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# Associations between growth, maturation and injury in youth athletes engaged in elite pathways: a scoping review

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## ABSTRACT

**Objective** To describe the evidence pertaining to associations between growth, maturation and injury in elite youth athletes.
**Design** Scoping review.
**Data sources** Electronic databases (SPORTDiscus, Embase, PubMed, MEDLINE and Web of Science) searched on 30 May 2023.
**Eligibility criteria** Original studies published since 2000 using quantitative or qualitative designs investigating associations between growth, maturation and injury in elite youth athletes.
**Results** From an initial 518 titles, 36 full-text articles were evaluated, of which 30 were eligible for final inclusion. Most studies were quantitative and employed prospective designs. Significant heterogeneity was evident across samples and in the operationalisation and measurement of growth, maturation and injury. Injury incidence and burden generally increased with maturity status, although growth-related injuries peaked during the adolescent growth spurt. More rapid growth in stature and of the lower limbs was associated with greater injury incidence and burden. While maturity timing did not show a clear or consistent association with injury, it may contribute to risk and burden due to variations in maturity status.
**Conclusion** Evidence suggests that the processes of growth and maturation contribute to injury risk and burden in elite youth athletes, although the nature of the association varies with injury type. More research investigating the main and interactive effects on growth and maturation on injury is warranted, especially in female athletes and across a greater diversity of sports.

### WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Growth and maturation during adolescence have been identified as risk factors for potential injury in young athletes.

### WHAT THIS STUDY ADDS

⇒ This review identified 30 contemporary studies. Injury incidence and burden appear most closely related to maturity status and tempo of growth, with growth-related injuries peaking during the adolescent growth spurt. Practitioners are advised to consider measures of growth and maturation alongside clinical and field-based measurements.

### HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Several methodological limitations and inconsistencies exist in the current evidence. Greater consistency and agreement on measurement practices could benefit future research quality, with the inclusion of female and non-football populations to address large gaps in the literature.

## INTRODUCTION

The relationship between growth, maturation and injury risk in youth athletes is a topic of increasing interest in sports medicine, with a particular focus on the adolescent growth spurt[1]. Initiated by changes in the endocrine system, adolescence is the transitional phase between childhood and adulthood, during which the body undergoes rapid changes in size, shape and composition.[2] It also involves transformation of the circulatory, respiratory and metabolic systems, resulting in substantial changes in athletic and functional capacity.[3] Although the processes of growth and maturation have been proposed as risk factors for injury in young athletes, the evidence to support this contention is limited.[4] Limitations within the research are, however, noted, including heterogeneity across samples, research designs and analytical methods, poor reporting quality and high loss to follow-up.[4]

Associating growth and maturation with injury in youth athletes is a logical premise.[5] Physeal injuries are a unique consideration for those working with youth populations.[6] Rapid asynchronous growth in skeletal, muscular and ligamentous structures creates increased ligament stress transfer through relatively weaker physeal plates and bone layers, increasing risk for such injuries. Age-related changes in bone mineral density, imbalances between flexibility and strength and alterations in joint stiffness further contribute towards an increased susceptibility to fractures at the growth plate and apophyses.[5,7] Apophyseal and physeal injuries also follow a distal-to-proximal[8] gradient, consistent with the sequential and asynchronous nature of adolescent growth.[8,9] For example, Sever's disease at the posterior calcaneus tends to present in advance of Osgood-Schlatter's or Sinding-Larsen at the knee, which, in turn, present in advance of apophyseal injuries at the sites of the iliac crest and ischial tuberosity of the hip. Apophyseal injuries are attributed to the softening or malformation of the articular cartilage, the latter of which is associated with more rapid growth during adolescence.[7] From

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a perceptual-motor perspective, rapid and asynchronous changes in skeletal, muscular and ligamentous structures, coupled with developmental changes in neurocognitive processing, have also been linked to temporary disruptions in mobility and motor-coordination, which may further increase injury risk.[5]

The introduction of injury surveillance and growth and maturation profiling systems in many elite performance pathways (eg, national athlete development programmes, professional sport academies) has afforded a more systematic and rigorous approach to monitoring physical development and health in young athletes.[10] Implemented in parallel and delivered by trained professionals and clinicians, these organised strategies have enabled the capture of high-quality longitudinal data in young athletes, stimulating further research related to growth, maturation and injury. Characterised by early specialisation and maintained elevated levels of training and competition, elite performance pathways may also provide a more conducive environment from which to observe and investigate associations between physical development and injury in youth.[1] Considering these advances, this scoping review endeavours to synthesise and expand on a previous systematic review,[4] with the aim of providing clinicians, researchers and other stakeholders with a description of contemporary research related to growth, maturation and injury in youth athletes engaged in current elite sports pathways, with a particular emphasis on the operationalisation of growth and maturation, methodological quality and assessment, sample populations, emerging evidence, knowledge gaps and limitations within the extant literature.

