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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; Slauterbeck, Hickox,

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Beynnon, & 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 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 ± 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, &

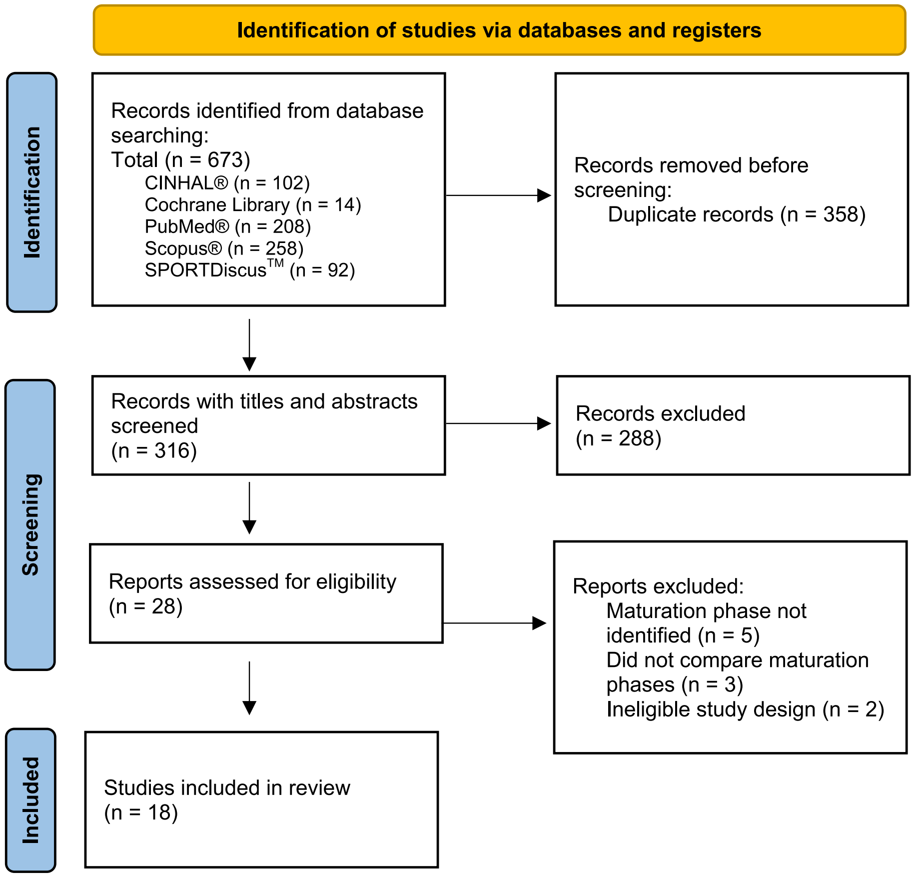

Fig. 1. PRISMA flow diagram of the search strategy and study selection process.

Powers, 2012), two (11.1 %) assessed a single-leg drop landing (Kim and Lim, 2014; Nasseri 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; Nasseri 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
Qualitive 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)[a]
Qualitive synthesis of studies (n = 9) reporting on biomechanics in DVJ tasks								
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 Den Bogert, & Hewett (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. $\sqrt{LH}$) ‘, post-pubertal: 0.55 + 0.21 N-(kg $\sqrt{LH}$)-f] 1.18 MD; $p < 0.001$), and ↓ knee extensor moments [pre-pubertal: 0.0124 + 0.001 Nm.(kg-BH. $\sqrt{LH}$)-‘, 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)

(continued on next page)

