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Biomechanical differences across pubertal maturation stages and sexes in a single-leg drop-land and a single-leg drop-land-and-cut task

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ABSTRACT

Anterior cruciate ligament (ACL) injuries account for 45% of internal knee injuries, often having prolonged recovery and substantial care costs. Higher non-contact ACL injury rates have been reported in post-pubertal females compared with males and pre-pubertal individuals, which is potentially linked with biomechanical changes associated with musculoskeletal and neuromuscular development. Up to 80% of non-contact ACL injuries occur during single-leg landing or cutting; hence, a single-leg drop-land and single-leg drop-land-and-cut task were used to investigate the effect of sex and maturation on biomechanics associated with ACL injury risk. Sixty-nine males and females at three maturation stages (Males $n = 16$ pre-pubertal, 11 mid-pubertal, 11 post-pubertal; Females $n = 10$ pre-pubertal, 9 mid-pubertal, 10 post-pubertal) were categorised using Tanner stages, peak height velocity and the pubertal maturation observation scale. Biomechanical metrics were compared using 3D motion capture and force plate technology using a two-by-three-way ANOVA. Post-pubertal females did not exhibit biomechanics suggesting comparatively higher ACL injury risk. Pre-pubertal participants exhibited greater relative vertical ground reaction forces and knee moments that suggested a lack of resistance to potentially injurious positions, compared to the other groups. Implementing screening and injury prevention pre-puberty could help develop safer movement patterns that reduce ACL injury risk with maturation.

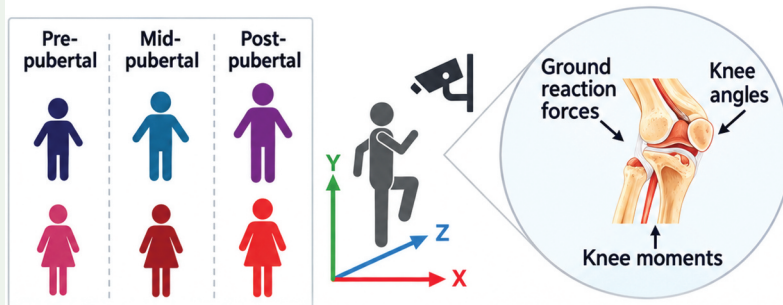
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Anterior cruciate ligament; maturation; biomechanics; sex; landing

Biomechanical differences across pubertal maturation stages and sexes in a single-leg drop-land and a single-leg drop-land-and-cut task



✗ No biomechanics suggesting increased ACL risk in post-pubertal females

- +** relative vertical ground reaction force in pre-pubertal
- +** knee varus moments in pre-pubertal
- +** external rotation moments in pre-pubertal

Early screening and prevention, pre-puberty, may help develop safer movement strategies and reduce ACL injury risk.

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Introduction

Anterior cruciate ligament (ACL) injuries are increasingly prevalent, particularly in young athletes (Hosseinizadeh & Kiapour, 2021; Maniar et al., 2022). Accounting for 45% of internal knee injuries (Majewski et al., 2006), the devastating nature of ACL injuries is augmented by prolonged recovery, substantial care costs (Janssen et al., 2012) and an increased risk of early-onset posttraumatic osteoarthritis (Lohmander et al., 2004; Nebelung & Wuschech, 2005). Non-contact mechanisms cause approximately 70% of all ACL tears (Boden et al., 2000) and usually involve single-leg landing or cutting manoeuvres (Koga et al., 2010; Yu & Garrett, 2007) that result in knee moments exceeding the loading capacity of the ACL.

Non-contact ACL injury rates have been reported up to eight times greater in females compared to males, illustrating sex differences during sporting participation (Mancino et al., 2023); however, these incidence rate differences do not appear until after puberty (Andrish, 2001). Biomechanical differences between sexes emerge at around 12 years old and appear to be exacerbated with age (Etzel et al., 2024; Lucarno et al., 2020; Sasaki et al., 2013; Yu et al., 2005).

Two mechanisms provide theoretic grounds for these maturation and sex-related changes in ACL injury risk biomechanics. Firstly, pubertal physical growth relative to neuromuscular development and strength is asynchronous for both sexes, potentially leading to increased joint loading during dynamic tasks (Hewett et al., 2004; Roemmich & Rogol, 1995). Secondly, hormonal changes, such as increased oestrogen levels in females, are associated with altered ligament morphology and laxity (Shultz & Fegley, 2023; Wild et al., 2012). Combined, these mechanisms propose that biomechanics associated with ACL injury risk changes across pubertal stages, potentially with greater or earlier magnitude in females.

Previous research has largely examined age-specific differences, with maturation status less consistently reported (Hewett et al., 2004; Roemmich & Rogol, 1995; Wild et al., 2012). Chronological age does not consider the considerable variation in growth, hormonal and neuromuscular changes between sexes and individuals (Roemmich & Rogol, 1995), hence classification by maturational stage, which considers biological processes, may better allow for appropriate isolation of mechanistically relevant differences in ACL injury-related biomechanics.

Few studies have addressed how ACL injury risk factors change across maturation, with the available literature using a variety of different, and therefore non-

standardised, maturation stage classification tools and tasks often not reflective of sport or ACL injury specific situations (Butcher et al., 2024). Sex-specific changes in height, mass, structural alignment (Wild et al., 2012) and hormones (Shultz & Fegley, 2023; Wild et al., 2012) are considered non-modifiable ACL injury risk factors. Changes to strength (Davidson & McLean, 2016), movement patterns, neuromuscular function and motor-control strategies (Atkins et al., 2016; Philippaerts et al., 2006; Van Der Sluis et al., 2013) are considered modifiable. Both modifiable and non-modifiable risk factors can contribute to ACL loading mechanics, which include excessive knee abduction angles and moments, internal or external tibial rotation, anterior tibial translation and a more extended knee angle upon landing (Acevedo et al., 2014; Holden et al., 2016; Quatman et al., 2009, 2010; Shimokochi & Shultz, 2008).

The double-leg drop jump task has been commonly used for ACL injury risk assessment (Ford et al., 2010; Hewett et al., 2004; Otsuki et al., 2021; Pedley et al., 2020; Sigward et al., 2012), but has been criticised for its mechanical simplicity, poor ACL injury prediction ability and lack of specificity to sporting/ injurious manoeuvres (Fox et al., 2017; Hanzlíková & Hébert-Losier, 2020; Krosshaug et al., 2016). Court- and field-based sports are largely comprised of unilateral manoeuvres, with running requiring single-leg support phases and landing and change-of-direction tasks characterised by high force production often through a single planted limb (Taylor et al., 2017). Up to 80% of non-contact ACL injuries occur during single-leg landing, cutting, or rotating manoeuvres (Koga et al., 2010); hence, tasks involving similar movements may better reflect sport and injury situation specific movement patterns. It should be noted that emerging research suggests potential for higher ACL injury risk during dual-tasking movements (Bertozzi et al., 2023), however, foundational knowledge in the absence of dual-tasking remains equivocal, with no clear consensus regarding sex- and maturation-related differences in landing biomechanics (Holden et al., 2016; Ramachandran et al., 2024).