## METHODS

### Equality diversity and inclusion statement

The author and article screening teams were gender-balanced and included senior and junior academic staff from multiple disciplines and professions. Articles were restricted to those published in English but were not excluded based on country of origin. Gender equity in the study of physical development and injury in young athletes is addressed in the discussion.

### Information sources and search strategy

This review was commissioned by the International Olympic Committee to describe the extent, type and quality of contemporary research and evidence pertaining to growth, maturation and injury in 'elite youth athletes', contributing towards a consensus statement on the health, safety and sustainability of young athletes competing at the Olympic games. A definition of 'elite youth athletes' as 'highly trained and invested youth athletes routinely participating at national level (Tier 3) to world-class (Tier 5) athletic competitions' was established in advance of the review[11 12] and extended to include dancers enrolled in professional dance schools.

The search was conducted, *in general,* adhering to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Extension for Scoping Reviews, PRISMA-ScR (online supplemental figure S1). All 20+2 PRISMA-ScR reporting items were met, except for protocol registration. Five databases (SPORTDiscus, Embase, PubMed, MEDLINE and Web of Science) were searched for relevant articles. As the review aimed to inform a contemporary consensus statement regarding the health and well-being of elite young athletes, the article search was restricted to peer-reviewed publications written in English from 1 January 2000 to 30 May 2023. A series of unique search terms were employed to identify relevant articles. The Boolean Operators "OR" and "AND" were used to broaden the search results, define the population of interest (ie, elite youth athletes), limit the intended outcomes of our search (ie, injury) and link the search terms. An asterisk (*) was applied to some keywords to search the database for all endings of the word or phrase (eg, matur*). The final search strategy being: (1) "elite" AND "youth" AND "athlete", (2) AND "growth" OR "matur*" OR "pubert*", (3) AND "Injur*" OR "medial epicondyle apophysitis" OR "Proximal Humeral Epiphysitis" OR "stress fracture" OR "growth plate fracture" OR "Pars" OR "Femoroacetabular impingement" OR "apophysitis" OR "Sever's" OR "Osgood" OR "osteochondrosis" OR "osteochondritis dissecans" OR "spondylolysis".

### Eligibility criteria and description of eligible studies

Inclusion criteria were articles based on primary research, using original data and related to elite youth athletes. To meet the definition of 'elite' and be included in the review, the samples within each study had to be described in a manner that aligned with the criteria for routine participation in national (Tier 3) to world-class (Tier 5) competition.[12] For example, athletes who were members of professional sports academies or national development programmes were considered to have met these criteria. Studies using quantitative designs had to include measures of injury and growth and/or maturation. Qualitative studies investigating associations between growth, maturation and injury in elite youth athletes were eligible for inclusion. Review articles and case studies were excluded. Two independent reviewers (GNP, SC) completed the review process in May 2023. Each reviewer screened the articles, first at the level of title and abstract and then at the level of full text, to judge if the eligibility criteria were met. Disagreements were resolved through discussion and final consensus.

### Data synthesis

To ensure consistency in the operationalisation of growth and maturation, the following definitions were adopted.[2] Growth was defined as rate of change in size of the body, its parts, or the proportions of various parts (eg, cm per annum, kg per annum). Maturation refers to the processes of progress towards the mature state occurring in multiple biological systems (eg, endocrine, sexual, skeletal and somatic) and was defined in terms of status, tempo and timing. Status denoted the stage of maturation attained at a specific time point, (eg, pre-peak height velocity (PHV), circa-PHV, post-PHV) whereas tempo described the rate at which maturation occurs. Timing was defined as the age at which maturational events (eg, PHV) occurred and/or the degree to which an athlete was advanced, on-time or delayed in maturation relative to age-specific and sex-specific standards. The data extracted from the eligible studies were summarised descriptively (online supplemental table S1) and appraised with respect to methodological quality.

