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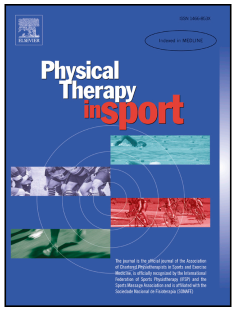

"The association between biological maturity and injury in young females participating in sport: A systematic review"

Anja Zoellner, PhD, Chris Whatman, PhD, Physiotherapist

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Title: ***"The association between biological maturity and injury in young females participating in sport: A systematic review"***

Authors: Anja Zoellner (PhD) [1], Chris Whatman (PhD, Physiotherapist)[1]

Institutional affiliations:
[1]AUT Millennium Sport Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand

Dr Anja Zoellner
Lecturer
School of Sport and Recreation
Faculty of Health and Environmental Sciences
Auckland University of Technology
Private Bag 92006, Auckland, New Zealand
Email: anja.zoellner@aut.ac.nz

Dr Chris Whatman
Associate Professor
School of Sport and Recreation
Faculty of Health and Environmental Sciences
Auckland University of Technology
Private Bag 92006, Auckland, New Zealand
Email: chris.whatman@aut.ac.nz

The association between biological maturity and injury in young females participating in sport: A systematic review

Abstract:

Background

Injuries in youth sport remain a concern. Biological maturity has been linked to injury risk but there is limited female specific evidence.

Aim

To evaluate the evidence for an association between biological maturity and injury in young females participating in sport.

Methods

A systematic search was conducted using EBSCO Health database from inception until April 2025. Studies were included if they investigated females in any sport and reported an assessment of biological maturity status and either injury rate or potential factors associated with injury. Study quality and risk of bias and the strength of evidence for findings was determined based on the consistency and quality of studies.

Finding

31 studies (n=10 reporting injury; n=21 reporting risk factors) were included in the review. Evidence supporting an association between injury and maturation was limited. There is moderate evidence of an association between potential injury risk factors and maturation. Most evidence is in the context of lower limb biomechanics during jump/landing tasks and potential risk of knee injury.

Conclusion

Current evidence for a link between maturity status and sport related injury in young females is limited, however there is moderate evidence that maturity status is associated with potential knee injury risk factors.

Highlights:

- There is limited evidence indicating injuries reported by young females playing sport are linked to biological maturity status.
- There is some evidence maturity status in young females is linked to potential injury risk factors.
- The strongest evidence supports a decrease in neuromuscular control of the knee during jump landings with increased maturity and rapid growth.

Keywords: Female, Growth, Injury, Maturation, Sport, Adolescents, Musculoskeletal Injury

Introduction:

Youth sports participation has many potential benefits including improvements in physical, social, and psychological development. However, there is evidence injuries are increasing, for example the rate of youth netball knee and ankle injuries were found to have doubled over 10 years in a recent review of national insurance data (Belcher et al., 2020). Thus, the risk of sports injury and the potential long-term consequences including future pain, disability and withdrawal from sport and physical activity remain a concern (Swain et al., 2018). Sport related injuries are reported to impact one in three youth annually and the associated costs of rehabilitation represent a significant public health burden (Black et al., 2021).

The period of accelerated growth occurring during adolescence, often coinciding with increased training and playing demands for young athletes, has been identified as a time of particular concern for sport related injury, particularly overuse injury (Johnson et al., 2020). As a result, it is suggested physical activity and sport be modified during periods of rapid growth, focussing more on movement development rather than high intensity training (Lloyd et al., 2016). Specifically, the American Medical Society for Sports Medicine recommends limiting training workloads and monitoring growth rates of adolescents to minimise the risk of overuse injuries (DiFiori et al., 2014).

Youth athletes may experience additional injury risk factors, unique to adults, due to physical, mental, and physiological changes occurring during the adolescent growth spurt (Vänttinen et al., 2011). Increases in limb length and discrepancies in periods of growth in bone versus development of connective tissue and muscle have been reported during peak height velocity (PHV), the period of most rapid growth in long bones (Lloyd et al., 2016). Active apophyses, lower bone mineral density and greater soft tissue elasticity are all unique to adolescents. These changes have been linked to growth related injuries such as Osgood-Schlatter's disease and Sinding-Larsen Johansson syndrome (Arnold et al., 2017; McKay et al., 2019). Additionally, growth-related injuries occur at different stages of growth, in a distal to proximal pattern, with Sever's and Osgood-Schlatter's diseases occurring earlier (pre-circa-PHV) and injuries such as pelvic apophysitis more likely to occur later (post-PHV) (Monasterio et al., 2021). Given the physical changes occurring, it is generally agreed the adolescent growth spurt is a time when sport related injuries can become more prevalent.

Although there is significant variability between individuals, peak growth rates (the period circa PHV) occur earlier in females than males, predominantly between 11-13 years of age, and average 7-9cm/year (Wik, 2022). In males, PHV typically occurs between the ages of 13-15 years. Alongside rapid increases in height and weight there are differences in body composition changes with girls, in general, proportionally gaining more fat mass and boys, more lean mass. Importantly, it appears most evidence reporting an increase in sport related injuries during the adolescent growth spurt comes from male youth football (Wik, 2022). In females, similar growth-related injuries are likely, however, differences in injury locations between adolescent boys and girls have been reported for which maturational differences may be important. Adolescent girls are likely at higher risk of knee injury (Montalvo et al., 2019) with recent evidence from netball suggesting ankle and knee injuries in girls aged 10-14 (likely a time of rapid growth for many) increased 84% and 133% respectively in the period from 2008 to 2017 (Belcher et al., 2020). Reasons for this are still unclear and likely include a range of biological and environmental factors (Parsons et al., 2021), however suggested mechanisms include reduced neuromuscular control, and altered lower limb biomechanics associated with the adolescent growth spurt (Beech et al., 2022; Hewett et al., 2006a). A recent systematic review reported some evidence potential biomechanical risk factors for ACL injury differ between females at different stages of maturity (Ramachandran et al., 2024). While ACL injuries are significant and costly, there are other more common injuries that require consideration. Further, a recent scoping review of youth athletes in elite pathways concluded there is evidence growth and maturation contribute to injury risk but highlighted the lack of research specific to females (Parry et al., 2024).

Understanding how the period of rapid growth during adolescence impacts injury risk in young females participating in sport will assist the development of injury prevention initiatives specific to this group. There is a need for an evaluation of the female specific evidence, across all injuries and levels of sport, to help inform sports organisation and educators as to how to best support the healthy engagement of young female participants. Given the anecdotal concerns there is also a need to better understand the evidence specific to apophyseal injuries. Thus, the aim of this systematic review is to evaluate the evidence for a link between biological age (maturational stage) and injury in young females participating in sport.

Methods:

Methods for this review followed those outlined in the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) statement (Page et al., 2021).

Search strategy

A systematic search strategy was developed based on the population of interest and two outcomes (biological maturity status and injury). A Word Frequency Analyser tool (https://sr-accelerator.com/#/help/wordfreq) and a Research Refiner tool (https://sr-accelerator.com/#/searchrefinery) were used to define and optimise search terms. This resulted in the following search string: ("maturation" OR "maturity" OR "biological age" OR "growth spurt") AND injur* AND ("female" OR “girl”) AND "sport". The search was carried out in EBSCO Health Databases to search the CINHAL, MEDLINE, and SPORTDiscus databases simultaneously. All Text was selected for each search term to ensure all relevant articles were included in the results. Results were restricted to those published in English and in academic journals. No additional restrictions were applied. Finally, the reference lists of all included articles were scanned for additional relevant articles. The search was initially performed on October 1, 2023, and repeated on April 1, 2025.

Text screening

Search results were downloaded to EndNote Desktop (version X9.3.3), where duplicates were removed by using the duplicate removal tool and then by scanning the remaining results. One author (AZ) first screened all titles and then all abstracts. The full texts of the remaining articles were screened by two authors (AZ and CW) independently, with any disagreements discussed until consensus was reached.

Eligibility criteria

All included studies were peer-reviewed, original research, published in English. Additionally, the studies included female athletes (of any sport with no restriction on playing level or age) and the outcomes assessed were required to include injury or a potential injury risk factor, and to report an association with maturation. There was no restriction on the method used to assess maturation, however it was required to be a measure of biological maturation (not purely based on chronological age), reporting at least two maturity stages (pre, circa, post-PHV) or related indicators such as pubertal status, menarche or growth rate. The decision to include both injury and injury risk factors as an outcome was taken as it was thought this would provide the most meaningful practical application of the evidence and because preliminary searches revealed very limited studies specific to injury. Additionally, given the small number of studies reporting injuries, all studies that included female specific or female/male combined analysis were included whereas articles reporting on an injury risk factor had to have analysis specific to females that could be extracted.

Articles were excluded if they did not meet the eligibility criteria or if they were investigating the effect of an intervention, were reviews, position statements, or abstracts of conference proceedings or posters.

Data extraction

Data was extracted by a single author (AZ) into an excel spreadsheet for the following categories determined *a priori*: (i) authors' names; (ii) study design and sample size; (iii) age and sex; (iv) sport/s investigated; (v) maturation measure; (vi) maturation grouping; (vii) maturation status; (viii) injury definition; (ix) injury outcome or injury risk factor; (x) association between maturation and injury (including confidence intervals and effect sizes where available). A random sample of 10% of the articles was checked for extraction by the second author (CW).

Study quality assessment

Study quality was assessed independently by two authors (AZ and CW) using an adapted version of the 'Strengthening the Reporting of Observational Studies in Epidemiology' (STROBE) guidelines (Vandenbroucke et al., 2007). This included a ten-point checklist (each criteria rated 0-2) used to give an indication of study quality and risk of bias. While we acknowledge this checklist was not designed specifically to assess risk of bias, it assesses elements of a study (design, conduct and analysis) that can lead to important bias in findings. Studies were considered high quality (lower risk of bias) if they scored ≥14/20 or low quality (higher risk of bias) if they scored ≤13/20 (Weiss & Whatman, 2015). The interpretation of the scoring criteria and scores for individual criteria for each study are presented in Appendix 1.

Due to the range of methods used to define and quantify both maturation and injury risk, no meta-analysis could be performed. However, the level of evidence for findings across similar studies was rated as strong, moderate, limited, or very limited based on the quality and quantity of studies across each finding (criteria adapted from those published previously) (Table 1) (van Tulder et al., 2003).