Despite growing interest in maturation-related ACL injury mechanisms, the evidence base remains limited and skewed toward female populations, likely owing to the greater occurrence of non-contact ACL injuries in females (Maniar et al., 2022). A systematic review by Ramachandran et al. (2024) provides comprehensive evidence for maturation-related changes in ACL injury risk biomechanics, reporting increases in external knee abduction and internal rotation moments, and decreased relative vertical ground reaction force (vGRF)

with maturation, but is restricted to females and jump-landing tasks (Ramachandran et al., 2024). Furthermore, a recent systematic review, which pooled both sexes, found greater knee abduction angles and moments and knee flexion angles, and lower relative vGRFs in females in the later pubertal maturation stages compared to males (Butcher et al., 2024). However, this evidence was drawn from heterogeneous primary studies which used inconsistent maturation classification tools and tasks lacking sport-specificity. Currently, no single study has examined whether the maturational trajectories are comparable between sexes, nor whether they translate to sport-specific unilateral tasks, where most non-contact ACL injuries occur. Early identification of biomechanical differences, or how biomechanics may differ across puberty, could lead to early intervention which may mitigate later ACL injury risk.

This study aimed to investigate differences between sexes and pubertal maturation stages in biomechanics associated with ACL injury risk during a single-leg landing (LAND) and a single-leg drop-land-and-cut (CUT) task across. An additional aim was to establish the test-retest reliability of biomechanical metrics from these tasks associated with ACL injury risk to determine their suitability for identifying differences in movement patterns between maturational stages (Yeow et al., 2011). We hypothesised that biomechanical measures linked to higher ACL injury risk (including knee valgus angles and moments, knee flexion angles, and ground reaction forces), would be observed in late- to post-pubertal females compared with earlier maturational stages and compared with their male counterparts.

Methods

Participants

Ethical approval was obtained prior to participant recruitment (HREC [Health] 2022#53) and adhered to the Code of Ethics of the World Medical Association and the Health Research Council's guidelines relating to research involving children (McIntosh et al., 2000) and UNICEF's principles guiding ethical research involving children (Graham et al., 2013).

Sample size calculations were performed in G*Power 3.1.9.7 *a priori* using the 'ANOVA: Fixed effects, special,

main effects and interactions' setting. Previously, Kim and Lim (Kim & Lim, 2014) detected a *large* effect size difference in knee abduction moment ($f = 0.5$) between pre-menarche and post-menarche females during a single-leg drop-land task. Hence, sample size calculations were based on detecting a *large* effect size difference in knee abduction moment ($f = 0.4$), requiring 64 participants given an alpha of 0.05 (5% significance level) 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). Up to 12 participants per maturational group and sex were targeted to account for 10% of missing data (i.e., $n = 72$). For reliability, 15 of the participants returned for a second testing session 48–72 hours following their first session (Table 1). Menstruating female participants attended their testing session during the first 5 days of the follicular phase of their menstrual cycle as identified by the onset of menstruation as it has the lowest sex hormone levels (Reilly, 2000). If females were participating in reliability testing, their second session was scheduled 48–72 hours, still within the first 5 days of their menstrual cycle.

Participants were included if they were: aged 7 to 21 years, had a BMI $< 30 \text{ kg/m}^2$, participated in a court or field sport at least twice per week that involved 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 4 days per week) according to the Children's Leisure Activity Study Survey (Telford et al., 2004). Exclusion criteria included the use of hormonal contraceptive medication (excluding the monophasic contraceptive pill) (Samuelson et al., 2017), 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 6 months prior to testing requiring surgery or more than 3 months of physiotherapy, a previous ACL or meniscal injury, a medical condition affecting performance of sporting tasks, or a current or recent (< 3 months) knee pain.

Participants were categorised into three pubertal maturation stages using a modified Pubertal Maturation Observational Scale (PMOS) and peak height velocity (PHV) calculations. The PMOS was used to classify participants as pre-pubertal (Tanner stage I), early-

Table 1. Demographic data of participants included in the determination of reliability of metrics associated with risk of ACL injury for the LAND and CUT tasks.

	Sample (n)	Age (y)	Height (cm)	Mass (kg)	BMI (kg/m^2)
Females	8	14.17 ± 4.72	153.38 ± 18.49	53.44 ± 19.52	21.90 ± 4.98
Males	7	16.27 ± 4.61	169.00 ± 38.19	73.41 ± 26.84	24.56 ± 6.87

Note: ACL = anterior cruciate ligament, BMI = body mass index, CUT = single-leg drop-land-and-cut, LAND = single-leg drop-land.

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 6 months), menarche status, body hair development, sweating, and muscular definition (Tanner, 1986; Tanner & Davies, 1985). The PHV was calculated using date of birth, measured standing height, seated height, leg length, body mass, and 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.

Demographic and anthropometric measures

A flow chart of the data collection procedure is presented in Figure 1. First, consent and assent forms were obtained including a baseline questionnaire composed of demographic characteristics (age, sex, leg dominance [leg to kick a ball], training history, and injury history). Females also completed a menstrual cycle tracking app (with at least 1 month of prior tracking), and a menstrual cycle questionnaire composed of regularity and timing characteristics of menses. Participant standing and seated height was measured using a stadiometer (Seca model, 0123), mass was taken from a Kistler 9260AA6 multicomponent force plate (Kistler Group, Winterthur, Switzerland), and leg length was

measured on the right leg using a tape measure, with 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).

Data collection

Forty-two 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) by one female practitioner (AB). 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 2). With all markers in place, a 1-second static trial was recorded for model calibration.

Two different landing tasks were assessed, the single-leg drop-land (LAND, Figure 3(A)) and the single-leg drop-land-and-cut (CUT, Figure 3(B)). The LAND and CUT were performed from a standardised box height of 30 cm (Kim & Lim, 2014). The LAND required participants to stand on one leg at the edge 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, remaining stable for 2 seconds (Kim & Lim, 2014). The CUT had similar requirements, but upon landing, participants immediately leapt 90° laterally towards the opposite side (Nasser et al., 2021), landing on a target placed at 150% of their leg length. Three