## RESULTS

### Study selection

The initial search retrieved 871 citations of which 518 remained after removing duplicates. Full texts of 37 articles were reviewed to determine eligibility, 30 of which were eligible for final inclusion. The eligible articles included 28 quantitative and 2 qualitative studies (figure 1).

### Data collection and risk of bias assessment/analysis of quality

Descriptive data were extracted from eligible studies, comprising study design, population, measures and operationalisation of

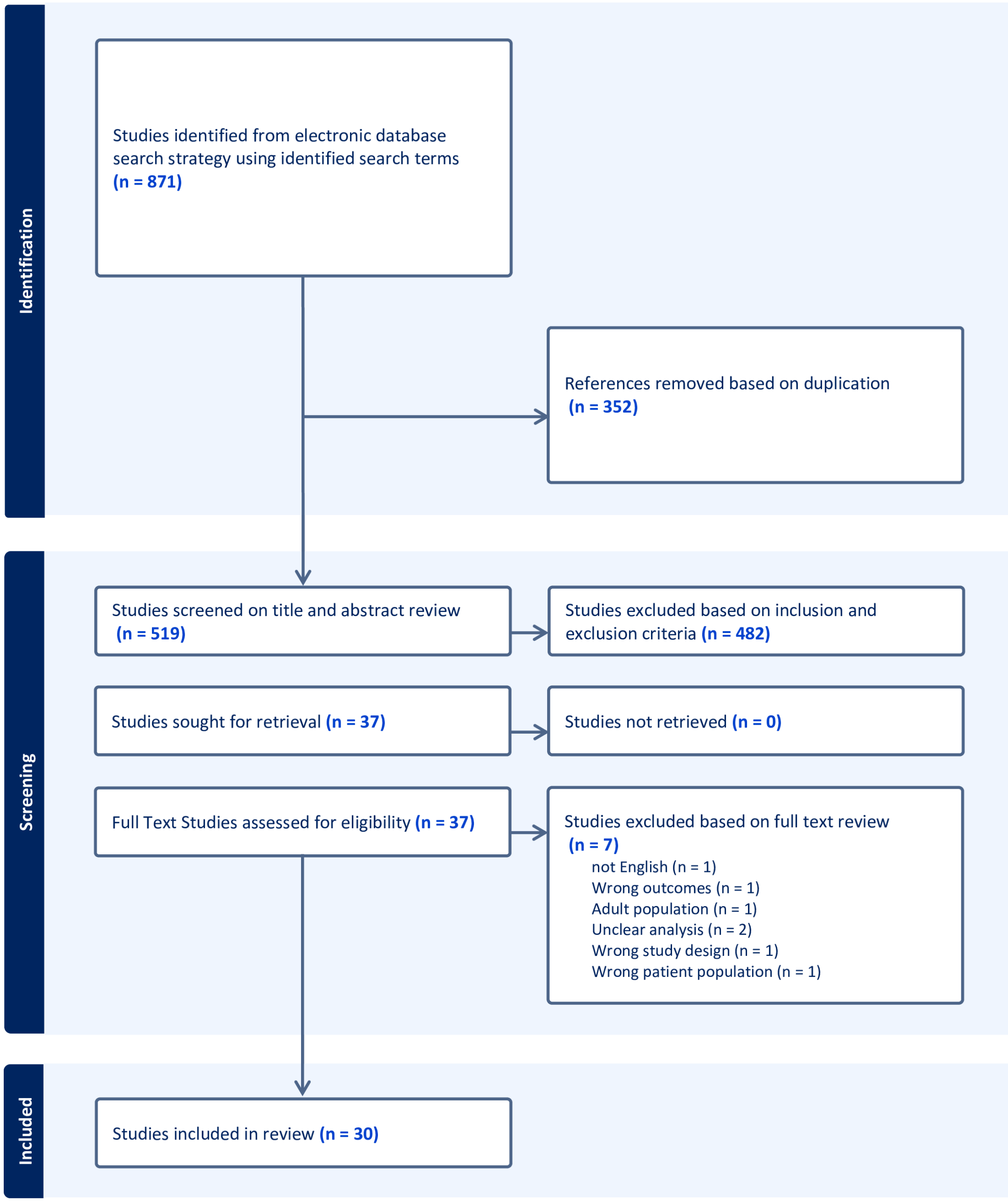


**Figure 1** Study selection process based on inclusion and exclusion criteria.

growth and maturation, and injury definition and outcomes (eg, incidence, burden) (online supplemental table S1). The methodological quality of the quantitative studies (n=28), as judged on the Downs and Black Scale,[13] ranged from 7 to 19 out of 32 points (online supplemental table S2). The Downs and Black Scale is a 28-item checklist used to assess the methodological quality of both randomised and non-randomised studies, evaluating factors such as reporting, external validity, internal validity (bias and confounding) and statistical power. The median quality score of these articles was low (14/32), attributable to study design and the absence of explicit explanations regarding variables of interest and consideration of confounding factors. While some articles included large samples, the distribution of participants by maturity status and/or timing categories was typically non-normal, resulting in inadequate statistical power in several studies. Most studies focused on soccer (n=19) and were exclusive to male participants (n=24). Only four quantitative studies included male and female athletes, and none considered female-only cohorts. The two qualitative papers appraised using the Joanna Briggs Institute (JBI) critical appraisal checklist for qualitative research[14 15] both met 8 out of the 10 criteria, with each noting a failure to consider potential researcher influence on the study findings as a limitation. A breakdown of the individual item scores for each article using the Downs and Black and JBI checklists is available in online supplemental file 2.

## Maturity status and injury

17 quantitative studies[8 16–31] adopting prospective designs and two qualitative studies[32 33] investigated associations between maturity status and injury (table 1). 16 of the quantitative studies[8 16–20 22–31] employed non-invasive estimates of somatic maturation with estimated age at PHV (EA PHV) (n=11) and percentage of predicted (%PAH) or attained adult height (%

