 $\pm$ 0.196	F(2, 54) = 0.932, $p = 0.400$ , partial $\eta^2 = 0.033$ [0.000, 0.114]	<b>F(2, 54) =</b> <b>13.428, p &lt;</b> <b>0.001, partial</b> <b><math>\eta^2 = 0.332</math></b> <b>[0.148, 0.447]</b>	F(1, 54) = 0.256, $p =$ 0.615, partial $\eta^2 =$ 0.005 [0.000, 0.071]
<b>Max internal</b> <b>rotation angle</b> (°)	9.893 $\pm$ 8.631	7.890 $\pm$ 5.547	6.907 $\pm$ 7.150	8.334 $\pm$ 7.202	9.446 $\pm$ 5.646	6.134 $\pm$ 5.520	7.343 $\pm$ 4.519	7.630 $\pm$ 5.211	9.701 $\pm$ 7.333	7.058 $\pm$ 5.454	7.125 $\pm$ 5.826	8.006 $\pm$ 6.309	F(2, 54) = 0.142, $p = 0.868$ , partial $\eta^2 = 0.005$ [0.000, 0.034]	F(2, 54) = 1.098, $p =$ 0.341, partial $\eta^2 = 0.039$ [0.000, 0.124]	F(1, 54) = 0.124, $p =$ 0.726, partial $\eta^2 =$ 0.002 [0.000, 0.058]
<b>Min internal</b> <b>rotation angle</b> (°)	-4.349 $\pm 7.856$	-3.974 $\pm 6.997$	-4.565 $\pm 5.776$	-4.299 $\pm 6.771$	-2.149 $\pm 4.850$	-5.623 $\pm 5.892$	-7.822 $\pm 5.860$	-5.291 $\pm 5.865$	-3.406 $\pm 6.678$	-4.755 $\pm 6.373$	-6.194 $\pm 5.904$	-4.762 $\pm 6.331$	F(2, 54) = 0.982, $p = 0.381$ , partial $\eta^2 = 0.035$ [0.000, 0.117]	F(2, 54) = 1.083, $p =$ 0.346, partial	F(1, 54) = 0.297, $p =$ 0.588, partial $\eta^2 =$

														$\eta^2 = 0.039$	0.005
														[0.000, 0.123]	[0.000, 0.074]
<b>Range</b>	14.242	11.864	11.472	12.633	11.594	11.757	15.165	12.922	13.107	11.813	13.319	12.768	<b>F(2, 54) = 3.404,</b>	F(2, 54) =	F(1, 54) =
<b>internal</b>	$\pm 5.186$	$\pm 3.603$	$\pm 4.762$	$\pm 4.639$	$\pm 2.450$	$\pm 3.597$	$\pm$	$\pm 3.212$	$\pm 4.368$	$\pm 3.232$	$\pm 4.303$	$\pm 4.007$	<b>p = 0.041, partial</b>	0.781, p =	0.096, p =
<b>rotation angle</b>							2.972*						<b><math>\eta^2 = 0.112</math></b>	0.463, partial	0.758,
<b>(°)</b>													<b>[0.003, 0.225]</b>	$\eta^2 = 0.028$	partial $\eta^2 =$
														[0.000, 0.104]	0.002
															[0.000, 0.053]
<b>Max internal</b>	0.417 $\pm$	0.527 $\pm$	0.482 $\pm$	0.472 $\pm$	0.444 $\pm$	0.443 $\pm$	0.375 $\pm$	0.419 $\pm$	0.429 $\pm$	0.487 $\pm$	0.428 $\pm$	0.447 $\pm$	F(2, 54) = 0.997,	F(2, 54) =	F(1, 54) =
<b>rotation</b>	0.129	0.165	0.175	0.158	0.160	0.189	0.145	0.162	0.140	0.177	0.166	0.161	p = 0.376, partial	0.769, p =	1.735, p =
<b>moment</b>													$\eta^2 = 0.036$ [0.000,	0.468, partial	0.193,
<b>(Nm/kg)</b>													0.118]	$\eta^2 = 0.028$	partial $\eta^2 =$
														[0.000, 0.103]	0.031
															[0.000, 0.132]
<b>Min internal</b>	-0.148	-0.091	-0.084	-0.110	-0.132	-0.100	-0.059	-0.096	-0.141	-0.095	-0.072	-0.103	F(2, 54) = 0.271,	<b>F(2, 54) =</b>	F(1, 54) =
<b>rotation</b>	$\pm 0.093$	$\pm 0.063$	$\pm 0.072$	$\pm 0.082$	$\pm 0.062$	$\pm 0.083$	$\pm 0.061$	$\pm 0.073$	$\pm 0.080$	$\pm 0.071$	$\pm$	$\pm 0.077$	p = 0.763, partial	<b>4.439, p =</b>	0.303, p =
<b>moment</b>													$\eta^2 = 0.010$ [0.000,	<b>0.016, partial</b>	0.584,
<b>(Nm/kg)</b>													0.057]	<b><math>\eta^2 = 0.141</math></b>	partial $\eta^2 =$
														<b>[0.015, 0.259]</b>	0.006
															[0.000, 0.075]
<b>Range</b>	0.566 $\pm$	0.617 $\pm$	0.566 $\pm$	0.582 $\pm$	0.575 $\pm$	0.543 $\pm$	0.435 $\pm$	0.515 $\pm$	0.570 $\pm$	0.582 $\pm$	0.500 $\pm$	0.550 $\pm$	F(2, 54) = 0.936,	F(2, 54) =	F(1, 54) =
<b>internal</b>	0.117	0.169	0.232	0.171	0.178	0.164	0.106	0.158	0.142	0.166	0.188	0.167	p = 0.399, partial	1.400, p =	2.344, p =
<b>rotation</b>													$\eta^2 = 0.033$ [0.000,	0.255, partial	0.132,
<b>moment</b>													0.114]	$\eta^2 = 0.049$	partial $\eta^2 =$
<b>(Nm/kg)</b>														[0.000, 0.141]	0.042