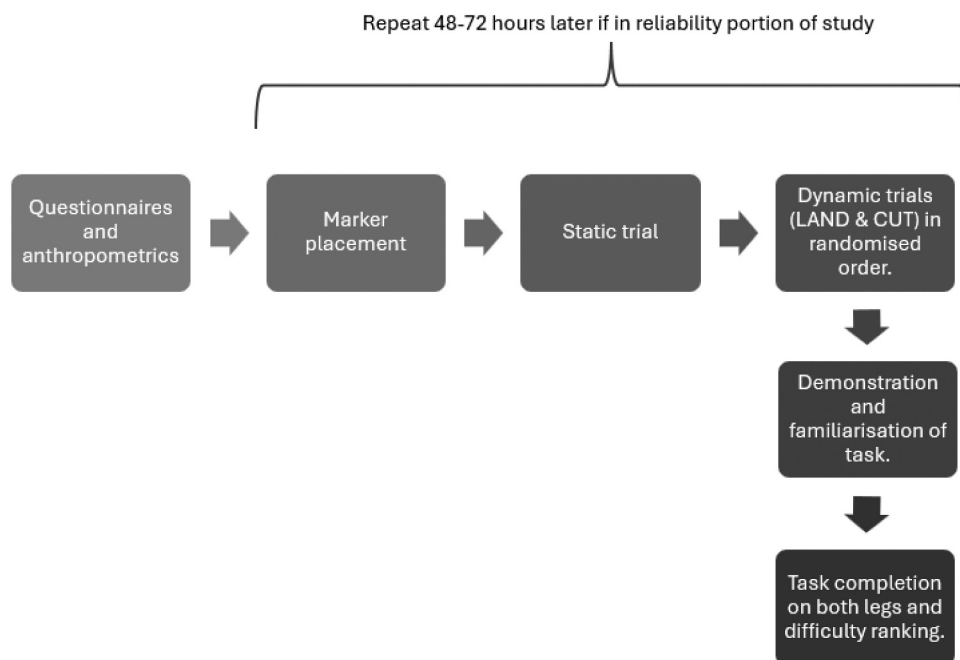


Figure 1. Flow chart of data collection procedure. CUT = single-leg drop-land-and-cut; LAND = single-leg drop-land.



Figure 2. 3D motion capture marker set based on the calibrated Anatomical system technique (CAST) model. Four-marker clusters are in green.

successful trials per leg were collected from each participant, as defined by the participant performing the tasks instructed in a fluid motion, and successful collection of biomechanical data. Trials were separated by a 30 second rest (Hanzlíková et al., 2021). The order of tasks and dominant/non-dominant legs were randomised. Participants wore minimal and tight-fitting clothing, such as sports bras and shorts, and their own

running shoes. The participants ranked the difficulty of each task after the completion of the three trials using the 5-point Likert scale (1 – very difficult, 2 – difficult, 3 – neutral, 4 – easy, 5 – very easy (Hanzlíková et al., 2021).

An 8-camera motion analysis system (Oqus 700+ cameras) and software (Qualisys Track Manager v.2019.1, Qualisys AB, Gothenburg, Sweden) captured 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 recorded kinetic data using a 5695B2 DAQ system (Kistler Group, Winterthur, Switzerland), synchronised to the 3D motion capture and collected within Qualisys Track Manager.

Data processing

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 the previously captured static trial. Knee joint kinematics were calculated as Cardan angles describing shank motion relative to the thigh, based on conventionally established segment coordinate systems (Grood & Suntay, 1983; Wu et al., 2002). Knee joint moments represent net external moments, expressed in the proximal segment (thigh) coordinate system. Axis directions and sign conventions were adjusted (using NEGATE options) for clinically meaningful interpretation.

Any potential marker data gaps, up to 10 frames (20 ms), were interpolated using a third-order polynomial fit

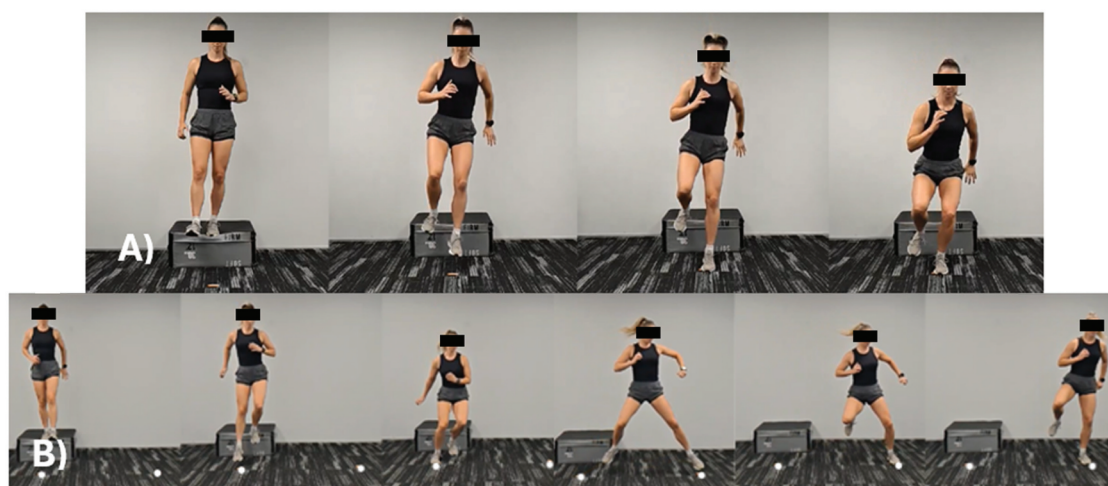


Figure 3. Depictions of the landing tasks performed by the participants. A) shows the single-leg drop-land (LAND) and B) shows the single-leg drop-land-and-cut (CUT).

algorithm. A fourth-order low-pass Butterworth filter with a cut-off frequency of 15 Hz was then applied to the marker 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). The metrics collected included knee angles and moments in all three planes of motion and ground reaction force (GRF) from initial contact to peak knee flexion angle. Moments were normalised to body mass and height (Nm/kg/m) to account for the variation in growth of participants. GRF were normalised to body weight (BW).

Statistical analysis

Descriptive statistics are reported as mean $\pm$ standard deviation (SD). For test–retest reliability, a two-way mixed-effects, absolute agreement, multiple measurement intra-class correlation coefficient (ICC) values with their 95% confidence intervals (CI) and statistical significant (p values) were calculated to assess the relative reliability of metrics (Koo & Li, 2016; Portney & Watkins, 2009). Q–Q plots were visually inspected to assess normality of distribution. ICC values less than 0.50 were deemed reflective of *poor* reliability, between 0.50 and 0.75 of *moderate* reliability, 0.75 and 0.90 of *good* reliability, and greater than 0.90 of *excellent* reliability (Koo & Li, 2016; Portney & Watkins, 2009). Absolute between-session reliability was assessed using typical error (TE) values, calculated according to Hopkins (Hopkins, 2000), and expressed in both unit and coefficient of variation percentage (CV%) values. Reliability was deemed suboptimal when CV% was 10% or greater. Corresponding 95% CI were also calculated. Paired t -tests were used to explore statistically significant differences between trials, and acknowledged if $p < 0.05$ (Myer et al., 2015). Metrics with *poor* reliability (ICC < 0.50) were not compared between groups.