Table 1: Level of evidence criteria

Strong	At least three high quality studies presenting consistent findings
Moderate	Two high quality studies presenting consistent findings
Limited	Multiple low-quality studies or one high quality study presenting results with limited consistency
Very limited	One low quality study presenting findings with very limited consistency

Results:

Search results

Figure 1 shows an overview of the study search and selection process. The initial search identified 4278 records. Duplicates were removed and the remaining 3014 titles were screened, resulting in 206 abstracts to be screened and 67 full texts. 26 articles were deemed to meet the inclusion criteria and their reference lists screened with an additional 5 studies identified and included (total included = 31). Studies were grouped into 10 focused on the association between an injury outcome and maturation, and 21 focussing on the association between potential injury risk factors and maturation.

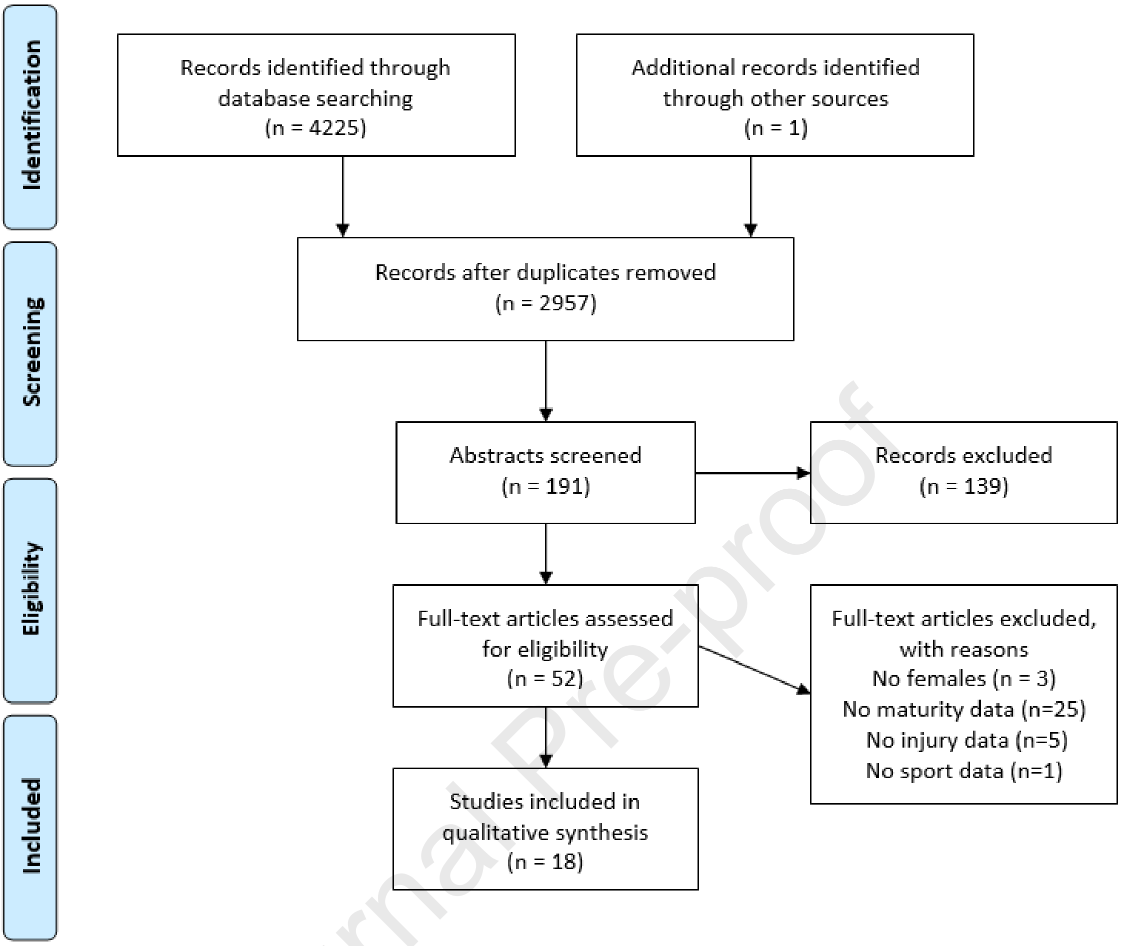

Figure 1: PRISMA flow chart to show search process.

Study characteristics

A summary of study characteristics for all included studies is presented in Table 2. Of the included studies, 15 were prospective or longitudinal, one was retrospective, and fifteen were cross-sectional. Ten studies exclusively included female participants (2 reported injuries, 8 reported injury risk factors), the rest included males and females with proportions ranging from 29-84% female. Only two of the mixed sex studies reporting injuries had female specific data and only one reported on apophyseal injuries specifically. The age of participants ranged from 9-21 years. A range of methods were used for measuring maturation, with some studies including more than one. Methods included maturation offset using the Mirwald equation (n=7) or Moore et al's equation (n=1); percentage of predicted adult height using the Khamis-Roche equation (n=3); Tanner staging via a pubertal maturation observation scale (PMOS) questionnaire (n=10), self-report (n=7), or parent reported (n=1); growth rate (n=3); menarcheal age (n=1); bone age as determined by wrist x-rays (n=1); and age at onset of menarche (n=1). Sports investigated included gymnastics (n=3), ballet (n=3), volleyball (n=8), basketball (n=11), soccer (n=10), Australian rules football (n=1), tennis (n=2), swimming (n=1), kung fu (n=1), karate (n=1), judo (n=1), alpine ski racing (n=2), and 4 studies which did not specify a sport.

Table 2: Characteristics of included studies

Authors	Study design (Sample size)	Sex, Age	Sport/s	Study Quality
(Bowerman et al., 2014)	Prospective (n=46)	30 F, 16 M 16 years ±1.58	Ballet	Low
(Caine et al., 1989)	Prospective (n=50)	All F 12.6 years	Gymnastics	Low
(Costa e Silva et al., 2017)	Retrospective (n=647)	307 F, 340 M 13.7±1.8 years (10-17 years)	SNR	Low
(Distefano et al., 2015)	Cross-sectional (n=113)	54 F, 59M 10-18 years	SNR	Low
(Ford et al., 2010)	Prospective (n=315)	265 F, 50 M pubertal 12.4±0.9 years post pubertal 14.5±1.4 years	Basketball (n=261) Soccer (n=61)	High
(Fort-Vanmeerhaeghe et al., 2019)	Cross-sectional (n=165)	92 F, 73 M 8-18 years	83 Basketball 81 Volleyball	High
(Galloway et al., 2018)	Prospective cohort over 2 years (n=506)	All F 13.6±1.8 years	Volleyball, basketball, soccer	Low
(Grinberg et al., 2024)	Cross-sectional (n=57)	All F 12.3 ±2.1 years	Volleyball	High
(Harris et al., 2021)	Cross-sectional (n=217)	64 F, 153 M 11-15 years	Basketball, Australian Rules, Volleyball, Tennis	High
(Hass et al., 2005)	Cross-sectional (n=32)	All F Postpubescent 20.2±1.2 years Prepubescent 9.0±1.0 years	Basketball, soccer, volleyball, gymnastics, dance	Low
(Hewett et al., 2004)	Cross-sectional (n=181)	100 F, 81 M Middle and high school aged	Basketball, soccer	High
(Hewett et al., 2015)	Longitudinal (n=892)	674 F, 218 M 10-18 years	Basketball, soccer	High
(Hewett et al., 2006b)	Cross-sectional (n=275)	F 87, M 188 Age not reported	SNR	Low

(Holden et al., 2019)	Prospective (n=184)	83 F, 101 M 13±0.3 years	SNR	High
(Jayanthi et al., 2015)	Case control, cross sectional (n=1190)	587 F, 603 M 13.7±2.3 years	SNR	Low
(Kim & Lim, 2014)	Cross-sectional (n=22)	All F 9-21 years	Artistic gymnastics	High
(Lopez-Valenciano et al., 2023)	Observational, cross-sectional (n=128)	60 F, 68 M U13 Boys 12.6 (12.5-12.7), Girls 12.6 (12.5-12.8) U15 Boys 14.6 (14.5-14.7), Girls 14.6 (14.5-14.7)	Tennis	High
(Lynch et al., 2017)	Longitudinal (n=184)	68 F, 116 M 12.6±1.6 years	Non-sports (n=47) Swimming (n=35) Impact sports (soccer, basketball, volleyball, karate, judo, kung-fu (n=102)	Low
(Müller et al., 2017)	Prospective (n=82)	31 F, 51 M 9-14 years	Alpine Ski Racing	Low
(Myer et al., 2009)	Prospective (n=1)	All F 14 years at time of injury	Basketball	High
(Pedley et al., 2021)	Prospective, longitudinal (n=1013)	All F Prepubertal 11.9±0.6 Pubertal 12.5±1.1 Postpubertal 14.8±1.6	Basketball, volleyball, soccer	Low
(Peek et al., 2022)	Secondary analysis of data from longitudinal cohort studies (n=257)	208 F, 49 M 11-18 years	Basketball, volleyball, soccer	Low
(Pletcher et al., 2021)	Cross-sectional (n=80)	F 38, M 42 42 Prepubertal 38 Postpubertal	SNR	Low
(Quatman et al., 2006)	Longitudinal, prospective (n=33)	F 16, M 17 Pubertal M 13.8±1.4 Postpubertal M 14.8±1.4 Pubertal F 12.6±1.0 Postpubertal F 13.6±1.0	Basketball	High

(Quatman et al., 2008)	Cross-sectional (n=418)	275 F, 143 M 11- 18 years	Basketball, soccer	Low
(Rudavsky et al., 2018)	Prospective (n=57)	34 F, 23 M 11-18 years	Ballet	Low
(Sayer et al., 2019)	Cross-sectional (n=93)	93 F 7-25 years	SNR	High
(Schmitz et al., 2009)	Prospective (n=157)	78 F, 79 M F 14.0±3.0 years, M 14.1±2.76 years	SNR	Low
(Steidl-Müller et al., 2020)	Prospective (n=89)	39 F, 50 M 10-14 years	Alpine Ski Racing	Low
(Swartz et al., 2005)	Cross-sectional (n=29)	29 F 9 to 24 years	SNR	Low
(Westbrook et al., 2020)	Cross-sectional (n=138)	All F 13.5±2.1	Soccer	Low