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]
							m.(kg.BH.√LH)-1] (0.0045 MD; p = 0.026) compared to pre-pubertal. *LH, landing height; BH, body height	
Hewett et al., 2004	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), 58 late/post pubertal (age, 15.5 ± 1.5 y; height, 168.3 ± 6.5 cm; mass, 63.4 ± 10.9 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 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)	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 torques ($p < 0.01$) vs M and significantly different maximum valgus angles between the dominant and non-dominant limbs after maturation.	Females Pre vs early pubertal Knee valgus angle at initial contact (g 0.632 medium) Peak knee valgus angle (g 1.697 large) Early vs late pubertal Knee valgus angle at initial contact (g 4.000 large) Peak knee valgus angle (g 3.333 large) Pre vs late pubertal Knee valgus angle at initial contact (g 4.525 large) Peak knee valgus angle (g 1.897 large) Males Values were not provided.
Hewett, Myer, Ford, and Slauterbeck (2006)	United States of America	Cross-sectional 6 stars: satisfactory	87 n for maturational groups and participant descriptives not reported	188 n for maturational 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 ($p = 0.002$). The ratios of drop landing force to drop take-off and maximum landing force to maximum take-off force ↓ in M as they matured ($p < 0.05$) but did not change in F between pubertal stages.	Data unavailable~
Otsuki, Benoit, Hirose, and Fukubayashi (2021)	Japan	Interventional 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), 36 (ctrl) and 33 (int) 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	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	Data unavailable~

(*continued on next page*)

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; $p < 00.001$); 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 ± 0.03 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~
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)[a]
			± 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)
Qualitive 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 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)[a]
				(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 ≤ 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)
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, Pollard, 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)[a]
								−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)
Qualitive 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 (Hedges's g)[a]
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), KAbM (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)
Wild, 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

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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]
			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).

[a] 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 susceptability 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 tendancy 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 quadricep 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[11,28,31,49]	Phase 1 (1) Phase 2 (3)	✓	Unclear	✓(2) X(2)	X(4)	✓(4)	**Unspecified** 182 pub 133 post **Female** 31 pre 45 early 32 pub 196 late/post **Male** 27 pre 24 early 30 late/post	Knee abduction angle increases with maturation.	☑☑☐☐ Low
Knee abduction moment	5[30,31,46,47,49]	Phase 2 (5)	✓	Present	✓(4) X(1)	X(5)	✓(5)	**Unspecified** 182 pub 133 post **Female** 53 pre 17 early 62 pub 22 late 185 post **Male** 32 pre 30 pub 43 post	Knee abduction moment increases with maturation.	☑☑☐☐ Low
Knee flexion angle	4[31,46,47,49]	Phase 2 (4)	✓	Absent	✓(2) X(2)	X(4)	✓(4)	**Female** 33 pre 17 early 190 pub 22 late 262 post **Male** 37 pub 13 post	Knee flexion angle increases with maturation.	☑☑☑☐ moderate
Ground reaction force	3[21,47,48]	Phase 2 (3)	X	Absent	✓(1) X(2)	X(3)	✓(3)	**Female** 87 not specified 16 pre 16 pub 32 post **Male** 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[27,29,31,50,51]	Phase 1 (2) Phase 2 (3)	✓	Present	✓(5)	✓(2) X(3)	✓(4) X(1)	**Female** 35 not specified 101 pre 212 pub 160 post **Male** 36 pre 53 pub 59 post	Knee abduction angle increases with maturation.	☑☑☐☐ Low
Knee abduction moment	3[29,31,51]	Phase 1 (1) Phase 2 (2)	✓	Absent	✓(3)	✓(1) X(3)	✓(2) X(1)	**Female** 35 not specified 32 pre 48 pub 29 post **Male** 16 pre 15 pub 29 post	Knee abduction moment increases with maturation.	☑☑☑☐ Moderate
Knee flexion angle	3[27,31,50,51]	Phase 1 (2) Phase 2 (2)	✓	Present	✓(4)	X(4)	✓(2) X(2)	**Female** 35 not specified 86 pre 197 pub 131 post **Male** 20 pre 38 pub 30 post	Knee flexion angle decreases with maturation.	☑☑☐☐ Low
Ground reaction force	2[29,51]	Phase 1 (1) Phase 2 (1)	✓	Absent	✓(2)	✓(1) X(1)	✓(1) X(1)	**Female** 35 not specified 15 pre 15 pub 29 post **Male** 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[55-57]	Phase 2 (3)	✓	Present	✓(3)	✓(2) X(1)	✓(3)	**Female** 33 across 5 stages 26 pre 55 post **Male** 15 pre 14 post	Knee abduction angle decreases with maturation in males and is unclear in females.	☑☑☑☐ moderate
Knee abduction moment	3[54,56,57]	Phase 2 (3)	✓	Unclear	✓(2) X(1)	✓(1) X(2)	✓(3)	**Female** 33 across 5 stages 42 pre 30 early 41 post	Knee abduction moment increases with maturation.	☑☑☐☐ Low
Knee flexion angle	3[54-57]	Phase 2 (3)	✓	Absent	✓(2) X(1)	✓(1) X(2)	✓(3)	**Female** 33 across 5 stages 57 pre 30 early 55 post **Male** 15 pre 14 post	Knee flexion angle decreases with maturation.	☑☑☐☐ Low
Ground reaction force	2[55,56]	Phase 2 (2)	✓	Present	✓(2)	✓(2)	✓(1) x(1)	**Female** 34 pre 19 pub 38 post **Male** 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.