To explore group differences, participants were grouped by sex (male, female) and maturational status as pre-pubertal (pre), early-/mid-pubertal (mid) and late-/post-pubertal (post). 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. Differences in demographics, anthropometrics and biomechanical variables between sex and maturation were assessed using two-by-three-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. F values and degrees of freedom were also calculated and presented. Effect size was calculated using the Hedges’ g formula as sample sizes were uneven between groups (Dhakal, 2023), and interpreted

as *small*, *medium* and *large* when reaching g thresholds of 0.20, 0.50 and 0.80, respectively (Bobbitt, 2021).

Residual analysis was performed to test for the assumptions of the two-by-three-way ANOVA. Outliers were assessed by inspection of boxplots. Outliers were removed if marker slippage or a mistrial was present; otherwise, outliers were deemed reflective of true readings. 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 (see supplementary material). There was homogeneity of variances ($p > 0.05$) for most metrics. To account for homogeneity violations, common logarithmic transformations (Log (10)) were performed on these data prior to ANOVA. For negative values, the data were translated using a constant value to a lower limit of one before being transformed. Statistical tests were performed using R studio (2023.12.0 + 369) and IBM SPSS Statistics 30.0.0.0(172), and statistical significance set to $p < 0.05$.

Studies have suggested that females are more likely to exhibit biomechanics linked with ACL injury mechanisms during cutting and landing tasks on their non-dominant leg (Brophy et al., 2010; Ghasemi et al., 2026; J. Wang & Fu, 2019; Warathanagasame et al., 2013); hence, the results presented are for the non-dominant leg.

Results

Participants

Sixty-nine individuals were recruited for this study. However, data from some participants were removed due to poor movement execution, discrepancies in marker tracking, or data capture issues. Therefore, the LAND task included 60 and the CUT task included 63 participants. Four participants were left leg dominant (~5%). Demographic data of the groups by sex and maturation stage are shown in Table 2.

Reliability

Reliability for the LAND task was *moderate* to *excellent* across most metrics (ICC 0.602–0.971). However, *poor* ICCs were identified for metrics of peak extension moment and range of sagittal moment. Significant differences were observed between trials for range of valgus moment. The CV% values were high across most metrics (CV 5.3–103.7%), with CV $< 10\%$ observed for only 6 metrics (see Appendix A).

Table 2. Demographic data for all participants in the LAND and CUT tasks grouped by sex and maturation stage.

	Males			Females		
	Pre	Mid	Post	Pre	Mid	Post
<i>LAND non-dominant leg</i>						
Sample (n)	12	10	11	8	9	10
Mass (kg)	33.13 ± 8.33	59.47 ± 11.20	83.09 ± 21.90	37.56 ± 4.71	50.92 ± 8.98	61.47 ± 12.54
Height (cm)	138.46 ± 9.87	168.85 ± 11.10	178.32 ± 5.77	144.13 ± 9.44	163.89 ± 9.38	162.40 ± 11.37
Age (y)	9.68 ± 1.71	14.34 ± 1.55	18.03 ± 1.95	10.60 ± 1.42	13.63 ± 2.02	16.67 ± 2.70
BMI (kg/m ²)	16.82 ± 2.08	20.63 ± 2.39	26.06 ± 7.31	17.90 ± 2.28	18.91 ± 2.42	22.86 ± 3.68
<i>CUT non-dominant leg</i>						
Sample (n)	16	11	8	9	9	10
Mass (kg)	33.69 ± 8.53	60.91 ± 11.65	83.77 ± 25.94	35.89 ± 6.68	50.92 ± 8.96	61.47 ± 12.54
Height (cm)	138.00 ± 9.33	169.36 ± 10.67	177.06 ± 5.58	141.17 ± 12.52	163.89 ± 9.38	162.40 ± 11.37
Age (y)	9.67 ± 1.50	14.51 ± 1.55	17.85 ± 1.92	10.04 ± 1.64	13.34 ± 1.88	16.58 ± 2.75
BMI (kg/m ²)	16.74 ± 2.05	20.96 ± 2.51	26.49 ± 7.64	17.27 ± 2.42	18.68 ± 2.38	22.93 ± 3.66
150% of leg length (cm)	109.8 ± 9.8	137.2 ± 10.0	146.7 ± 10.6	112.8 ± 11.5	134.8 ± 8.7	134.1 ± 13.5

Note: BMI, body mass index; CUT, single-leg drop-land-and-cut; LAND, single-leg drop-land.

Reliability for the CUT task was mostly *moderate* to *excellent* (ICC 0.655–0.988; Table 4). However, *poor* ICCs were identified for metrics of peak extension moment and range of sagittal moment. The CV% values were suboptimal across most metrics (CV 4.3–125.6%), with CV < 10% observed for only 3 metrics (see Appendix B)

Group comparisons for LAND

A statistically significant interaction effect was observed between sex and maturation stage for peak knee flexion moment ($F_{(2, 54)} = 3.657$) with the remaining metrics showing no interaction (Table 3). Within the post-pubertal group, males had a significantly higher peak knee flexion normalised moments than females. Within females, both pre-pubertal and mid-pubertal exhibited greater peak knee flexion moments than post-pubertal.

Significant main effects of maturation were observed for peak knee varus moment ($F_{(2, 54)} = 5.703$), peak knee external rotation moment ($F_{(2, 54)} = 3.878$) and peak vertical GRF (vGRF) ($F_{(2, 54)} = 15.382$). Based on pairwise comparisons (Table 4), the mid-pubertal and post-pubertal groups had a significantly greater peak knee varus moment than pre-pubertal. The post-pubertal group

also had a significantly higher peak knee external rotation moment than pre-pubertal. Peak vGRF was higher in both pre-pubertal and mid-pubertal than post-pubertal, and higher in pre-pubertal than mid-pubertal.

No significant main effects of sex were observed. Overall, analyses on the dominant leg provided similar results (Supplementary material). A summary of LAND findings for both legs is presented in Figure 4.

Group comparisons for CUT

No significant interaction effects between sex and maturation were found for any of the CUT metrics on the non-dominant leg (Table 5). Significant main effects of maturation were observed for peak knee varus angle ($F_{(2, 57)} = 3.746$), peak knee varus moment ($F_{(2, 57)} = 6.756$), peak knee external rotation moment ($F_{(2, 57)} = 4.449$) and peak vGRF ($F_{(2, 56)} = 13.912$). Pairwise comparisons (Table 6) revealed that the pre-pubertal group had a significantly greater peak varus angle than post-pubertal, but lower peak knee varus and external rotation moments than both the post-pubertal and mid-pubertal groups. The pre-pubertal group had greater peak vGRFs than both the mid-pubertal and post-pubertal groups.

Table 3. The mean and standard deviations (SD), main effects and interactions between sex and maturation stage groups during the LAND task on the non-dominant leg for biomechanical variables associated with ACL injury risk, performed by two-by-three-way analysis of variance.