F=female; M=male; SNR = Specific sport not reported

Summary of study quality and level of evidence

Twelve studies were rated as high quality, low risk of bias, with the top score 17/20, achieved by four studies (Grinberg et al., 2024; Holden et al., 2019; Myer et al., 2009; Quatman et al., 2006). ~~Three studies achieved 16/20 (Fort-Vanmeerhaeghe et al., 2019; Harris et al., 2021; Hewett et al., 2004), three 15/20 (Ford et al., 2010; Hewett et al., 2015; Sayer et al., 2019), and two 14/20 (Kim & Lim, 2014; Lopez-Valenciano et al., 2023). The lowest rated study scored 8/20 (Jayanthi et al., 2015), two scored 10/20 (Hass et al., 2005; Schmitz et al., 2009), five scored 11/20 (Bowerman et al., 2014; Hewett et al., 2006b; Müller et al., 2017; Steidl-Müller et al., 2020), seven scored 12/20 (Bowerman et al., 2014; Caine et al., 1989; Costa e Silva et al., 2017; Pedley et al., 2021; Peek et al., 2022; Quatman et al., 2008; Sigward et al., 2012; Westbrook et al., 2020), and the remaining four scored 13/20 (Galloway et al., 2018; Lynch et al., 2017; Rudavsky et al., 2018).~~ The most commonly missed criterion was the power analysis and sample size justification, which was only reported in eight studies (Fort-Vanmeerhaeghe et al., 2019; Grinberg et al., 2024; Holden et al., 2019; Kim & Lim, 2014; Lynch et al., 2017; Pedley et al., 2021). The remaining criteria were "clearly/maybe" achieved by a minimum of 24 studies except for the criterion regarding missing data (18 studies). Additionally, the criterion "athletes or groups of athletes were similar at baseline or differences were accounted for and explained" was achieved by 26 studies, but 22 of these only scored 1, "maybe", as there was no or minimal description of initial differences between groups, only that they were sampled from the same population and thus were likely similar.

Based on the quality and findings of the studies investigating the association between maturation and injury, there is limited evidence to support this relationship in females given the very small number of studies reporting data specific to females (four), inconsistency of findings and the low-quality of studies. Based on the seven studies reporting on combined male and female data (mostly low quality but with generally consistent findings), there is some evidence supporting a lack of association between maturity status and injury.

However, there is moderate evidence supporting an association between potential injury risk factors (primarily knee injury) and maturation. Specifically, moderate evidence supports an increase in knee valgus and knee abduction moment during jump landings with increased maturation or circa-PHV, with limited evidence Knee flexion also decreases. Conversely moderate evidence also supports a lack of association between increased knee valgus/abduction angle and increased maturity. There is limited evidence knee flexion and hip flexion/adduction/internal rotation are not associated with increased maturation and that in fact females post puberty land with less knee valgus angle (and greater hip/knee flexion) than those pre puberty. There is very limited evidence hip (flexion, internal rotation, but not abduction) and knee (abduction/flexion/internal rotation) moments increase with increasing maturity. There is very limited evidence knee flexion/extension torque is greater post compared to pre-puberty and that knee stiffness and visual information processing/selective attention increases. In contrast there is also limited evidence isometric hip/knee strength, balance and jump performance do not improve with increasing maturity.

Evidence of an association between injury and maturation

Ten studies reported on the association between a documented injury and maturity status or growth rate (Table 3). These studies covered a range of sports including basketball (n=3), volleyball (n=3), soccer (n=2), ballet (n=2), alpine skiing (2) and one study each reporting on gymnastics, swimming, kung fu, karate, judo, Australian rules football, and tennis. Two studies did not report a specific sport of interest.

The results from these 10 studies were mixed and at times contradictory. Only two studies investigated females only, both reporting injury was associated with growth rate (Costa e Silva et al., 2017; Myer et al., 2009). Two further studies with female specific analysis found injury rate higher in early maturers, those more mature (based on bone age; odds ratio [OR]=2.1), those closer to PHV (Costa e Silva et al., 2017) and those less mature (Jayanthi et al., 2015). Several studies reported on overuse injuries but only one study reported specifically on apophyseal injuries (Tibial tubercle) (Jayanthi et al., 2015), finding females with apophyseal injuries were earlier Tanner stage than those without apophyseal injuries. Of the seven studies reporting outcomes based on combined male and female data one reported increased injury risk associated with increased rate of foot growth (relative risk [RR] = 1.4) (Bowerman et al., 2014), while another found maturity offset was a significant injury risk factor (Steidl-Müller et al., 2020). In contrast, six of the studies reported at least one outcome where there was no association between injury and maturity status or growth rate (Bowerman et al., 2014; Harris et al., 2021; Jayanthi et al., 2015; Lynch et al., 2017; Müller et al., 2017; Rudavsky et al., 2018). The majority of these studies investigated the association between maturity offset and injury.

An interesting case study presented by Myer et al. (2009) reported details on a basketball player with an ACL rupture with advancing maturation. Reported changes associated with advancing maturity included an increase in height, body mass, and BMI. Factors suggested to have influenced risk of injury included increased knee laxity, increased knee abduction impulse during jump landings, and decreased relative knee flexor-to-extensor strength.

Evidence of an association between injury risk factors and maturation

Twenty one studies reported on an association between a potential injury risk factor/s and maturity status based on female specific data. The sports included basketball (n=10), soccer (n=9), volleyball (6), gymnastics (n=2), dance (n=1), tennis (n=1) and six studies which did not report a specific sport.

The results from these studies included 14 studies reporting increased maturity was associated with a factor/s that could increase injury risk (DiStefano et al., 2015; Grinberg et al., 2024; Hass et al., 2005; Hewett et al., 2004; Hewett et al., 2006b; Hewett et al., 2015; Kim & Lim, 2014; Pedley et al., 2021; Peek et al., 2022; Quatman et al., 2006; Quatman et al., 2008; Sayer et al., 2019; Schmitz et al., 2009; Westbrook et al., 2020) and four studies reporting that increased maturity was associated with a factor/s that could decrease injury risk (Fort-Vanmeerhaeghe et al., 2019; Galloway et al., 2018; Pletcher et al., 2021; Swartz et al., 2005). A further eight studies reported increased maturity was not associated with a particular injury risk factor/s (DiStefano et al., 2015; Fort-Vanmeerhaeghe et al., 2019; Galloway et al., 2018; Holden et al., 2019; Lopez-Valenciano et al., 2023; Pedley et al., 2021; Pletcher et al., 2021; Sayer et al., 2019).

Increased injury risk was mostly associated with changes in jump/landing strategies. Decreases in knee flexion, increases in medial knee motion/knee valgus, knee abduction/flexion/internal rotation moments and active knee stiffness were observed with increasing maturity (DiStefano et al., 2015; Ford et al., 2010; Hewett et al., 2004; Hewett et al., 2015; Kim & Lim, 2014; Schmitz et al., 2009). In total 13 studies suggested changes in jump/landing strategies associated with advancing maturity could contribute to increased knee injury risk. In contrast three studies reported tuck jump performance (Fort-Vanmeerhaeghe et al., 2019) and hip mechanics on landing (Galloway et al., 2018;

Swartz et al., 2005) improved with increased maturity. A further two studies reported either no change in knee valgus angles (Holden et al., 2019) or a reduction in knee valgus angle (Swartz et al., 2005).

Additionally increased joint laxity (Quatman et al., 2008) and H-Q ratios (greater quadricep than hamstring activation) were reported with increasing maturity (Kim & Lim, 2014; Sigward et al., 2012). In contrast, no difference was observed in active ankle and hip stiffness once athletes were post-pubertal (Ford et al., 2010). Nor did increasing maturity change hip, hamstrings or quadriceps strength (Hewett et al., 2004; Lopez-Valenciano et al., 2023) or balance (Lopez-Valenciano et al., 2023; Pletcher et al., 2021). Finally, one study reported knee and hip strength declined with increasing maturity (DiStefano et al., 2015).

Table 3: Summary of studies reporting injuries

Authors	Maturation measure	Maturation groupings	Maturation status	Injury definition	Injury outcome	Association between maturation and injury
(Bowerman et al., 2014)	Growth (change in foot length) Self-reported tanner stage	Less mature: Tanner stages 2 and 3 More mature: Tanner stages 4 and 5	41% less mature 59% more mature	Any physical harm resulting in pain or discomfort that required modified activity during ≥1 class or cease all dance related activity.	Injury incidence per 1000hr and per 1000 exposures	0.5cm change in right foot length → moderate ↑ in injury risk (RR=1.41, CI=0.93-2.13) No clear association between maturity status and injury risk.
(Caine et al., 1989)	Maturation rate determined by Tanner stage at start and midpoint of surveillance period	Stable growth: breast stage 1 or menarche onset before the 2nd rating. Rapid growth: not 'stable growth' for most of the surveillance period	50% stable growth 50% rapid growth	Any gymnastics-related incident that resulted in the gymnast missing any portion of a workout or competitive event.	Injury incidence per 1000hr exposure	**F - Injury risk associated with rapid growth (P<0.06).**
(Costa e Silva et al., 2017)	Bone age from left wrist and hand x-rays Maturity offset (Mirwald equation)	Late maturing (bone age<chronological age -1) normal maturing (bone age=chronological age ±1) early maturing (bone age>chronological age +1)	Not reported	Musculoskeletal condition/ symptom and at least 1 of: (1) PA restriction for ≥24hr, (2) affected performance in quantitative or qualitative terms, or (3) required medical attention.	Injury incidence per 1000hr exposure	**F - Injury rate ↑ in early vs late maturation group (p=0.007), and in girls with higher bone age (p=0.012) and lower maturity offset (just past PHV) (p=0.033).**
(Harris et al., 2021)	Maturity offset (Mirwald equation)	Pre-PHV (>1 year pre PHV) Peri-PHV (1 year ± PHV) Post-PHV (>1 year post PHV)	Offset mean±SD = -0.6±1.1	Presence of AKP during single leg decline squats.	Prevalence of AKP measured using VISA-P Score	Maturation status was not significantly associated with AKP (X^2=0.00; p=0.95).
(Jayanthi et al., 2015)	Annual growth rate (over past 6 months) Self-reported Tanner stage	None	Mean growth rate 4.8±4.6cm/y	Acute (single traumatic event) Overuse (gradual onset without a specific sports-related traumatic event) Serious overuse (overuse and physician recommended	Prevalence of injury	Growth rates were similar between injured and uninjured athletes (4.8 cm/y for both groups; P = 0.96). **F - Girls with apophyseal injuries were earlier Tanner stages for pubic**

				treatment that typically requires ≥1 month off sport)		**(1.8±0.71 vs 2.7±1.28; p<0.05) and breast stage (2.4±0.92 vs 3.2±1.37; p<0.05)**
(Lynch et al., 2017)	Maturity offset (Mirwald equation)	None	Maturation offset in: Injured: -1.24±1.2 Uninjured: -1.12±1.5	Severity of fractures: Low impact (e.g., low-impact collision) Medium impact (e.g., sports, bicycling) High impact (e.g., car accident)	Prevalence of stress fractures	No relationship between maturation offset and the occurrence of fractures (p=0.733).
(Myer et al., 2009)	Self (and parent)-reported Tanner stages and menstrual status	Prepubertal (Tanner stage 1) early pubertal (Tanner stage 2) pubertal (Tanner stages 3 and 4) postpubertal (Tanner stage 5)	At the time of injury, case was post pubertal	None reported	MRI to confirm ACL rupture	**F - At time of injury athlete had ↑ height (4%)**
(Müller et al., 2017)	Age at Peak Height Velocity (APHV), Maturity offset (Mirwald equation)	Early-maturing: APHV < mean - SD; Normal-maturing: APHV within mean ± SD; Late-maturing: APHV > mean + SD	Early (n=9) Normal (n=63) Late (n=10) APHV males (13.7 ±0.5yrs), females (12.0±0.5yrs)	Traumatic Injury: sudden onset based on time loss Overuse Injury: Any physical complaint not attributable to a single identifiable event causing time loss	Injury Incidence: Traumatic and overuse injuries per 1000 hours of training	No significant differences in injury rates between different maturity groups.