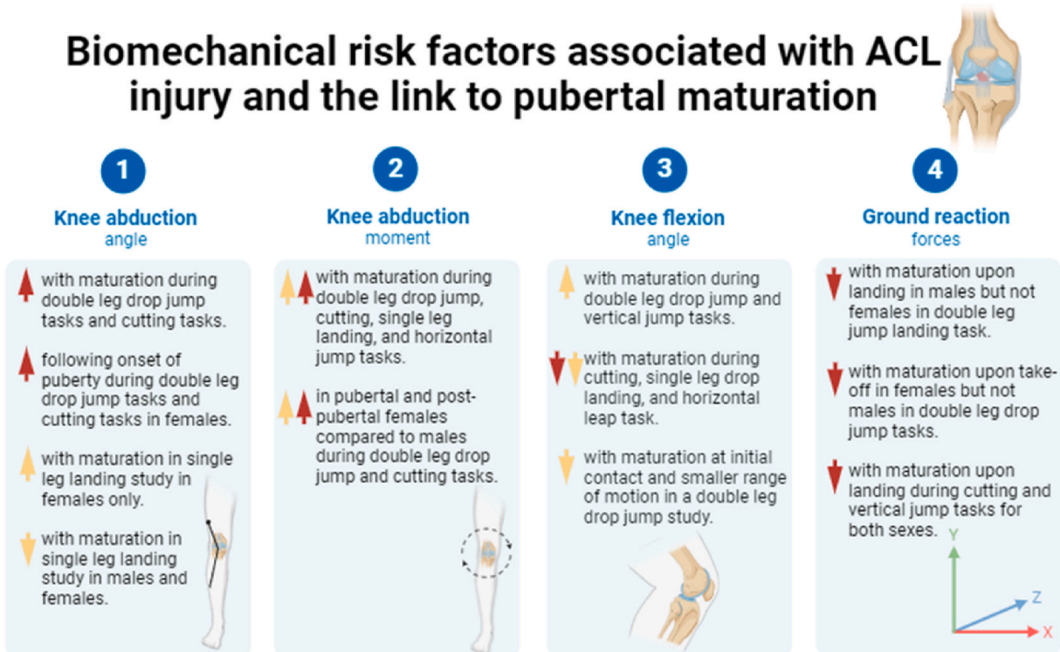

Fig. 2. Summary of the observed links between maturation and changes in biomechanics associated with anterior cruciate ligament (ACL) injury as reported in the literature.
Note: Red arrows indicate low certainty of evidence, yellow arrows indicate moderate certainty of evidence (as determined by GRADE). 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, & Hébert-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 (Balachandar, Marciniak, Wall, & Balachandar, 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, 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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