Variable	Males			Females			Effects P -value (η_p^2)		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
Peak knee flexion angle (°)	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)
Peak knee extension angle (°)	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)
Peak knee flexion moment (Nm/kg/m)	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)
Peak knee extension moment (Nm/kg/m)	−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)
Peak knee valgus angle (°)	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)
Peak knee varus angle (°)	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)
Peak knee valgus moment (Nm/kg/m)	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)
Peak knee varus moment (Nm/kg/m)	−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)
Peak knee IR 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 knee ER 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)
Peak knee IR 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 knee ER 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)

Note: *significant main effects ($p < 0.05$) † significant interaction effect ($p < 0.05$) from 2×3 way analysis of variance ^ log transformed metrics. ACL = anterior cruciate ligament, BW = body weight, ER = external rotation, LAND = single-leg drop-land, PKF = peak knee flexion, IR = internal rotation, vGRF = vertical ground reaction force.

Table 4. Pairwise comparisons for the main effects of maturation during the 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]	P -value	g (magnitude)
Peak knee varus moment (Nm/kg/m)	Pre Mid	−0.12 [−0.22, −0.03]	0.013*	0.774 (medium)
	Pre Post	−0.15 [−0.24, −0.06]	0.002*	0.989 (large)
	Mid Post	−0.03 [−0.12, 0.07]	0.593	—
Peak knee ER moment (Nm/kg/m)	Pre Mid	−0.02 [−0.06, 0.02]	0.231	—
	Pre Post	−0.05 [−0.09, −0.01]	0.008*	0.876 (large)
	Mid Post	−0.03 [−0.07, 0.01]	0.133	—
Peak vGRF (BW)	Pre Mid	0.52 [0.17, 0.86]	0.004*	1.034 (large)
	Pre Post	0.93 [0.59, 1.26]	<0.000*	1.715 (large)
	Mid Post	0.41 [0.08, 0.75]	0.017*	0.794 (medium)

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, ER = external rotation, LAND = single-leg drop-land, vGRF = vertical ground reaction force.

For sex, a significant main effect was seen for peak knee external rotation moment ($F_{(1, 57)} = 4.125$). Pairwise comparisons indicated significantly greater peak external rotation moments in females than males.

Overall, analyses on the dominant leg provided similar results (Supplementary material). A summary of CUT findings for both legs is presented in Figure 5.

Discussion

Our results demonstrated *moderate* to *excellent* reliability for most metrics during LAND and CUT. However, *poor* levels of reliability were observed for the metrics of peak knee extension moment, knee sagittal and transverse moment ranges and medial/lateral and anterior/posterior GRF when interpreting ICC values. Large CV% values were commonly

Biomechanical differences in maturation and sex during a land task

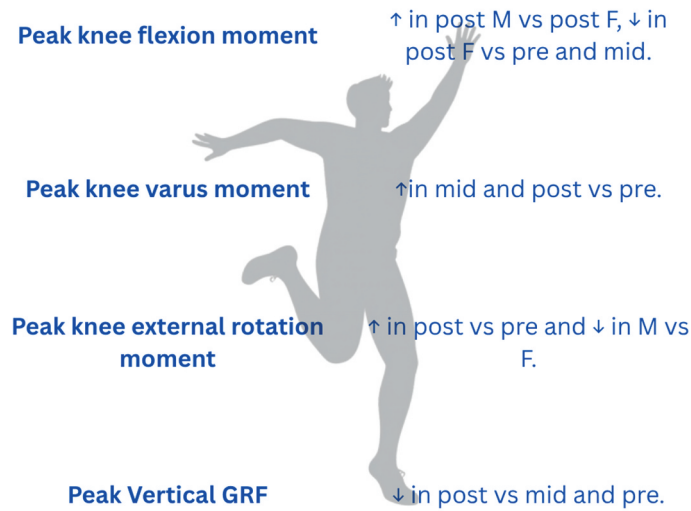


Figure 4. LAND task results infographic. Note: F, females; GRF, ground reaction force; LAND, single-leg drop-land; M, males; mid, early/mid-pubertal; post, late/post-pubertal; pre, pre-pubertal.

Table 5. The mean and standard deviations (SD), main effects and interactions between sex and maturation stage groups during the CUT task on the non-dominant leg for biomechanical variables associated with ACL injury risk, performed by two-by-three-way analysis of variance.

Variable	Males			Females			Effects P -value (η_p^2)		
	Pre	Mid	Post	Pre	Mid	Post	Maturation	Sex	Interaction
Peak knee flexion angle (°)	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)
Peak knee extension angle (°)	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)
Peak knee flexion moment (Nm/kg/m)	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)
Peak knee extension moment (Nm/kg/m) ^	-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)
Peak knee valgus angle (°)	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)
Peak knee varus angle (°)	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)
Peak knee valgus moment (Nm/kg/m)	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)
Peak knee varus moment (Nm/kg/m)	-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)
Peak knee IR angle (°)	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)
Peak knee ER angle (°)	-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)
Peak knee IR moment (Nm/kg/m)	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)
Peak knee ER moment (Nm/kg/m)	-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)
Peak vGRF (BW)	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)

Note: *significant main effects ($p < 0.05$) † significant interaction effect ($p < 0.05$) from 2×3 way analysis of variance ^ log transformed metrics. ACL = anterior cruciate ligament, BW = body weight, CUT = single-leg drop-land-and-cut, ER = external rotation, GRF = ground reaction force, PKF = peak knee flexion, IR = internal rotation.

Table 6. Pairwise comparisons for the main effects of maturation during the 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]	P-value	g (magnitude)
Peak knee varus angle (°)				
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	—
Peak knee varus moment (Nm/kg/m)				
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	—
Peak knee ER moment (Nm/kg/m)				
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>)
Peak vGRF (BW)				
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, CUT = single-leg drop-land-and-cut, ER = external rotation, vGRF = vertical ground reaction force.