(Rudavsky et al., 2018)	Maturity offset (Mirwald equation)	None	Maturation offset at the start of the study: Normal group: 0.38±1.33 Pathology group: 0.24±2.11	Patellar tendon pathology defined as a focal hypoechoic lesion at the proximal attachment of the tendon.	VISA-P questionnaire and VAS pain scale used for assessing prevalence of patellar tendon pain during single leg decline squat. Patellar tendon pathology measured by ultrasound.	Maturity offset not different in normal vs pathology groups (p=0.79 at baseline, p=0.97 throughout the study).
(Steidl-Müller et al., 2020)	Age at peak height velocity (APHV), maturity offset (Mirwald equation)	Early-maturing: APHV < mean - SD; Normal-maturing: APHV within mean ± SD; Late-maturing: APHV > mean + SD	Early (n=16) Normal (n=56) Late (n=17) APHV males (13.7±0.5), females (12.0±0.4)	Traumatic Injury: sudden onset based on time loss; Overuse Injury: Any physical complaint not attributable to a single identifiable event causing time loss	Injury Incidence: Traumatic and overuse injuries per 1000 hours of training	Maturity offset was a significant injury risk factor (Wald = 4.818; p = 0.028), but no significant difference in maturity offset or leg length changes between injured and uninjured groups.

F = female specific analysis (bold text); PMOS = pubertal maturation observation scale; VISA-P= Victorian Institute of Sport Assessment for the Patellar Tendon; VAS = visual analogue scale; PHV = peak height velocity; CSA = cross-sectional area; PA = physical activity; AKP = anterior knee pain; ACL = anterior cruciate ligament; COM = centre of mass; BMI= body mass index; APHV=age peak height velocity; RR=relative risk

Table 4: Summary of studies reporting factors associated with injury (based on female specific data)

Authors	**Maturation measure**	**Maturation groupings**	**Maturation status**	**Injury risk factor**	**Association between maturation and injury risk factor**	**Practical Interpretation**
(DiStefano et al., 2015)	PMOS	Pre, Circa, Post	Pre (n=15, age 9 ±1) Circa (n=12, age 12 ±3) Post (n=27, age 16 ±2)	Hip and knee kinematics, jump/landing task. Hip and knee isometric strength.	Knee flexion ↓ with ↑ maturity ($p<0.05$). No diff in Initial or peak knee abduction, hip flex/add/IR displacement/ROM ($p>0.05$). Knee Ext, Flex and hip ER and Ext, strength ↓ with ↑ maturity ($p<0.05$).	Post-pubertal - lack of strength development and reduced sagittal plane motion may increase risk of ACL injury.
(Ford et al., 2010)	Modified PMOS questionnaire	Pubertal Post-pubertal	Pubertal (n=182, age 12.4±0.9) Post-pubertal (n=133, age 14.5±1.4)	Active joint stiffness of the ankle, knee and hip during 30cm drop jump.	Active knee (but not hip and ankle) stiffness ↑ with maturation (R^2=0.92; $p<0.05$)).	Active knee stiffness (but not ankle and hip) increased with maturity in females. Increased stiffness may contribute to increased rick of ACL injury.
(Fort-Vanmeerhaeghe et al., 2019)	Mirwald equation	Prepubertal (PHV-1 year) Pubertal (at PHV) Post-pubertal (PHV+1)	Prepubertal M 37, F 21 Pubertal M 7, F 41 Post-pubertal M 29, F 30	Tuck jump assessment	No change in knee valgus with increasing maturation. All other jump technique deficits decreased with increased maturity.	Overall jump-landing performance improved with maturation for most criteria, but knee valgus alignment did not

						improve. This persistent knee valgus may contribute to higher risk of ACL injuries.
(Galloway et al., 2018)	Modified PMOS questionnaire	Pre-pubertal ≤1 point in PMOS Pubertal 2-4 points Post-pubertal ≥5 points	53% pre-pubertal 47% post-pubertal at baseline 46% pre-pubertal 54% post-pubertal at follow-up	High risk knee profile - ↓ knee flexion, ↑ knee abduction, external KAM, rotator moments. Low risk knee profile - ↑ knee flexion, ↓ knee abduction, external KAM, rotator moments. High risk hip profile - ↑ hip flexion angles with ↓ KAM, hip extensor, rotator moments. Low risk hip profile - ↓ hip flexion with ↑ KAM, hip extensor, rotator moments.	High risk hip profile and pre-pubertal at baseline → post-pubertal at follow up ↑ odds of reaching low risk hip profile vs those who had not reached post pubertal (OR=2.1, p=0.02). No association between change in pubertal status and knee risk profile.	Progression from pre-pubertal to post-pubertal protective on high-risk hip mechanics, with athletes more likely to transition to a low-risk hip profile, but this was not the case for knee mechanics.
(Grinberg et al., 2024)	% adult stature (Khamis-Roche equation)	Pre-pubertal (PRE < 85%), early pubertal (EPUB ≥ 85% to < 90%), mid-	PRE; *n* = 13, EPUB; *n* = 7, MPUB; *n* = 8 and LPUB; *n* = 24	Flanker test; evaluation of	↓ RTs (both congruent and incongruent) for the LPUB compared to PRE and EPUB groups	Maturation level significantly impacts visual information

		pubertal (MPUB ≥ 90% to < 95%) and late-pubertal (LPUB ≥ 95%)		selective visual attention and response inhibition. Outcome = response time (RT) and success rate.	(Δmean = 199-230ms, $P < 0.002$; Δmean = 200-213ms $P < 0.03$, for PRE and EPUB respectively). ↓congruent RTs for MPUB compared to PRE (Δmean = 155ms, $P = 0.010$) and to EPUB (Δmean= 156ms, $P = 0.017$).	processing and selective attention - more mature adolescents have superior reaction times.
(Hass et al., 2005)	Onset of menarche and associated growth phase (increase in height ≥5cm or weight ≥ 10% in previous 3 months)	Postpubescent Prepubescent	Postpubescent n=16 Prepubescent n=16	Knee joint moments and forces during single leg DJ static landing, vertical landing, and lateral landing tasks.	Postpubescent participants exhibited reduced knee flexion (4.5°) at initial contact, increased mediolateral knee joint forces and reduced knee extensor moments compared to prepubescent participants.	Postpubescent females exhibited landing strategies that may increase the risk of knee injuries - reduced knee flexion and increased mediolateral forces.
(Hewett et al., 2004)	Modified PMOS questionnaire	Prepubertal (Tanner stage 1) Early pubertal (Tanner stage 2 and 3) Late/post pubertal (Tanner stage 4 and 5)	F prepubertal 11.5±0.7y (n=14) F early pubertal 12.6±1.1y (n=28) F late/ post pubertal 15.5±1.5y (n=58) M prepubertal 12.0±0.6y (n=27) M early pubertal 14.2±1.4y (n=24) M late/post pubertal 15.8±1.7y (n=30)	Medial knee motion, lower extremity valgus angle, flexor/extensor torques	Initial contact and max valgus angle ↑ in late/post pubertal girls vs early puberty) and prepubertal girls. Hamstring, quadriceps peak torque not associated with maturity.	Maturation leads to decreased neuromuscular control of the knee in female athletes, contributing to a higher risk of ACL injuries.

(Hewett et al., 2006b)	Tanner stages	Tanner stages	Stages 2-5	Vertical GRF during Drop vertical jumps	No increase in jump height with increased maturity No change in ratio of landing to take-off forces with increased maturity	Lack of a neuromuscular spurt in females during puberty may contribute to higher risk of ACL injuries compared to males.
(Hewett et al., 2015)	% adult stature (Khamis-Roche equation)	None	% adult height ranged from 82-100% PHV = 91%-92% adult stature	Knee abduction moments and angles during DJ	Peak KAM ↑ with increase in maturity Peak KAM associated with tibia (r = 0.431, P<0.001) length and femur length (r = 0.254, P<0.001).	Increased maturity leads to increased peak knee abduction moments in females.
(Holden et al., 2019)	Maturation offset (Moore et al)	Pre-PHV (three-one year before PHV) Around-PHV (one year ± PHV) Post-PHV (one-three years post PHV)	Not reported	DVJ - Knee flex angle immediately pre initial contact and at max flex Knee valgus displacement	No effect of time (maturation) on knee flex or knee valgus displacement.	Increased maturation did not change knee flexion or knee valgus angles in females.
(Kim & Lim, 2014)	Menarcheal age	pre-menarche (n=11) post-menarche (n=11)	pre-menarche: 11.6±2.2 years post-menarche: 19.14±3.2 years	Knee flexion angles, KAA, max knee internal rotation angle, max KAM, H-Q muscle activity ratio during single leg drop jump	Post menarche ↓ max knee flexion angle (p=0.019), ↑ max KAA (p=0.039), max internal rotation angle (p=0.043), max KAM (p=0.049), H-Q ratio (more quadricep than hamstring activation; p=0.033) vs pre-menarche.	More mature (post-menarche) group exhibited greater knee loads compared to the pre-menarche group.