**Table 1** Associations between maturational status and injury for all eligible studies

| Paper | Sport | Maturity status | Criteria | Findings |
|---|---|---|---|---|
| Bult *et al*[16] | Soccer | EA PHV (MO) | Pre-PHV 1 (>12 months pre-PHV)<br>Pre-PHV 2 (6–12 months pre-PHV)<br>Pre-PHV 3 (<6 months pre-PHV)<br>Post-PHV 4 (<3 months post-PHV)<br>Post-PHV 5 (3–6 months post-PHV)<br>Post-PHV 6 (>6 months post PHV) | ↑ injury incidence and burden in post-PHV 4+5<br>↓ injury incidence burden in pre-PHV 1<br>↓ injury burden in pre-PHV 2 |
| Fawcett *et al*[32] | Gymnastics | Perceived maturational status | NA | ↑ risk for injury and lower back pain circa-PHV especially, when combined with excessive training load |
| Hall *et al* (2022) | Soccer | EA PHV (MO) | Pre-PHV (<–1.0)<br>Circa-PHV (–0.5 to 0.5)<br>Post-PHV (>1.0) | ↓ incidence of overall, non-contact, soft-tissue, muscle, non-contact soft tissue and thigh injuries in pre-PHV vs post-PHV<br>↓ incidence of non-contact, soft-tissue, muscle and thigh injuries in circa-PHV vs post-PHV<br>↑ incidence of growth-related injuries in pre-PHV and circa-PHV vs post-PHV<br>↑ prevalence of overall and non-contact soft-tissue in post-PHV vs pre-PHV<br>↑ prevalence of non-contact, soft-tissue, muscle, thigh injuries in post-PHV vs pre-PHV and circa-PHV<br>↓ prevalence of growth-related injuries in post-PHV vs pre-PHV and circa-PHV<br>↑ injury burden in players recording at least one soft-tissue injury in post-PHV vs pre-PHV |
| Horobeanu *et al*[18] | Squash | EA PHV (MO) | Pre-PHV (<–1.0)<br>Circa-PHV (–1.0 to 1.0)<br>Post-PHV (>1.0) | No statistically significant difference in the proportion of osteochondrosis growth related injuries occurred circa-PHV (56%) vs pre-PHV (21%) and post-PHV (23%) |
| Johnson *et al*[19] | Soccer | %PAH (KR) | NA | Non-linear association (inv.-U) between maturity status and incidence and burden for non-contact injuries with peaks at 92%–95% PAH, respectively |
| Johnson *et al*[20] | Soccer | %PAH (KR) | Pre-PHV (<88% PAH)<br>Circa-PHV (88%–95% PAH)<br>Post-PHV (>95% PAH) | ↑ incidence and burden of non-contact injuries in circa-PHV vs pre-PHV |
| Monaco *et al*[21] | Handball | Physician assessed testicular volume | Immature—4–14 cm testicular volume<br>Mature—≥15 cm testicular volume | ↑ incidence of apophysitis in immature vs mature |
| Monasterio *et al*[8] | Soccer | %AAH | Pre-PHV <88% AAH<br>Circa-PHV 88–96% AAH<br>Post-PHV >96% AAH | ↑ prevalence of growth-related injuries circa-PHV vs pre-PHV and post-PHV<br>Prevalence of growth-related injuries followed a distal-to-proximal gradient consistent with asynchronous and sequential growth of human skeleton.<br>↑ prevalence of muscle, groin pain, knee joint/ligament, ankle joint/ligament in post-PHV vs pre-PHV and circa-PHV |