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

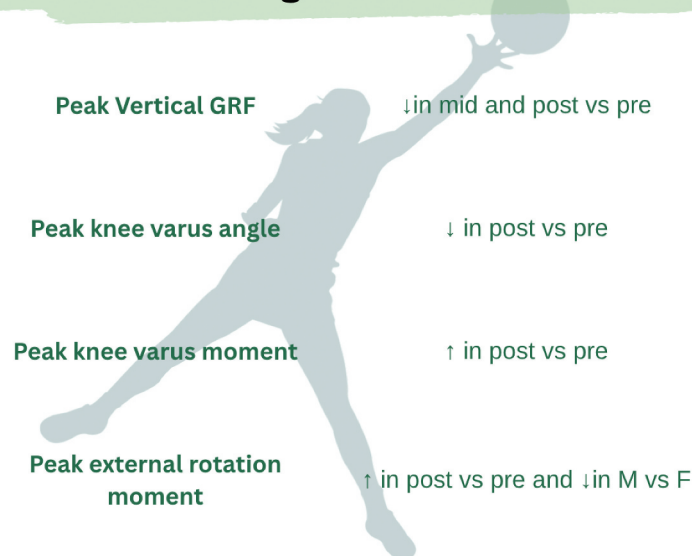


Figure 5. CUT task results infographic. Note: F, females; GRF, ground reaction force; M, males; mid, early/mid-pubertal; post, late/post-pubertal; pre, pre-pubertal.

observed for most metrics. As the TEs were generally small, the restricted range and low average values of metrics potentially inflated these CV% values (Hopkins, 2000). Caution is advised when interpreting differences in metrics with large CV% values, with raw TEs potentially more appropriate for establishing meaningful differences. The observed variability is likely multifactorial, owing to participant's movement inconsistencies or kinematic errors (Butler et al., 2021;

Colyer et al., 2018; McGinley et al., 2009; Piazza & Cavanagh, 2000; Ramakrishnan & Kadaba, 1991; Scataglini et al., 2024). Errors were minimised by standardising marker placement and static alignment (Ford et al., 2007), and having one experienced practitioner position all markers. Due to the *poor* levels of reliability; range of angles and moments, anterior/posterior GRF and medial/lateral GRF were not considered for group comparisons.

The results were largely contrary to our hypothesis, and to the pattern reported in the literature which has predominantly included female, single-sex investigations using non-sport-specific jump-landing tasks (Hewett et al., 2004; Ramachandran et al., 2024). The main findings across both tasks suggested that pre-pubertal, rather than post-pubertal, participants exhibited biomechanics suggestive of a higher risk of ACL injury, regardless of sex. Specifically, for both tasks, the post-pubertal groups demonstrated lower peak relative vGRFs, higher peak knee varus moments (suggesting resistance to knee valgus) and higher peak knee external rotation moments (suggesting resistance to knee internal rotation) than pre-pubertal groups. Peak knee external rotation moments were also higher in females than males for both tasks. During the CUT task, peak knee varus angle was larger in the pre-pubertal than the post-pubertal group. In conjunction with the extended knee position upon landing observed in all groups, the pre-pubertal participants commonly exhibited greater relative vGRFs, smaller peak varus moments and smaller peak external rotation moments (suggesting less resistance to knee valgus and internal rotation), mechanics which when combined, suggest potential for a higher ACL injury risk compared to the other groups. This pattern diverges from the prevailing hypothesis, informed largely by female-only evidence from uniplanar movement tasks, that ACL injury risk biomechanics worsen through puberty in females (Hewett et al., 2004; Ramachandran et al., 2024). The more complex, sport-specific unilateral tasks used in the current study may better reveal underlying movement patterns than tasks of prior work, suggesting ACL injury risk biomechanics may be established in earlier, pre-pubertal movement patterns, rather than emerging as a potential consequence of puberty itself. Our findings align with previous literature suggesting no sex differences in knee biomechanics, similarly to studies examining across various tasks in pre-pubertal and pubertal participants (Hewett et al., 1996; Sigg et al., 2001; Swartz et al., 2005). However, our results found that most biomechanical differences were identified between maturation groups, independent of sex. These results highlight that landing strategies observed in pre-pubertal participants are not evident when analysis is limited to sex-based comparisons alone, suggesting maturation, rather than sex, underpins the observed biomechanical differences.

Despite no significant differences in knee flexion angles between groups, it is noteworthy that landing with a more extended knee ($<30^\circ$ of knee flexion) has been associated with an increased risk of ACL injury (Leppänen et al., 2017). All groups had peak knee extension angles between 10 and 30° , suggesting potential for

a higher ACL injury risk in combination with other factors, such as higher peak knee flexion moment (Beaulieu et al., 2023; Boden et al., 2000; Olsen et al., 2004). Furthermore, during the LAND task, peak knee flexion moment was lower in post-pubertal females than in post-pubertal males and less biologically mature females. Knee flexion moment reflects overall sagittal plane loading rather than ACL-specific strain, which may be an indicator of ACL injury risk when in conjunction with other biomechanical risk factors such as anterior tibial shear and excessive quadriceps contraction (Sell et al., 2006).

Peak relative vGRF decreased with maturation during the LAND task, suggesting a general improvement in force attenuation ability with maturation, likely due to skill acquisition and physical development (Angulo-Barroso et al., 2022). Peak vGRF in this study ranged between 3.6- and 4.8-times BW, consistent with findings of previous research (Ramachandran et al., 2024). Notably, elite female athletes have sustained ACL injury during a modelled peak vGRF between 3.2 and 4.5 times BW at 40 ms after initial ground contact (Koga et al., 2010). Despite being beyond the scope of this study to examine the vGRF value at exact time points, our peak vGRF data suggest tasks were reasonably sport specific. Pre-pubertal athletes have lower rates of ACL injuries compared to their more biologically mature peers (Maniar et al., 2022), suggesting that higher relative vGRF is not a standalone risk factor. Compromising knee joint angles and moments, and the timing of high vGRFs are important to consider alongside vGRF values.

Alongside the decreases in relative vGRF, during both tasks, the post-pubertal group had higher varus and external rotation moments, suggesting a potential resistance to valgus and internal rotation with maturation. During the CUT task, the pre-pubertal group also had greater knee varus angles than post-pubertal, but the other two groups had close to neutral angles. As all the groups had relatively extended knee positions upon landing, reducing external rotation moments and limiting knee valgus angles would be beneficial for ACL injury risk reduction in the pre-pubertal group. The greater external rotation and varus moments observed in the more mature individuals potentially reflected task competence and safer knee positioning. Cutting tasks require single-leg control of momentum, impact absorption, sudden deceleration and re-direction of the body's momentum (Jindrich & Qiao, 2009; Jindrich et al., 2006). 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), potentially explaining our results. Increases in physical sporting demands with age, coupled with an apparent lack of corresponding adaptation in key ACL injury-related biomechanics, may partially explain the increased occurrence of ACL injuries in late-to-post-pubertal groups (Maniar et al., 2022). Although strength, speed and exposure to higher-intensity tasks increase with maturation, neuromuscular control and landing mechanics do not appear to adapt proportionally, potentially resulting in mismatched load tolerance and movement quality.

Distinguishing between biomechanical origin and exacerbation may help reconcile our findings with the established rise in ACL injury incidence in post-pubertal females (Maniar et al., 2022). Despite improvements in some metrics (reduced relative vGRF, increased rotational resistance moments), other key metrics associated with ACL injury risk demonstrated no significant change with maturation. When combined with considerations of substantial increases in sporting exposure, loading demands and frequency of high-injury-risk scenarios (Maniar et al., 2022), the lack of biomechanical improvements may explain the increases in post-pubertal ACL injury occurrence in the absence of higher-risk biomechanical movement profiles.