(Lopez-Valenciano et al., 2023)	Maturation offset (Mirwald) Age at PHV	pre-PHV (<-1) around PHV (-0.5-0.5) post PHV (>1)	U13 Boys -2.4 (-2.6 to -2.2) U13 Girls 0.2 (0.1 to 0.4) U15 Boys -0.7 (-0.9 to -0.5) U15 Girls 1.7 (1.5 to 1.8)	Unilateral balance (y-balance) Isometric hip abduction and adduction strength Bilateral asymmetries (Hip ROM, Hip Strength, Balance)	No significant differences between maturity levels (around PHV vs post-PHV) for any of the factors measured.	Maturity status did not impact on balance or hip strength performance.
(Pedley et al., 2021)	PMOS	Pre-pubertal Pubertal Post-pubertal	Pre-pubertal (n=279) Pubertal (n=401) Post-pubertal (n=333)	Drop vertical jump peak landing force, peak take off force, ratio of peak landing to peak take off force COM displacement, stretch-shortening cycle (SSC) function	Significant differences in absolute peak landing and take- off force were evident between all maturational stages (p<0.05). Relative to bodyweight normalized forces, only peak take-off force was significantly different between pre-pubertal and post-pubertal groups (p<0.05; d=0.22). Spring- like behavior showed small improvements from pubertal to post-pubertal (p<0.05; d=0.25). Most females displayed poor SSC function at pre-pubertal (79.6%), pubertal (77.3%), and post-pubertal (65.5%) stages of maturity.	Most adolescent female athletes display poor stretch-shortening cycle (SSC) function irrespective of maturity, which may contribute to the higher incidence of ACL injuries.
(Peek et al., 2022)	Modified PMOS	Pre-pubertal, Pubertal, Post-pubertal	Needed at least one measure across at least two maturation	Knee flexion and extension	With increasing maturity relative knee extensor	Maturity status did not lead to

			status: Pre-pubertal M 20, F 75 Pubertal M 37, F 169 Post-pubertal M 33, F 123	concentric strength measured using isokinetic dynamometer	torque increased and knee flexor torque decreased.	significant improvements in neuromuscular performance for females. This lack of improvement may contribute to the higher risk of ACL injuries observed in female athletes as they mature.
(Pletcher et al., 2021)	Self-reported Tanner stages	Prepubertal Postpubertal	M 22 pre, 20 post F 20 pre, 18 post	Knee Flex/Ext strength and ratio Balance Landing mechanics (IC Knee Flex, Abd; Peak VGRF	Average Peak Knee Flex/ext torque (abs and %) Post>Pre No difference in balance No difference in IC, Knee Flex/Abd angle	More mature females were stronger than less mature but landing mechanics and balance did not differ.
(Sayer et al., 2019)	PMOS	Pre: Tanner stage 1 Pub: Tanner stages 2 and 3 Post: Tanner stages 4 and 5	Pre n=31 Pub n=31 Post n=31	Hip and knee moments during single leg drop lateral jump	Differences in peak Knee Abd Moment, Post>Pre (Nm/kg), and Post>Pub>Pre (Nm/m). Difference in peak Knee Flex Moment, Post&Pub>Pre (Nm/kg) and Post>Pub>Pre (Nm/m). Differences in Knee IR moment Post>Pub>Pre (Nm/Kg; Nm/m). Differences in Hip Flex moment Post>Pub>Pre (Nm/m).	Increases in triplanar knee and sagittal plane hip moments across pubertal stages are related to growth-related increases in body mass and height and may impact knee injury risk.

					Differences in Hip IR moment Post>Pub>Pre (Nm/kg). No differences in Hip Ab Moments. No differences in Hip Flex Moments (Nm/kg).	
(Schmitz et al., 2009)	Self-reported Tanner stages	MatGrp1 = tanner stages 1-2 MatGrp2 = stages 3-4 MatGrp3 = stage 5	MatGrp1 n= 25 F, 23 M MatGrp2 n= 28 F, 33 M MatGrp3 n= 25 F, 23 M	Dynamic valgus alignment during drop jump test	↑ valgus displacement from MatGrp1 to MatGrp3 (11.5°±6.9 vs 15.5°±8.7; ES 0.48)	Increased dynamic valgus alignment in females throughout maturation may contribute to a higher risk of knee injuries, such as ACL injuries.
(Swartz et al., 2005)	Tanner group	Pubertal Post-pubertal	Pre = 15, Post = 14	Vertical Jump	Knee Flex, valgus, and Hip Flex Post>Pre	More mature females land with more hip and knee flexion and less knee valgus.
(Quatman et al., 2006)	PMOS	Pubertal Post-pubertal	Year 1 pubertal Year 2 post-pubertal	Vertical GRF during Drop vertical jumps	No significant change in maximum jump height or landing vertical GRF from pubertal to post-pubertal. Dominant (but not non) side take off GRF decreased from pubertal to post-pubertal. Decreased loading rates during the post-pubertal stage compared to pubertal.	Female athletes did not exhibit the same neuromuscular adaptations as males during maturation, which may contribute to their higher risk of ACL injuries.

(Quatman et al., 2008)	Modified PMOS questionnaire	Pre-pubertal (Tanner stage 1) Early pubertal (Tanner stage 2-3) Post-pubertal (Tanner stage 4-5)		Generalised joint laxity using the Beighton and Horan Joint Mobility Index	Significantly ↑ in joint laxity from pre to post puberty (p=0.042).	Increases in joint laxity associated with the onset of puberty in females may be related to their concomitant increase in knee and ACL injury incidence in athletic populations.
(Westbrook et al., 2020)	Khamis-Roche method	Pre-pubertal (PRE) Pubertal (PUB) Post-pubertal (POST)	Pre-pubertal (n=17) Pubertal (n=32) Post-pubertal (n=90)	Lower extremity biomechanics (knee abduction, knee flexion, knee moments) during drop vertical jump and single leg unanticipated cutting task	POST exhibited greater peak abduction angles and moments compared to PUB and PRE in both tasks POST/PUB exhibited greater peak knee flexion moments compared to PRE, as well as POST compared to PUB in both tasks No significant difference in knee flexion angle.	Post-pubertal female athletes exhibit greater knee abduction angles and moments, which are associated with a higher risk of ACL injuries

F=female; M=male; PMOS = pubertal maturation observation scale; VISA-P= Victorian Institute of Sport Assessment for the Patellar Tendon; VAS = visual analogue scale; PHV = peak height velocity; CSA = cross-sectional area; PA = physical activity; AKP = anterior knee pain; ACL = anterior cruciate ligament; COM = centre of mass; BMI= body mass index; KAM = knee abduction moment; KAA = knee abduction angle; GRF=ground reaction force; IR=internal rotation; IC=initial contact; Ab=abduction

Discussion

Several expert sport medicine groups recommend monitoring growth and maturation in young adolescent athletes due to concerns there is an increased risk of injuries during this time (DiFiori et al., 2014; Lloyd et al., 2016. While there is a strong theoretical link between biological age (maturational stage) and some injuries, particularly around periods of peak growth, there is a need to better understand the evidence for this link in young females playing sport. We first discuss the evidence based on studies reporting injury outcomes and then evidence based on studies reporting potential injury risk factors.

Maturity links to reported injuries

Based on the available literature, the findings of this review suggest evidence to support a link between maturity status and injury in female youth sport is limited. In fact, based on the studies reviewed, analysing combined data from boys and girls, there is some evidence that maturity status is not associated with injury risk. The variation in maturity estimation methods and injury definitions clearly limit the strength of this evidence and any conclusions. These findings agree with a previous systematic review that concluded there was no clear evidence of an association between maturation, growth and general musculoskeletal conditions (including sports injuries) in adolescents (Swain et al., 2018). A more recent scoping review concluded that growth and maturation do contribute to injury risk in elite youth athletes, however the authors acknowledged the methodological limitations highlighted by Swain (2018) persist, alongside a lack of female evidence, limiting the strength of evidence (Parry et al., 2024). Importantly there is very limited evidence of increased risk of apophyseal injuries in female youth athletes circa PHV as only one study has specifically reported on this (Jayanthi et al., 2015).

In agreement with the scoping review by Parry et al. (2024), the findings of this review clearly show a lack of studies focused on young females. This also aligns with a recent mini review investigating links between maturation and injury in high level youth football that reported nine out of ten studies reported injury data only for boys (Wik, 2022). Given the sex specific biological changes occurring during puberty, young females and males may be predisposed to different levels of risk and thus female specific studies are a necessity. Specifically, studies are needed that target injuries for which females may be at greater risk than males (e.g. knee injuries). Additionally, the earlier onset of puberty in females may result in unique interactions with competition/training levels in specific sports that differ from males and contribute to injury risk. In males PHV typically occurs two years later than in females, at an age when the training demands for many sports are increasing, contributing to the increased injury risk. The earlier timing of PHV, relative to increasing sporting demands, may act as one factor protecting females from growth related injuries.

Importantly and consistent with the larger number of male specific studies, the available studies in young females are limited in their ability to make strong recommendations due to heterogenous study designs, inconsistent injury definitions, a lack of focus on specific injuries, the variety of methods used to estimate maturity and growth rate, poor control for confounding factors and the unique demands and risk posed by specific sports. These limitations result in a high risk of bias and poor overall quality in many of the reviewed studies, which limits the strength of the evidence reported. While these limitations have been regularly acknowledged the solution is more difficult. Well designed, female specific prospective longitudinal studies (able to establish causality and long enough to establish growth rates) are needed but difficult and costly to conduct. Additionally, while the use of maturity prediction equations, derived from anthropometric measurements, has become common in youth sport (Towlson et al., 2021), there is a need for further evidence of their validity in a wider range of populations. The most common growth reference datasets used in these estimations of biological maturity are based on American and European populations which may not be appropriate for other populations (Sweeney et al., 2024). Recent evidence suggests the choice of reference dataset impacts on the athlete biological maturity classification (Sweeney et al., 2024). Furthermore, while beyond the scope of this review, readers should be aware of the strengths and weaknesses of the other methods used to assess maturity status (Monasterio et al., 2024).