| Monasterio *et al*[22] | Soccer | EA PHV (SITAR) | Pre-PHV (>6 months before PHV)<br>Circa-PHV (±6 months from PHV)<br>Post-PHV (>6 months after PHV until growth velocity was <1 cm/year) | ↑ burden of overall, growth-related, AIIS osteochondrosis, muscle, hamstring injuries in circa-PHV vs pre-PHV<br>↑ burden of overall, muscle, hamstring, quadricep, joint/ligament, knee, meniscal ankle, lateral sprain ↓ burden Sever's, Osgood-Schlatter's in post-PHV vs pre-PHV<br>↑ burden of Sever's, Osgood-Schlatter's, AIIS osteochondrosis<br>↓ burden of muscle, knee, meniscal ankle, lateral sprain in circa-PHV vs post-PHV |
| Monasterio et al[23] | Soccer | EA PHV (SITAR) | Circa-PHV (±6 months from PHV)<br>Post-PHV (>6 months from PHV and until growth velocities were <1 cm/year) | ↑ burden of overall injuries players that experience fast vs average or slow growth in stature circa-PHV, but not post-PHV<br>↑ burden of growth-related injuries for players experiences fast vs slow growth in stature circa-PHV but not post-PHV |
| Patel *et al*[24] | Trampolining gymnastics | %PAH (KR) | NA | Non-linear association (inv. U) between maturity status and injury probability with peak at 90% PAH |
| Patel *et al*[33] | Gymnastics | Perceived maturational status | NA | ↑ incidence growth-related, bone, lower extremity, back injuries and stress fractures of the back/wrist circa-PHV |

Continued

**Table 1** Continued

| Paper | Sport | Maturity status | Criteria | Findings |
|---|---|---|---|---|
| Rinaldo et al[25] | Soccer | EA PHV (MO) | Decimal age (DA)-EA PHV >–1<br>► –2 years<DA EA PHV≤–1 year<br>► –3 years<DA EA PHV≤–2 years<br>DA-EA PHV ≤–3 years | ↑ probability of injury with ↑ DA-EA PHV<br>↑ frequency of injury in athletes >–1 DA-EA PHV |
| Read et al[26] | Soccer | EA PHV (MO) | NA | ↑ probability of lower-limb injuries in U13–14 players more years (–0.7 vs –0.4) from PHV |
| Rudavsky *et al*[31] | Dance—Ballet | EA PHV (MO) | Pre-PHV (>0 years to PHV)<br>Post-PHV (>0 years from PHV) | No difference in years to or from PHV in dancers did or did not develop proximal patellar tendon pathology |
| Steidl-Muller[27] *et al* | Alpine skiing | EA PHV (MO) | NA | ↑ probability of injury (traumatic and overuse) with greater years to EA PHV |
| Van der Sluis et al[28] | Soccer | EA PHV (MO) | Pre-PHV (>6 months to PHV)<br>PHV (<6 months and <6 months from PHV)<br>Post-PHV (>6 months from PHV) | ↑ incidence of traumatic injuries in circa-PHV and post-PHV vs pre-PHV |
| Van der Sluis *et al*[29] | Soccer | EA PHV (MO) | Pre-PHV (>6 months to PHV)<br>PHV (<6 months and <6 months from PHV)<br>Post-PHV (>6 months from PHV) | ↑ incidence of traumatic injuries from pre-PHV to post-PHV then ↓ from PHV to post-PHV in earlier and later maturing players<br>↑ incidence of overuse injuries from pre-PHV to post-PHV then ↑ from PHV to post-PHV in earlier, but not later, maturing players |
| Wik *et al*[34] | Track and Field | SA (Fels) | NA | ↓ incidence of growth plate injuries with ↑ skeletal age and %PAH |