Practical applications

Based on our findings, preventative training interventions should be implemented in younger (pre-pubertal) athletes, with sex-specificity of these programmes not of immediate concern. Biomechanical deficits appear present prior to puberty and may be exacerbated, rather than caused, by increased exposure to higher injury risk situations that accompany maturation. Establishing movement patterns in an earlier pubertal window may prove more effective than implementing interventions following the increases high ACL injury risk exposure. Neuromuscular training (incorporating strength, plyometrics, balance, speed and agility) has been recommended to improve landing and cutting biomechanics, such as increasing peak knee flexion, reducing knee valgus motion and reducing vGRFs (Ford et al., 2025; Mattu et al., 2022; Myer et al., 2013; Ramachandran et al., 2025). Interventions should be progressed to meet maturation changes and increasing sport demands.

Limitations

Our study is not without limitations. Despite consistencies in settings, models and marker placement with previously reported studies, the findings are specific to our laboratory conditions and included participants, hence

the generalisability to a wider population is limited (Alenezi et al., 2014). The total sample did not reach the target identified in the a priori power analysis, as trials were removed to maintain high data quality. This reduced statistical power limited the ability to detect group differences, thereby increasing chances of Type II error. A standardised box height of 30 cm was used for all of the tasks irrespective of body height to align with previous literature (Kim & Lim, 2014; Nasser et al., 2021) and recommendations for single-leg drop-landing tasks (L. I. Wang & Peng, 2014). During the CUT task, the cutting distance was normalised to leg length to account for anthropometric differences. Using a box height normalised to individual leg length or maximal jump height might increase group comparability (Weinhandl et al., 2015). Furthermore, variables such as fatigue, cognitive demand, or diverted attention were not assessed and may provide more sport-specific insights.

Conclusion

This study provides novel evidence of direct, within-cohort comparison of both sexes across three maturation stages using a standardised maturation classification tool and sport-specific tasks, with established metric reliability prior to interpretation. Few significant differences were observed between sexes or within sex-specific maturation groups, with maturation appearing to have a greater influence on biomechanical profiles. Notable biomechanical differences between maturation groups were evident in several variables, suggesting potential for some lower-risk movement patterns with maturation. However, many biomechanical variables did not appear to differ between maturation groups, particularly in females. It is possible that the observed altered mechanics may not be enough to combat the increased demands of sport. In contrast with the prevailing literature, this pattern suggests that pre-pubertal groups, rather than post-pubertal females, demonstrate higher ACL injury risk biomechanical profiles, regardless of sex. Biomechanical movement patterns associated with increased ACL injury risk may be established pre-puberty, and are exacerbated, rather than caused, by the increased sporting demands and situational injury risk exposure that accompany maturation. The findings should be interpreted within the constraints of controlled task conditions, which do not fully capture the motor control and perceptual demands of sport. Collectively, our findings emphasise maturation as a key factor shaping biomechanical patterns in youth athletes and support a maturation-informed approach to develop pre-pubertal movement patterns in both sexes.

Author contributions

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

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Appendices

Appendix A

Between session reliability of metrics collected from the LAND task on the non-dominant leg

	Trial A mean $\pm$ SD	Trial B mean $\pm$ SD	Difference mean $\pm$ SD	TE [95% CI]	CV% [95% CI]	ICC [95% CI]	ICC P- value	Paire t-test P- value
Peak knee flexion angle (°)	65.41 $\pm$ 10.27	63.42 $\pm$ 10.73	1.99 $\pm$ 5.03	3.56 [2.52, 6.04]	5.5 [3.9, 9.4]	0.920 [0.736, 0.977]	<0.001	0.244
Peak knee extension angle (°)	15.72 $\pm$ 2.60	13.38 $\pm$ 5.44	2.35 $\pm$ 3.99	2.82 [2.00, 4.79]	19.4 [13.7, 32.9]	0.602 [-0.209, 0.880]	0.053	0.089
Range of sagittal knee angle (°)	49.68 $\pm$ 9.53	50.04 $\pm$ 7.75	-0.35 $\pm$ 3.77	2.66 [1.89, 4.52]	5.3 [3.8, 9.1]	0.941 [0.794, 0.983]	<0.001	0.778
Peak knee flexion moment (Nm/kg/m)	0.37 $\pm$ 0.20	0.42 $\pm$ 0.13	-0.05 $\pm$ 0.11	0.08 [0.05, 0.13]	19.5 [13.8, 33.1]	0.833 [0.301, 0.955]	0.005	0.162
Peak knee extension moment* (Nm/kg/m)	-1.75 $\pm$ 0.27	-1.71 $\pm$ 0.26	-0.04 $\pm$ 0.13	0.09 [0.07, 0.16]	5.5 [3.9, 9.3]	0.396 [-0.026, 0.777]	0.052	0.413
Range of sagittal knee moment* (Nm/kg/m)	2.12 $\pm$ 0.37	2.13 $\pm$ 0.29	0.02 $\pm$ 0.20	0.14 [0.10, 0.23]	6.5 [4.6, 11.1]	0.397 [-0.024, 0.778]	0.050	0.818
Peak knee valgus angle (°)	4.98 $\pm$ 5.64	5.01 $\pm$ 7.75	0.03 $\pm$ 4.49	3.18 [2.25, 5.39]	63.6 [45.0, 107.9]	0.849 [0.457, 0.957]	0.003	0.984
Peak knee varus angle (°)	-3.06 $\pm$ 4.46	-4.09 $\pm$ 7.13	-1.02 $\pm$ 5.24	3.71 [2.63, 6.29]	103.7 [73.5, 176.1]	0.686 [-0.113, 0.910]	0.036	0.559
Range of coronal knee angle (°)	8.05 $\pm$ 2.27	9.10 $\pm$ 3.66	-1.05 $\pm$ 2.57	1.82 [1.29, 3.08]	21.2 [15.0, 36.0]	0.708 [0.057, 0.914]	0.020	0.227
Peak knee valgus moment (Nm/kg/m)	0.39 $\pm$ 0.14	0.48 $\pm$ 0.17	-0.09 $\pm$ 0.10	0.07 [0.05, 0.12]	15.7 [11.1, 26.7]	0.799 [0.146, 0.948]	0.011	0.012
Peak knee varus moment (Nm/kg/m)	-0.23 $\pm$ 0.13	-0.23 $\pm$ 0.20	0.00 $\pm$ 0.12	0.08 [0.06, 0.14]	35.6 [25.2, 60.5]	0.854 [0.476, 0.958]	0.001	0.986
Range of coronal knee moment (Nm/kg/m)	0.62 $\pm$ 0.15	0.71 $\pm$ 0.25	-0.09 $\pm$ 0.10	0.10 [0.07, 0.17]	15.5 [11.0, 26.3]	0.685 [-0.017, 0.914]	0.029	0.084
Peak knee IR angle (°)	7.88 $\pm$ 6.52	8.36 $\pm$ 6.29	0.48 $\pm$ 4.56	3.22 [2.28, 5.47]	39.7 [28.1, 67.4]	0.820 [0.357, 0.949]	0.005	0.753
Peak knee ER angle (°)	-4.63 $\pm$ 6.40	-5.38 $\pm$ 8.97	0.75 $\pm$ 6.63	4.69 [3.32, 7.96]	93.7 [66.4, 159.1]	0.717 [-0.031, 0.919]	0.028	0.734
Range of transverse knee angle (°)	12.51 $\pm$ 3.85	13.74 $\pm$ 5.43	1.23 $\pm$ 3.67	2.60 [1.84, 4.41]	19.8 [14.0, 33.6]	0.764 [0.219, 0.931]	0.010	0.322
Peak knee IR moment (Nm/kg/m)	0.26 $\pm$ 0.09	0.26 $\pm$ 0.09	0.00 $\pm$ 0.08	0.06 [0.04, 0.09]	21.1 [15.0, 35.9]	0.632 [-0.056, 0.891]	0.035	0.939
Peak knee ER moment (Nm/kg/m)	-0.07 $\pm$ 0.05	-0.07 $\pm$ 0.06	0.01 $\pm$ 0.03	0.02 [0.01, 0.03]	29.2 [20.7, 49.6]	0.920 [0.712, 0.977]	<0.001	0.405
Range of transverse knee moment (Nm/kg/m)	0.33 $\pm$ 0.09	0.34 $\pm$ 0.09	0.01 $\pm$ 0.07	0.05 [0.03, 0.08]	14.7 [10.4, 24.9]	0.625 [-0.053, 0.892]	0.039	0.662
Peak vertical GRF (BW)	4.05 $\pm$ 0.68	3.97 $\pm$ 0.69	0.08 $\pm$ 0.36	0.25 [0.18, 0.41]	6.3 [4.6, 10.2]	0.928 [0.781, 0.977]	<0.001	0.421
Peak anterior GRF (BW)	0.14 $\pm$ 0.13	0.11 $\pm$ 0.08	0.03 $\pm$ 0.11	0.07 [0.05, 0.12]	58.1 [42.1, 93.6]	0.675 [0.022, 0.895]	0.023	0.327
Peak posterior GRF (BW)	-0.12 $\pm$ 0.07	-0.12 $\pm$ 0.07	-0.01 $\pm$ 0.03	0.02 [0.02, 0.03]	18.5 [13.4, 29.9]	0.950 [0.848, 0.984]	<0.001	0.399
Peak lateral GRF (BW)	0.31 $\pm$ 0.13	0.30 $\pm$ 0.12	0.01 $\pm$ 0.07	0.05 [0.04, 0.08]	16.6 [12.1, 26.8]	0.911 [0.727, 0.971]	<0.001	0.547
Peak medial GRF (BW)	-0.60 $\pm$ 0.16	-0.60 $\pm$ 0.16	0.01 $\pm$ 0.06	0.04 [0.03, 0.06]	6.5 [4.7, 10.5]	0.971 [0.911, 0.991]	<0.001	0.551
Time-to-PKF (s)	0.24 $\pm$ 0.07	0.24 $\pm$ 0.07	0.00 $\pm$ 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, ER = external rotation, GRF = ground reaction forces, ICC = intraclass coefficient, IR = internal rotation, LAND = single-leg drop-land, PKF = peak knee flexion, SD = standard deviation, TE = typical error.