Maturity links to potential injury risk factors

While the evidence supporting a link with injury is limited, we did find moderate evidence supporting a link between maturation and some potential injury risk factors in female youth sport. This aligns with a recent systematic review that concluded there is moderate-to-limited evidence potential biomechanical risk factors for ACL injury differ across the stages of maturation (Ramachandran et al., 2024). The most frequently reported association was that between increasing maturity and lower limb biomechanics during jump/landing tasks. Several studies reported increases in knee valgus angle and/or knee abduction moment and concluded decreased neuromuscular control of the knee, with advancing maturity, could contribute to increased knee injury risk. Multiple studies suggested this may be because females do not benefit from the same neuromuscular spurt, circa-PHV, as males. This is consistent with the lack of increase in hip and knee strength reported with increasing maturity (Hewett et al., 2004; Lopez-Valenciano et al., 2023; Pletcher et al., 2021). Furthermore, females demonstrated greater knee valgus than males at all maturation levels (Holden et al., 2019). Frontal plane hip and knee control has been reported as a common biomechanical risk factor for knee injury in sports (Weiss & Whatman, 2015). However, it is unlikely that deteriorating hip and/or knee control is an independent effect of sex specific maturational differences. It has recently been highlighted that environmental factors likely play a significant role in differences in physical development between boys and girls, particularly during adolescence (Parsons et al., 2021). It should be noted there is some evidence from this review that jump/landing performance may improve (or remain unchanged) in females as they mature. These contradictory findings could be the result of participants coming from a range of environmental contexts or due to different methods used (e.g. maturity estimates, performance tests) and thus direct comparison between studies is difficult. That said the evidence in this review supports the potential for increased risk of knee injury during and after periods of rapid growth in females, particularly those in sports involving frequent jump landings (e.g. basketball, netball). This suggests young female athletes playing sports which require frequent jump landings or other movements associated with high knee load will benefit from additional neuromuscular training as they mature, focused on strength and dynamic control of the lower extremity. Unsurprisingly these recommendations align with well-known neuromuscular training programmes shown to reduce knee injury risk (Webster & Hewett, 2018). Additionally, training modifications could include increased emphasis on landing mechanics and monitoring the number of landings and other high knee load activities during training.

Although the evidence for a causal link between maturation and injury risk in young females remains limited, concerns regarding the long-term consequences of sport related injury (especially knee injury) support the monitoring of growth and maturation in female youth. The focus should be on education and the use of maturity data to maximise healthy engagement in female youth sport with a focus on long term rather than short term outcomes. Embedding educational opportunities in school curriculum could be a vehicle to maximise uptake. To monitor change, several options exist for support practitioners, coaches, and parents, although resources in community sport are limited. These include websites that give estimates of maturation stage, or regular height measures to monitor growth rates (Swain et al., 2018). Sensitivity clearly exists in female youth regarding measures of mass (needed for some maturity estimates) and this needs to be managed and/or alternate methods used. Logistically, the large individual variation in maturity timing creates several challenges in a team sport environment, especially in community sport. These include the appropriate programming of individual training and team training for an age based team with substantial variation in biological age (Wik, 2022). The rapid size and weight increases, and associated changes in mechanics, as well as the difficulties of playing against (and with) players who may be significantly larger (or smaller), feed into injury risk and potentially help to explain increases in injury rates during adolescence. There is a clear need in community sport for more support for and improved education of players and coaches who are often volunteers and time poor. A recent example is the "SmartHealth" resource developed by Netball New Zealand to support female player health throughout adolescence and early adulthood (NetballSmart, n.d.). More work is needed to determine how community sports can best support female players during adolescence.

Study limitations

This review has several limitations readers should be aware of. As with all reviews we can't be certain we found all relevant evidence and specifically we didn't have access to the Web of Science database. To allow use to report level of evidence based on quality scores across all studies, we used a single set of criteria for several different study designs. While this maintains consistency and aids the level of evidence statement for associations, it doesn't consider the benefits of designs that may be able to determine causal relationships. Finally, we were not able to report injury burden as most studies reviewed did not provide the necessary data for this to be estimated and we were unable to meta-analyse the data due to the heterogeneity of outcomes.

Conclusion

There is limited evidence supporting a link between maturity and injury in young females participating in sport, however there is moderate evidence that maturity status is associated with potential knee injury risk factors. The strongest evidence is for a decrease in neuromuscular control of the knee during jump landings with increased maturation and during periods of rapid growth.

Practical implications

There may be an opportunity to reduce sport injury rates in young females with education of parents, coaches, and players regarding the adolescent growth spurt, particularly in sports requiring frequent jump landing. This could include how to identify maturity status, appropriate training to maximise movement competency during this period (particularly around jump landings), and appropriate training modifications during periods of rapid growth. Sporting organisations need to consider how their systems can best support female players during adolescence.

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References:

Arnold, A., Thigpen, C. A., Beattie, P. F., Kissenberth, M. J., & Shanley, E. (2017). Overuse Physeal Injuries in Youth Athletes:Risk Factors, Prevention, and Treatment Strategies. *Sports Health, 9*(2), 139-147. https://doi.org/10.1177/1941738117690847

Beech, J., Jones, B., King, R., Bennett, P., Young, S., Williams, S., Stokes, K., & Emmonds, S. (2022). The incidence and burden of injuries in elite English youth female soccer players. *Science & Medicine in Football, 6*(5), 605-615. https://research.ebsco.com/linkprocessor/plink?id=29fdd0d5-2520-3492-84d7-d29ccb9da0c5

Belcher, S., Whatman, C., Brughelli, M., & Borotkanics, R. (2020, 2020/10/01/). Ten-year nationwide review of netball ankle and knee injuries in New Zealand. *Journal of science and medicine in sport, 23*(10), 937-942. https://doi.org/https://doi.org/10.1016/j.jsams.2020.04.004

Black, A. M., Meeuwisse, D. W., Eliason, P. H., Hagel, B. E., & Emery, C. A. (2021, 2021/09/01/). Sport participation and injury rates in high school students: A Canadian survey of 2029 adolescents. *Journal of Safety Research, 78*, 314-321. https://doi.org/https://doi.org/10.1016/j.jsr.2021.06.008

Bowerman, E., Whatman, C., Harris, N., Bradshaw, E., & Karin, J. (2014). Are maturation, growth and lower extremity alignment associated with overuse injury in elite adolescent ballet dancers? *Physical Therapy in Sport, 15*(4), 234-241. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=99005206&site=ehost-live&scope=site

Caine, D., Cochrane, B., Caine, C., & Zemper, E. (1989). An epidemiologic investigation of injuries affecting young competitive female gymnasts. *American Journal of Sports Medicine, 17*(6), 811-820. http://articles.sirc.ca/search.cfm?id=248967

Costa e Silva, L., Fragoso, M. I., & Teles, J. (2017). Physical Activity-Related Injury Profile in Children and Adolescents According to Their Age, Maturation, and Level of Sports Participation. *Sports Health: A Multidisciplinary Approach, 9*(2), 118-125. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=121559583&site=ehost-live&scope=site

DiFiori, J. P., Benjamin, H. J., Brenner, J. S., Gregory, A., Jayanthi, N., Landry, G. L., & Luke, A. (2014). Overuse injuries and burnout in youth sports: a position statement from the American Medical Society for Sports Medicine. *British Journal of Sports Medicine, 48*(4), 287. https://doi.org/10.1136/bjsports-2013-093299

DiStefano, L. J., Martinez, J. C., Crowley, E., Matteau, E., Kerner, M. S., Boling, M. C., Nguyen, A.-D., & Trojian, T. H. (2015). Maturation and Sex Differences in Neuromuscular Characteristics of Youth Athletes. *The Journal of Strength & Conditioning Research, 29*(9), 2465-2473. https://doi.org/10.1519/jsc.0000000000001052

Ford, K. R., Myer, G. D., & Hewett, T. E. (2010). Longitudinal Effects of Maturation on Lower Extremity Joint Stiffness in Adolescent Athletes. *American Journal of Sports Medicine, 38*(9), 1829-1837. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=60094993&site=ehost-live&scope=site

Fort-Vanmeerhaeghe, A., Benet, A., Mirada, S., Montalvo, A. M., & Myer, G. D. (2019, Aug 1). Sex and Maturation Differences in Performance of Functional Jumping and Landing Deficits in Youth Athletes. *J Sport Rehabil, 28*(6), 606-613. https://doi.org/10.1123/jsr.2017-0292

Galloway, R. T., Xu, Y., Hewett, T. E., Barber Foss, K., Kiefer, A. W., DiCesare, C. A., Magnussen, R. A., Khoury, J., Ford, K. R., Diekfuss, J. A., Grooms, D., Myer, G. D., & Montalvo, A. M. (2018). Age-Dependent Patellofemoral Pain: Hip and Knee Risk Landing Profiles in Prepubescent and Postpubescent Female Athletes. *American Journal of Sports Medicine, 46*(11), 2761-2771. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=131548278&site=ehost-live&scope=site

Grinberg, A., Hanzlíková, I., Lehnert, M., & Abdollahipour, R. (2024). The impact of maturation level, not chronological age, on attentional control: implications for sports injury prevention in female adolescents. *BMC Sports Science, Medicine and Rehabilitation, 16*(1), 1-9. https://research.ebsco.com/linkprocessor/plink?id=023c34bc-124e-3940-a9b1-96fd2a7e39bd

Harris, M., Edwards, S., Rio, E., Cook, J., Cencini, S., Hannington, M. C., Bonello, C., & Docking, S. (2021). Nearly 40% of adolescent athletes report anterior knee pain regardless of maturation status, age, sex or sport played. *Physical Therapy in Sport, 51*, 29-35. https://doi.org/10.1016/j.ptsp.2021.06.005

Hass, C. J., Schick, E. A., Tillman, M. D., Chow, J. W., Brunt, D., & Cauraugh, J. H. (2005, Jan). Knee biomechanics during landings: comparison of pre- and postpubescent females. *Medicine and science in sports and exercise, 37*(1), 100-107. https://doi.org/10.1249/01.mss.0000150085.07169.73

Hewett, T. E., Ford, K. R., & Myer, G. D. (2006a). Anterior Cruciate Ligament Injuries in Female Athletes:Part 2, A Meta-analysis of Neuromuscular Interventions Aimed at Injury Prevention. *The American journal of sports medicine, 34*(3), 490-498. https://doi.org/10.1177/0363546505282619

Hewett, T. E., Myer, G. D., & Ford, K. R. (2004). Decrease in Neuromuscular Control About the Knee with Maturation in Female Athletes. *Journal of Bone and Joint Surgery, 86*(8), 1601-1608. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=13954306&site=ehost-live&scope=site

Hewett, T. E., Myer, G. D., Ford, K. R., & Slauterbeck, J. R. (2006b, Jul). Preparticipation physical examination using a box drop vertical jump test in young athletes: the effects of puberty and sex. *Clinical Journal of Sport Medicine, 16*(4), 298-304. https://doi.org/10.1097/00042752-200607000-00003