%AAH, percentage of attained adult height; EA PHV, estimated age at peak height velocity; KR, Khamis-Roche method; MO, maturity offset; %PAH, percentage of predicted adult height; SA, skeletal age; SITAR, super-imposition by translation and rotation.

AAH) (n=5) the most common methods. One study used an estimate of sexual maturation to classify youth handball players as mature or immature. Wik and colleagues[30] employed estimates of both skeletal and somatic maturation in study of maturation and injury in male track and field athletes. Most studies categorised athletes into groups based on maturity status, however, five studies treated maturation as a continuous variable.[19 24 26 27 30] Samples sizes varied from n=21[24] to n=502.[17] The methodological quality of the quantitative studies ranged from poor[29] to fair.[34] Two qualitative studies[32 33] investigated coaches' and practitioners' perceptions of how maturational status was related to injury risk in male and female gymnasts. Both of these studies achieved JBI scores of 8 out of 10, indicating a high quality of qualitative research.

The maturational stage associated with the adolescent growth spurt (ie, circa-PHV) appears to yield the greatest increase in injury incidence per 1000 hours, in papers reporting competition, training and overall time loss. When broad definitions of injury were observed, circa-PHV status was associated with greater incidences of overall,[25] non-contact[19 20] and traumatic[28 29] injuries in academy soccer, and higher incidences of all-complaint injuries in both male and female elite youth gymnasts with the peak approximating 90% PAH.[24] While the evidence suggests a general trend towards increased injury incidence and burden with advancing maturation,[16 17 21] the nature of reported associations varied relative to injury type.[8 17] Circa-PHV and pre-PHV status were associated with a higher incidence or prevalence of injuries classified as growth-related in track and field,[34] handball[21] and soccer,[8 17] but not squash.[18] Both qualitative studies also identified the growth spurt as a maturational stage where incidence and burden for growth-related and lower back injuries was greater.[32 33] Moreover, growth-related injuries followed a distal-to-proximal gradient aligned with the sequential and asynchronous nature of adolescent growth.[8] Specifically, these injuries tended to present first in the more distal segments of the lower limbs, before presenting in the more proximal segments of the lower extremities, and finally the trunk and pelvis. Consistent with this pattern, a higher probability for non-contact lower extremity injuries was observed in U13–14 soccer players during the earlier phases of the adolescent growth spurt.[26] A greater number of years to EA PHV was, however, associated with an increased probability for traumatic and overuse injuries in male and female alpine skiers.[27] Mature athletes, or those advanced in maturity status (post-PHV), exhibited the lowest incidence and burden of growth-related injuries,[8 22 23 34] yet evidenced a higher incidence and burden for muscular, cartilaginous and ligamentous injuries in soccer,[8 23] but not in handball where these injuries were higher in immature athletes.[21] Maturity status was unrelated to patellar tendinopathy in male and female ballet dancers.[31]

Associations between advancing maturity status and injury burden were observed in several studies. As with injury incidence, associations with burden varied by time-loss definitions and injury type. Six studies in soccer[16 17 19 20 22 23] that used various definitions of time loss reported an increase in injury burden with advancing maturity, with one study documenting peak burden for non-contact injuries at 95% PAH.[19] There were notably higher burdens of growth-related injuries in athletes during the pre and circa-PHV stages in soccer.[17 22 23] The post-PHV stage is associated with a reduced burden for growth-related injury burden,[17 22] but an increase in burden for non-contact[19] and muscle and joint-related injury,[22] although these findings are currently limited to male soccer players.