Appendix B***Between session reliability of metrics collected from the CUT task on the non-dominant leg***

	Trial A mean $\pm$ SD	Trial B mean $\pm$ SD	Difference mean $\pm$ SD	TE [95% CI]	CV% [95% CI]	ICC [95% CI]	ICC P- value	Paired t-test P- value
Peak knee 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 knee 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 of sagittal knee 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 knee 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 knee 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 of sagittal knee 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 knee 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 knee 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 of coronal knee 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 knee 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 knee 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 of coronal knee 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 knee IR 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 knee ER 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 of transverse knee 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 knee IR 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
Peak knee ER moment (Nm/kg/m)	-0.07 $\pm$ 0.05	-0.07 $\pm$ 0.06	0.00 $\pm$ 0.03	0.02 [0.01, 0.03]	28.2 [20.2, 46.5]	0.905 [0.677, 0.973]	<0.001	0.940
Range of transverse knee moment (Nm/kg/m)	0.32 $\pm$ 0.12	0.32 $\pm$ 0.13	0.00 $\pm$ 0.09	0.07 [0.05, 0.11]	20.4 [14.6, 33.7]	0.710 [0.027, 0.919]	0.021	0.922
Peak vertical GRF (BW)	4.34 $\pm$ 1.67	4.42 $\pm$ 1.66	-0.08 $\pm$ 0.37	0.26 [0.19, 0.41]	5.9 [4.3, 9.3]	0.988 [0.965, 0.996]	<0.001	0.434
Peak anterior GRF (BW)	0.25 $\pm$ 0.29	0.21 $\pm$ 0.26	0.03 $\pm$ 0.09	0.06 [0.04, 0.10]	26.6 [19.5, 41.9]	0.974 [0.923, 0.991]	<0.001	0.186
Peak posterior GRF (BW)	-0.45 $\pm$ 0.12	-0.49 $\pm$ 0.15	0.04 $\pm$ 0.13	0.09 [0.07, 0.15]	20.2 [14.8, 31.9]	0.655 [0.016, 0.882]	0.023	0.964
Peak lateral GRF (BW)	0.08 $\pm$ 0.10	0.06 $\pm$ 0.09	0.01 $\pm$ 0.06	0.04 [0.03, 0.07]	60.2 [44.1, 94.9]	0.898 [0.705, 0.966]	<0.001	0.380
Peak medial GRF (BW)	-0.52 $\pm$ 0.16	-0.54 $\pm$ 0.16	0.02 $\pm$ 0.09	0.06 [0.05, 0.10]	12.0 [8.8, 18.9]	0.916 [0.758, 0.972]	<0.001	0.306
Flight time (s)	0.14 $\pm$ 0.05	0.14 $\pm$ 0.06	0.01 $\pm$ 0.03	0.02 [0.01, 0.03]	13.4 [9.8, 21.1]	0.947 [0.845, 0.982]	<0.001	0.418
Time-to-PKF (s)	0.26 $\pm$ 0.09	0.26 $\pm$ 0.10	0.00 $\pm$ 0.07	0.05 [0.03, 0.07]	18.0 [13.2, 28.4]	0.875 [0.620, 0.958]	<0.001	0.964
Stance time (s)	0.51 $\pm$ 0.13	0.50 $\pm$ 0.11	0.01 $\pm$ 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, CUT = single-leg drop-land-and-cut, CV = coefficient of variation, ER = external rotation, GRF = ground reaction forces, ICC = intraclass coefficient, IR = internal rotation, PKF = peak knee flexion, SD = standard deviation, TE = typical error.