Hewett, T. E., Myer, G. D., Kiefer, A. W., & Ford, K. R. (2015). Longitudinal Increases in Knee Abduction Moments in Females during Adolescent Growth. *Medicine and Science in Sports & Exercise, 47*(12), 2579-2585. https://doi.org/10.1249/MSS.0000000000000700

Holden, S., Doherty, C., Boreham, C., & Delahunt, E. (2019). Sex differences in sagittal plane control emerge during adolescent growth: a prospective investigation. *Knee Surgery, Sports Traumatology, Arthroscopy, 27*(2), 419-426. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=134969937&site=ehost-live&scope=site

Jayanthi, N. A., LaBella, C. R., Fischer, D., Pasulka, J., & Dugas, L. R. (2015). Sports-Specialized Intensive Training and the Risk of Injury in Young Athletes: A Clinical Case-Control Study. *American Journal of Sports Medicine, 43*(4), 794-801. https://doi.org/10.1177/0363546514567298

Johnson, D. M., Williams, S., Bradley, B., Sayer, S., Murray Fisher, J., & Cumming, S. (2020, May). Growing pains: Maturity associated variation in injury risk in academy football. *Eur J Sport Sci, 20*(4), 544-552. https://doi.org/10.1080/17461391.2019.1633416

Kim, K.-W., & Lim, B.-O. (2014). Effects of menarcheal age on the anterior cruciate ligament injury risk factors during single-legged drop landing in female artistic elite gymnasts. *Archives of orthopaedic and trauma surgery, 134*(11), 1565-1571. https://doi.org/10.1007/s00402-014-2055-z

Lloyd, R. S., Cronin, J. B., Faigenbaum, A. D., Haff, G. G., Howard, R., Kraemer, W. J., Micheli, L. J., Myer, G. D., & Oliver, J. L. (2016). National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. *The Journal of Strength & Conditioning Research, 30*(6), 1491-1509. https://doi.org/10.1519/jsc.0000000000001387

Lopez-Valenciano, A., Ayala, F., De Ste Croix, M. B. A., Barbado, D., Moreno-Perez, V., Sanz-Rivas, D., & Fernandez-Fernandez, J. (2023, Mar-Apr). The Association Between Chronological Age and Maturity Status on Lower Body Clinical Measurements and Asymmetries in Elite Youth Tennis Players. *Sports Health, 15*(2), 250-259. https://doi.org/10.1177/19417381221083319

Lynch, K. R., Kemper, H. C. G., Turi-Lynch, B., Agostinete, R. R., Ito, I. H., Luiz-De-Marco, R., Rodrigues-Junior, M. A., & Fernandes, R. A. (2017). Impact sports and bone fractures among adolescents. *Journal of Sports Sciences, 35*(24), 2421-2426. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=125089045&site=ehost-live&scope=site

McKay, C. D., Cumming, S. P., & Blake, T. (2019, 2019/02/01/). Youth sport: Friend or Foe? *Best Practice & Research Clinical Rheumatology, 33*(1), 141-157. https://doi.org/https://doi.org/10.1016/j.berh.2019.01.017

Monasterio, X., Gil, S. M., Bidaurrazaga-Letona, I., Cumming, S. P., Malina, R. M., Williams, S., Lekue, J. A., Santisteban, J. M., Diaz-Beitia, G., & Larruskain, J. (2024, Jun 1). Estimating Maturity Status in Elite Youth Soccer Players: Evaluation of Methods. *Med Sci Sports Exerc, 56*(6), 1124-1133. https://doi.org/10.1249/mss.0000000000003405

Monasterio, X., Gil, S. M., Bidaurrazaga-Letona, I., Lekue, J. A., Santisteban, J., Diaz-Beitia, G., Martin-Garetxana, I., Bikandi, E., & Larruskain, J. (2021, 2021/03/01/). Injuries according to the percentage of adult height in an elite soccer academy. *Journal of science and medicine in sport, 24*(3), 218-223. https://doi.org/https://doi.org/10.1016/j.jsams.2020.08.004

Montalvo, A. M., Schneider, D. K., Yut, L., Webster, K. E., Beynnon, B., Kocher, M. S., & Myer, G. D. (2019, Aug). "What's my risk of sustaining an ACL injury while playing sports?" A systematic review with meta-analysis. *British Journal of Sports Medicine, 53*(16), 1003-1012. https://doi.org/10.1136/bjsports-2016-096274

Müller, L., Hildebrandt, C., Müller, E., Oberhoffer, R., & Raschner, C. (2017). Injuries and illnesses in a cohort of elite youth alpine ski racers and the influence of biological maturity and relative age: a two-season prospective study. *Open Access Journal Sports Medicine, 8*, 113-122. https://doi.org/10.2147/oajsm.S133811

Myer, G. D., Ford, K. R., Divine, J. G., Wall, E. J., Kahanov, L., & Hewett, T. E. (2009). Longitudinal assessment of noncontact anterior cruciate ligament injury risk factors during maturation in a female athlete: a case report. *Journal of athletic training, 44*(1), 101-109. https://doi.org/10.4085/1062-6050-44.1.101

Netball NZ, N. R. (nd). *SmartHealth Handbook*. https://netballsmart.co.nz/netball-smart/resources.html

Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., & McKenzie, J. E. (2021). PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ, 372*, n160. https://doi.org/10.1136/bmj.n160

Parry, G. N., Williams, S., McKay, C. D., Johnson, D. J., Bergeron, M. F., & Cumming, S. P. (2024). Associations between growth, maturation and injury in youth athletes engaged in elite pathways: a scoping review. *British Journal of Sports Medicine, 58*, 1001-1010. https://doi.org/10.1136/bjsports-2024-108233

Parsons, J. L., Coen, S. E., & Bekker, S. (2021, Sep). Anterior cruciate ligament injury: towards a gendered environmental approach. *British Journal Sports Medicine, 55*(17), 984-990. https://doi.org/10.1136/bjsports-2020-103173

Pedley, J. S., DiCesare, C. A., Lloyd, R. S., Oliver, J. L., Ford, K. R., Hewett, T. E., & Myer, G. D. (2021, Nov). Maturity alters drop vertical jump landing force-time profiles but not performance outcomes in adolescent females. *Scandinavian Journal of Medicine and Science in Sports, 31*(11), 2055-2063. https://doi.org/10.1111/sms.14025

Peek, K., Ford, K. R., Myer, G. D., Hewett, T. E., & Pappas, E. (2022, Oct). Effect of Sex and Maturation on Knee Extensor and Flexor Strength in Adolescent Athletes. *American Journal of Sports Medicine, 50*(12), 3280-3285. https://doi.org/10.1177/03635465221118081

Pletcher, E. R., Dekker, T. J., Lephart, S. M., & Sell, T. C. (2021). Sex and Age Comparisons in Neuromuscular And Biomechanical Characteristics of the Knee in Young Athletes. *International Journal of Sports Physical Therapy, 16*(2), 438-449. https://doi.org/10.26603/001c.21358. PMID:33842039

Quatman, C. E., Ford, K. R., Myer, G. D., & Hewett, T. E. (2006, May). Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study. *American Journal of Sports Medicine, 34*(5), 806-813. https://doi.org/10.1177/0363546505281916

Quatman, C. E., Ford, K. R., Myer, G. D., Paterno, M. V., & Hewett, T. E. (2008). The effects of gender and pubertal status on generalized joint laxity in young athletes. *Journal of science and medicine in sport, 11*(3), 257-263. https://doi.org/10.1016/j.jsams.2007.05.005

Ramachandran, A. K., Pedley, J. S., Moeskops, S., Oliver, J. L., Myer, G. D., & Lloyd, R. S. (2024, Jul). Changes in Lower Limb Biomechanics Across Various Stages of Maturation and Implications for ACL Injury Risk in Female Athletes: a Systematic Review. *Sports Medicine, 54*(7), 1851-1876. https://doi.org/10.1007/s40279-024-02022-3

Rudavsky, A., Cook, J. L., & Docking, S. (2018). Proximal patellar tendon pathology can develop during adolescence in young ballet dancers—A 2-year longitudinal study. *Scandinavian Journal of Medicine and Science in Sports, 28*(9), 2035-2041. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=131260978&site=ehost-live&scope=site

Sayer, T. A., Hinman, R. S., Paterson, K. L., Bennell, K. L., Fortin, K., Timmi, A., Pivonka, P., & Bryant, A. L. (2019, Jan). Differences in Hip and Knee Landing Moments across Female Pubertal Development. *Medicine and science in sports and exercise, 51*(1), 123-131. https://doi.org/10.1249/mss.0000000000001753

Schmitz, R. J., Shultz, S. J., & Anh-Dung, N. (2009). Dynamic Valgus Alignment and Functional Strength in Males and Females During Maturation. *Journal of Athletic Training 44*(1), 26-32. https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=37588130&site=ehost-live&scope=site

Sigward, S. M., Pollard, C. D., & Powers, C. M. (2012). The influence of sex and maturation on landing biomechanics: implications for anterior cruciate ligament injury. *Scandinavian Journal of Medicine & Science in Sports, 22*(4), 502-509.

https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=77960331&site=ehost-live&scope=site

Steidl-Müller, L., Hildebrandt, C., Müller, E., & Raschner, C. (2020). Relationship of Changes in Physical Fitness and Anthropometric Characteristics over One Season, Biological Maturity Status and Injury Risk in Elite Youth Ski Racers: A Prospective Study. *International Journal of Environmental Research and Public Health, 17*(1), 364. https://www.mdpi.com/1660-4601/17/1/364

Swain, M., Kamper, S. J., Maher, C. G., Broderick, C., McKay, D., & Henschke, N. (2018, Oct). Relationship between growth, maturation and musculoskeletal conditions in adolescents: a systematic review. *Br J Sports Med, 52*(19), 1246-1252. https://doi.org/10.1136/bjsports-2017-098418

Swartz, E. E., Decoster, L. C., Russell, P. J., & Croce, R. V. (2005, Mar). Effects of Developmental Stage and Sex on Lower Extremity Kinematics and Vertical Ground Reaction Forces During Landing. *Journal of athletic training, 40*(1), 9-14.