																[0.000, 0.149]
<b>Max internal rotation moment (Nm/kg/m)</b>	0.300 ± 0.091	0.308 ± 0.091	0.269 ± 0.098	0.293 ± 0.092	0.316 ± 0.126	0.268 ± 0.106	0.229 ± 0.087	0.269 ± 0.109	0.307 ± 0.105	0.289 ± 0.098	0.249 ± 0.092	0.282 ± 0.100	<b>F(2, 54) = 3.970, p = 0.025, partial η<sup>2</sup> = 0.128 [0.009, 0.251]</b>	F(2, 54) = 1.827, p = 0.171, partial η <sup>2</sup> = 0.063 [0.000, 0.162]	F(1, 54) = 0.679, p = 0.413, partial η <sup>2</sup> = 0.012 [0.000, 0.095]	
<b>Min internal rotation moment (Nm/kg/m)</b>	-0.109 ± 0.071	-0.053 ± 0.036	-0.047 ± 0.040	-0.072 ± 0.059	-0.093 ± 0.048	-0.061 ± 0.050	-0.039 ± 0.044	-0.063 ± 0.051	-0.102 ± 0.061	-0.057 ± 0.043*	-0.043 ± 0.041*	-0.068 ± 0.055	F(2, 54) = 0.293, p = 0.747, partial η <sup>2</sup> = 0.011 [0.000, 0.060]	<b>F(2, 54) = 7.405, p &lt; 0.001, partial η<sup>2</sup> = 0.215 [0.057, 0.337]</b>	F(1, 54) = 0.174, p = 0.678, partial η <sup>2</sup> = 0.003 [0.000, 0.064]	
<b>Range internal rotation moment (Nm/kg/m)</b>	0.410 ± 0.095	0.361 ± 0.091	0.316 ± 0.129	0.365 ± 0.109	0.409 ± 0.145	0.330 ± 0.088	0.267 ± 0.062	0.333 ± 0.116	0.409 ± 0.116 <sup>#</sup>	0.346 ± 0.088	0.292 ± 0.102	0.350 ± 0.113	F(2, 54) = 0.272, p = 0.763, partial η <sup>2</sup> = 0.010 [0.000, 0.057]	<b>F(2, 54) = 6.461, p &lt; 0.003, partial η<sup>2</sup> = 0.193 [0.043, 0.314]</b>	F(1, 54) = 0.979, p = 0.327, partial η <sup>2</sup> = 0.018 [0.000, 0.107]	

Key: **Bold** = p < 0.05. \* = higher than pre, ^ higher than mid, # higher than post, “ = higher than M total, ‘ = higher than F today, † = higher than M in same maturation stage, ‡ = higher than F in same maturation stage.

## Appendix AH Co-authorship form for chapter two.



### Co-Authorship Form

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Chapter 2- Systematic review. Maturation and biomechanical risk factors associated with Anterior cruciate ligament injury: Is there a link? A systematic review.  
Butcher, A. J., Ward, S., Clissold, T., Richards, J., & Hebert-Losier, K. (2024). Phys Ther Sport 2024;68:31-50. doi:10.1016/j.ptsp.2024.06.002  
PMID: 3890822

Nature of contribution by PhD candidate	Design, literature search, quality assessment screening, risk of bias screening, figure design and creation, writing.
Extent of contribution by PhD candidate (%)	90%

#### CO-AUTHORS

Name	Nature of Contribution
Kim Hebert-Losier	Design, supervision, risk of bias screening, editing
Sarah Ward	Design, literature search, editing
Tracey Clissold	Design, editing
Jim Richards	Design, editing

#### Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ that the candidate wrote all or the majority of the text.