Sweeney, L., MacNamara, Á., Taylor, J., & Lundberg, T. R. (2024). Selection of reference data significantly influences biological maturity timing classification in national youth soccer players. *International Journal of Sports Science & Coaching, 19*(6), 2356-2365. https://doi.org/10.1177/17479541241277661

Towlson, C., Salter, J., Ade, J. D., Enright, K., Harper, L. D., Page, R. M., & Malone, J. J. (2021, Jul). Maturity-associated considerations for training load, injury risk, and physical performance in youth soccer: One size does not fit all. *Journal of Sport and Health Science, 10*(4), 403-412. https://doi.org/10.1016/j.jshs.2020.09.003

van Tulder, M., Furlan, A., Bombardier, C., Bouter, L., & Group, t. E. B. o. t. C. C. B. R. (2003). Updated Method Guidelines for Systematic Reviews in the Cochrane Collaboration Back Review Group. *Spine, 28*(12), 1290-1299. https://doi.org/10.1097/01.Brs.0000065484.95996.Af

Vandenbroucke, J. P., von Elm, E., Altman, D. G., Gøtzsche, P. C., Mulrow, C. D., Pocock, S. J., Poole, C., Schlesselman, J. J., Egger, M., & Initiative, f. t. S. (2007). Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): Explanation and Elaboration. *Epidemiology, 18*(6), 805-835. https://doi.org/10.1097/EDE.0b013e3181577511

Vänttinen, T., Blomqvist, M., Nyman, K., & Häkkinen, K. (2011). Changes in Body Composition, Hormonal Status, and Physical Fitness in 11-, 13-, and 15-Year-Old Finnish Regional Youth Soccer Players During a Two-Year Follow-Up. *The Journal of Strength & Conditioning Research, 25*(12), 3342-3351. https://doi.org/10.1519/JSC.0b013e318236d0c2

Webster, K. E., & Hewett, T. E. (2018, Oct). Meta-analysis of meta-analyses of anterior cruciate ligament injury reduction training programs. *Journal of Orthopaedic Research, 36*(10), 2696-2708. https://doi.org/10.1002/jor.24043

Weiss, K., & Whatman, C. (2015, Sep). Biomechanics Associated with Patellofemoral Pain and ACL Injuries in Sports. *Sports Medicine, 45*(9), 1325-1337. https://doi.org/10.1007/s40279-015-0353-4

Westbrook, A. E., Taylor, J. B., Nguyen, A. D., Paterno, M. V., & Ford, K. R. (2020). Effects of maturation on knee biomechanics during cutting and landing in young female soccer players. *PloS one, 15*(5), e0233701. https://doi.org/10.1371/journal.pone.0233701

Wik, E. H. (2022). Growth, maturation and injuries in high-level youth football (soccer): A mini review. *Frontiers in Sports and Active Living, 4*, 975900. https://doi.org/10.3389/fspor.2022.975900

Appendix 1: Study Quality Assessment Results

Table A1: Study quality assessment

Criteria	(Bowerman et al., 2014)	(Caine et al., 1989)	(Costa e Silva et al., 2017)	(Distefano et al., 2015)	(Ford et al., 2010)	(Fort-Vanmeerhaeghe et al., 2019)	(Galloway et al., 2018)	(Grinberg et al., 2024)	(Harris et al., 2021)	(Hass et al., 2005)	(Hewett et al., 2004)	(Hewett et al., 2015)	(Hewett et al., 2006).	(Holden et al., 2019)	(Jayanthi et al., 2015)
Power analysis was performed and/or justification of study sample was given.	0	0	0	0	0	2	0	2	0	0	0	0	0	2	0
Describes relevant dates (period of recruitment &/or, exposure, follow-up, data collection).	1	2	2	1	1	1	1	2	2	0	1	1	0	2	0
Athlete characteristics (sport, experience, activity level or level of play at time of test) and demographics (sex, age, body height/mass, and injury status) were clearly defined.	2	2	1	1	2	2	1	2	1	2	2	2	1	1	0
Inclusion and exclusion criteria were given.	0	0	1	2	2	2	1	2	2	1	2	2	2	2	1
Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	1	2	1	1	1	1	1	2	1	1	1	1	0	1	1
Describes methods of follow-up, analysis of injuries, and data collection procedures. Methods included enough detail to allow replication of the testing. Testing devices, number of trials, number and duration of test, data analysis process, and injury evaluation were included when applicable.	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Test-retest reliability of measurement devices or analyses were reported.	0	1	2	2	1	2	1	0	2	0	2	2	2	1	0
Indicated number of participants with missing data and explains how it was addressed.	1	1	0	0	2	0	2	2	2	0	2	1	0	2	1
Outcome variables were clearly defined.	2	2	2	2	2	2	2	1	2	2	2	2	2	2	1
Statistical analyses were appropriate.	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2
Total	11	12	12	13	15	16	13	17	16	10	16	15	11	17	8
Quality	Low	Low	Low	Low	High	High	Low	High	High	Low	High	High	low	High	Low

Criteria	(Kim & Lim, 2014)	(Lopez-Valenciano et al., 2023)	(Lynch et al., 2017)	(Müller et al., 2017).	(Myer et al., 2009)	(Pedley et al., 2021)	(Peek et al.t, 2022)	Pletcher et al., (2021)	(Quatman et al., 2008)	(Quatman et al. 2006)	(Rudavsky et al., 2018)	Sayer et al., (2019)	(Schmitz et al., 2009)	(Steidl-Müller et al., 2020).	Swartz et al., (2005)	(Westbrook et al., 2020)
Power analysis was performed and/or justification of study sample was given.	2	0	2	0	0	2	1	0	0	0	0	2	0	0	2	0
Describes relevant dates (period of recruitment &/or, exposure, follow-up, data collection).	1	2	2	2	2	0	0	0	1	1	1	1	1	2	1	0
Athlete characteristics (sport, experience, activity level or level of play at time of test) and demographics (sex, age, body height/mass, and injury status) were clearly defined.	1	2	1	2	2	1	1	2	2	2	2	2	1	2	1	2
Inclusion and exclusion criteria were given.	1	2	2	1	1	2	2	2	0	2	2	2	0	1	2	2
Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	1	1	1	0	2	1	0	1	1	2	1	1	0	0	1	1
Describes methods of follow-up, analysis of injuries, and data collection procedures. Methods included enough detail to allow replication of the testing. Testing devices, number of trials, number and duration of test, data analysis process, and injury evaluation were included when applicable.	1	2	1	2	2	1	1	2	1	2	1	2	2	2	1	2
Test-retest reliability of measurement devices or analyses were reported.	2	1	1	0	2	1	2	1	2	2	2	1	2	0	0	1
Indicated number of participants with missing data and explains how it was addressed.	1	0	0	1	2	0	1	0	1	2	2	0	1	0	0	0
Outcome variables were clearly defined.	2	2	1	2	2	2	2	2	2	2	1	2	2	2	2	2
Statistical analyses were appropriate.	2	2	2	1	2	2	2	1	2	2	1	2	1	2	2	2
Total	14	14	13	11	17	12	12	11	12	17	13	15	10	11	12	12
Quality	High	High	Low	Low	High	Low	low		Low	High	Low	high	Low	Low	low	Low

0=clearly no; 1=maybe or inadequate information; 2=clearly yes

Criteria	(Bowerman et al., 2014)	(Caine et al., 1989)	(Costa e Silva et al., 2017)	(Distefano et al., 2015)	(Ford et al., 2010)	(Fort-Vanmeerhaeghe et al., 2019)	(Galloway et al., 2018)	(Grinberg et al., 2024)	(Harris et al., 2021)	(Hass et al., 2005)	(Hewett et al., 2004)	(Hewett et al., 2015)	(Hewett et al., 2006).	(Holden et al., 2019)	(Jayanthi et al., 2015)	(Kim & Lim, 2014)	(Lopez-Valenciano et al., 2023)	(Lynch et al., 2017)	(Müller et al., 2017).	(Myer et al., 2009)	(Pedley et al., 2021)	(Peek et al.t, 2022)	Pletcher et al., (2021)	(Quatman et al., 2008)	(Quatman et al. 2006)	(Rudavsky et al., 2018)	Sayer et al., (2019)	(Schmitz et al., 2009)	(Steidl-Müller et al., 2020).	Swartz et al., (2005)	(Westbrook et al., 2020)
Power analysis was performed and/or justification of study sample was given.	0	0	0	0	0	2	0	2	0	0	0	0	0	2	0	2	0	2	0	0	2	1	0	0	0	0	2	0	0	2	0
Describes relevant dates	1	2	2	1	1	1	1	2	2	0	1	1	0	2	0	1	2	2	2	2	0	0	0	1	1	1	1	1	2	1	0

(period of recruitment &/or, exposure, follow-up, data collection).																															
Athlete characteristics (sport, experience, activity level or level of play at time of test) and demographics (sex, age, body height/mass, and	2	2	1	1	2	2	1	2	1	2	2	2	1	1	0	1	2	1	2	2	1	1	2	2	2	2	2	1	2	1	2

injury status) were clearly defined.																															
Inclusion and exclusion criteria were given.	0	0	1	2	2	2	1	2	2	1	2	2	2	2	1	1	2	2	1	1	2	2	2	0	2	2	2	0	1	2	2
Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	1	2	1	1	1	1	1	2	1	1	1	1	0	1	1	1	1	1	0	2	1	0	1	1	2	1	1	0	0	1	1

Describes methods of follow-up, analysis of injuries, and data collection procedures. Methods included enough detail to allow replication of the testing. Testing devices, number of trials,	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1	2	2	1	1	2	1	2	1	2	2	2	1	2

number and duration of test, data analysis process, and injury evaluation were included when applicable.																															
Test-retest reliability of measurement devices or analyses were reported.	0	1	2	2	1	2	1	0	2	0	2	2	2	1	0	2	1	1	0	2	1	2	1	2	2	2	1	2	0	0	1

Indicated number of participants with missing data and explains how it was addressed.	1	1	0	0	2	0	2	2	2	0	2	1	0	2	1	1	0	0	1	2	0	1	0	1	2	2	0	1	0	0	0
Outcome variables were clearly defined.	2	2	2	2	2	2	2	1	2	2	2	2	2	2	1	2	2	1	2	2	2	2	2	2	2	1	2	2	2	2	2
Statistical analyses were appropriate.	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	2	2	1	2	2	1	2	1	2	2	2
Total	11	12	12	13	15	16	13	17	16	10	16	15	11	17	8	14	14	13	11	17	12	12	11	12	17	13	15	10	11	12	12

Quality	Low	Low	Low	Low	High	High	Low	High	High	Low	High	High	Low	High	Low	High	High	Low	Low	High	Low	Low	Low	Low	High	Low	high	Low	Low	Low	Low

This systematic review did not require ethics approval.

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Conflict of interest statement

The authors declare no conflict of interest in submitting this article.