Name	Signature	Date
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Sarah Ward		23-06-2025
Jim Richards		23-06-25
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## Appendix A1 Co-authorship form for chapter three.



### Co-Authorship Form

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This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in your appendices for all the copies of your thesis submitted for examination and library deposit (including digital deposit).

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 3- Pilot study. Maximise or normalise? Examining single-leg drop-land-cut distances in young athletes. A pilot study. Submitted to Journal of Applied Biomechanics.

Nature of contribution by PhD candidate: Research design, participant recruitment, data collection, statistical analysis, writing

Extent of contribution by PhD candidate (%): 90%

#### CO-AUTHORS

Name	Nature of Contribution
Kim Hebert-Losier	Design, supervision, statistical analysis assistance, editing
Tracey Clissold	Design, editing
Sarah Ward	Design, editing
Jim Richards	Design, editing

#### Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ that the candidate wrote all or the majority of the text.

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**Appendix AJ** Between session reliability of knee marker placement collected from the static trials on the dominant and non-dominant legs.

	Trial A ± SD	Trial B ± SD	Diff ± SD	TE [lower, upper]	CV% [lower, upper]	Average measures ICC [95% CI]	Single measures ICC [95% CI]	ICC p-value	Paired t-test p value
<b>Metrics Dominant leg</b>									
Med to lat X	-3.55 ± 13.21	-5.29 ± 15.56	-1.74 ± 12.89	9.11 [6.67, 14.3]	206.24 [150.99, 325.26]	0.760 [0.276, 0.920]	0.613 [0.160, 0.852]	0.007	0.610
Med to lat Y	-88.89 ± 61.17	-83.54 ± 59.40	5.35 ± 14.20	10.04 [7.35, 15.84]	11.65 [8.53, 18.37]	0.985 [0.955, 0.995]	0.970 [0.914, 0.990]	<0.001	0.166
Med to lat Z	11.62 ± 6.65	10.22 ± 6.61	-1.40 ± 9.91	7.00 [5.13, 11.05]	64.13 [46.95, 101.15]	0.371 [-0.272, 0.754]	0.227 [-0.120, 0.605]	0.050	0.593
Med to mid tibia X	1.62 ± 6.65	3.41 ± 7.92	1.80 ± 7.67	5.42 [3.97, 8.55]	215.44 [157.73, 339.77]	0.624 [-0.103, 0.873]	0.454 [-0.049, 0.775]	0.040	0.379
Med to mid tibia Y	44.48 ± 30.60	33.06 ± 48.11	-11.41 ± 40.23	28.45 [20.83, 44.86]	73.37 [53.72, 115.72]	0.665 [0.040, 0.886]	0.499 [0.020, 0.796]	0.024	0.291
Med to mid tibia Z	-5.80 ± 3.32	-4.42 ± 4.73	1.38 ± 6.10	4.31 [3.16, 6.80]	84.44 [61.82, 133.17]	0.288 [-0.272, 0.695]	0.168 [-0.120, 0.532]	0.102	0.396
Lat to mid tibia X	-1.93 ± 6.55	-3.26 ± 7.65	-1.33 ± 6.85	4.85 [3.55, 7.64]	186.64 [136.65, 294.35]	0.705 [0.122, 0.901]	0.544 [0.065, 0.820]	0.016	0.466
Lat to mid tibia Y	-44.42 ± 30.57	-36.52 ± 38.31	7.89 ± 26.79	18.94 [13.87, 29.87]	46.80 [34.26, 73.81]	0.822 [0.487, 0.939]	0.697 [0.322, 0.886]	0.001	0.273
Lat to mid tibia Z	5.82 ± 3.33	4.71 ± 4.02	-1.11 ± 5.53	3.91 [2.86, 6.16]	74.18 [54.31, 116.98]	0.348 [-0.298, 0.739]	0.210 [-0.130, 0.585]	0.091	0.448
<b>Metrics Non-Dominant leg</b>									
Med to lat X	1.48 ± 12.91	1.36 ± 12.34	-0.12 ± 11.95	8.45 [6.19, 13.33]	595.34 [435.86, 938.91]	0.725 [0.149, 0.909]	0.569 [0.080, 0.833]	0.013	0.968
Med to lat Y	87.99 ± 61.73	88.32 ± 56.69	0.33 ± 7.22	5.11 [3.74, 8.06]	5.79 [4.24, 9.14]	0.997 [0.990, 0.999]	0.993 [0.979, 0.998]	<0.001	0.863
Med to lat Z	12.95 ± 7.20	13.09 ± 6.60	0.14 ± 10.25	7.25 [5.31, 11.43]	55.69 [40.77, 87.83]	0.364 [-0.243, 0.754]	0.222 [-0.108, 0.605]	0.027	0.958
Med to mid tibia X	-0.89 ± 6.56	-0.83 ± 6.22	0.06 ± 6.04	4.27 [3.12, 6.73]	496.46 [363.47, 782.97]	0.727 [0.153, 0.909]	0.571 [0.083, 0.834]	0.013	0.970
Med to mid tibia Y	-44.01 ± 30.87	-44.15 ± 28.34	-0.14 ± 3.61	2.56 [1.87, 4.03]	5.80 [4.24, 9.14]	0.997 [0.990, 0.999]	0.993 [0.979, 0.998]	<0.001	0.882
Med to mid tibia Z	-6.46 ± 3.60	-6.56 ± 3.33	-0.10 ± 5.18	3.67 [2.68, 5.78]	56.31 [41.23, 88.81]	0.209 [-0.428, 0.660]	0.117 [-0.176, 0.493]	0.246	0.942
Lat to mid tibia X	0.59 ± 6.35	0.53 ± 6.13	-0.06 ± 6.13	4.33 [3.17, 6.83]	773.90 [566.60, 1220.52]	0.697 [0.058, 0.900]	0.535 [0.030, 0.818]	0.020	0.968
Lat to mid tibia Y	43.98 ± 30.86	44.17 ± 28.34	0.19 ± 3.61	2.55 [1.87, 4.03]	5.80 [4.24, 9.14]	0.997 [0.990, 0.999]	0.993 [0.979, 0.998]	<0.001	0.844
Lat to mid tibia Z	6.49 ± 3.60	6.53 ± 3.27	0.04 ± 5.30	3.75 [2.75, 5.91]	57.60 [42.17, 90.83]	0.274 [-0.253, 0.682]	0.158 [-0.112, 0.517]	0.094	0.975

Note: CV, coefficient of variation; Diff, difference; ICC, intraclass correlation coefficient; Med, medial; Mid, middle; Lat, lateral; SD, standard deviation; TE, typical error.

## Appendix AK Descriptions of the biomechanical metrics.

Metric	Description
Peak flexion angle (°)	Maximum knee bend (largest flexion angle) from initial ground contact to peak knee flexion.
Peak extension angle (°)	Maximum knee straightening (smallest flexion angle) from initial ground contact to peak knee flexion.
Range sagittal angle (°)	Difference between maximum flexion and extension angles - total knee motion in the sagittal plane.
Peak flexion moment (Nm/kg/m)	Maximum external moment loading the knee into flexion, relative to mass and height.
Peak extension moment (Nm/kg/m)	Maximum external moment loading the knee into extension, relative to mass and height.
Range sagittal moment (Nm/kg/m)	Difference between peak flexion and extension moments - overall sagittal plane loading span.
Peak valgus angle (°)	Maximum medial angulation between the femur and shank in the frontal plane – tibial abduction (knee collapsing inward).
Peak varus angle (°)	Maximum lateral angulation between the femur and shank in the frontal plane – tibial adduction (knee collapsing outward).
Range coronal angle (°)	Total angular motion in the coronal plane (tibial abduction–adduction).
Peak valgus moment (Nm/kg/m)	Maximum external moment driving the knee inward.
Peak varus moment (Nm/kg/m)	Maximum external moment driving the knee outward.
Range coronal moment (Nm/kg/m)	Difference between peak valgus and varus moments - overall frontal plane loading span.
Peak internal rotation angle (°)	Maximum inward twist of the tibia relative to the femur.
Peak external rotation angle (°)	Maximum outward twist of the tibia relative to the femur.
Range transverse angle (°)	Total rotation range (tibial internal–external twist).
Peak internal rotation moment (Nm/kg/m)	Maximum external moment twisting the tibia inward.
Peak external rotation moment (Nm/kg/m)	Maximum external moment twisting the tibia outward.
Range transverse moment (Nm/kg/m)	Difference between peak internal and external rotation moments – overall transverse plane loading span.
Peak vertical GRF (BW)	Maximum vertical force relative to body weight - impact load at landing.
Peak anterior GRF (BW)	Maximum forward-directed force (pushing the body backward).
Peak posterior GRF (BW)	Maximum backward-directed force (braking force).
Peak lateral GRF (BW)	Maximum outward-directed force (toward the body's lateral side).
Peak medial GRF (BW)	Maximum inward-directed force (toward the midline).
Time to PKF (s)	Time from initial ground contact to peak knee flexion - indicates how quickly the knee bends to absorb impact.