## Maturity timing and injury

10 quantitative studies[20 22 28 35–41] using prospective designs (table 2) investigated associations between maturity timing and injury. Six studies employed estimates of somatic maturation with EA PHV (n=4)[29 40 41] and %PAH[20 37] (n=2) the preferred methods. There was substantial heterogeneity in the criteria used to define early maturation, on-time maturation and late maturation across methods. Four studies[35 36 38 39] employed estimates of skeletal age via hand-wrist radiographs. To define

**Table 2** Associations between maturational timing and injury for all relevant selected studies

| Study | Sport | Maturity | Timing criteria | Injury outcome | Early $^{(E)}$ | On-time $^{(O)}$ | Late $^{(L)}$ |
|---|---|---|---|---|---|---|---|
| Fourchet *et al*[41] | Athletics | EAPHV (MO) | EAPHV <13.2 or ≥15.2 | Incidence | – | – | $\uparrow^{O\ E}$ Foot, ankle, lower leg |
| Johnson *et al*[35] | Soccer | SA (Fels) | SA-CA ±1.0 years | Incidence | – | – | – |
| Johnson *et al*[20] | Soccer | %PAH (KR) | Z-Score ±0.5 | Incidence | – | – | – |
| Le Gall *et al*[36] | Soccer | SA (GP) | SA-CA ±1.0 years | Incidence | $\uparrow^{L}$ Moderate Inc.<br>$\uparrow^{L}$ Tendinopathies<br>$\uparrow^{L}$ Groin<br>$\uparrow^{L\ O}$ Groin strains<br>$\uparrow^{L\ O}$ Re-injuries | $\uparrow^{L}$ Moderate Inc.<br>$\uparrow^{L}$ Groin<br>$\uparrow^{L}$ Tendinopathies<br>$\uparrow^{E}$ Osteochondrosis | $\uparrow^{E}$ Major Inc.<br>$\uparrow^{E}$ Osteochondrosis<br>$\uparrow^{E\ O}$ Osteochondral disorder knee* |
| Light *et al* (2021) | Soccer | KR %PAH | Z-Score ±1.0 | Frequency | – | – | – |
| Materne *et al*[38] | Soccer | SA (Fels) | SA-CA ±1.0 years | Incidence | $\uparrow^{O}$ Overall<br>$\uparrow^{O}$ Sprain/ligament<br>$\uparrow^{O}$ Functional muscle disorder<br>$\uparrow^{O}$ Head/face | $\uparrow^{E}$ Other bone injury<br>$\uparrow^{E}$ AIIS avulsion<br>$\uparrow^{E}$ Osgood-Schlatter disease<br>$\uparrow^{E}$ Knee apophyseal<br>$\uparrow^{E}$ Sever disease | $\uparrow^{E}$ Other bone injury<br>$\uparrow^{E\ O}$ Tendinopathy<br>$\uparrow^{E}$ Thigh<br>$\uparrow^{E}$ Osgood-Schlatter disease<br>$\uparrow^{E}$ Knee apophyseal |
| Monasterio *et al*[8] | Soccer | SA (TW2-RUS) | SA-CA ±0.5 years | Burden | $\uparrow^{L}$ Overall<br>$\uparrow^{L\ O}$ Muscle<br>$\uparrow^{O}$ Hamstring<br>$\uparrow^{L}$ Joint/ligament<br>$\uparrow^{L}$ Ankle | $\uparrow^{L}$ Joint/ligament | – |
| Monasterio *et al*[22] | Soccer | EA PHV (SITAR) | APHV <12.8 or >13.8 | Burden | – | $\uparrow^{L}$ O Overall<br>$\uparrow^{L}$ Growth-related<br>$\uparrow^{L}$ AIIS<br>$\uparrow^{L}$ Knee injuries | – |
| Muller *et al*[40] | Skiing | EAPHV (MO) | ♂ EAPHV <13.2 or >14.2<br>♀ EAPHV <11.5 or >12.5 | Frequency | – | – | – |
| Van der Sluis *et al*[29] | Soccer | EAPHV (MO) | EAPHV< or ≥13.92 | Incidence | – | NA | $\uparrow^{E}$ Overuse |

*Finding confirmed with co-author after discrepancy in published result noted.
EAPHV, estimated age at peak height velocity; GP, Greulich-Pyle; KR, Khamis-Roche method; MO, maturity offset; %PAH, percentage of predicted adult height; SA, skeletal age; SITAR, super-imposition by translation and rotation; TW2, Tanner-Whitehouse 2nd method.

early maturation, on-time maturation and late maturation, three studies[35 36 38] used the traditional criterion of ±1 years SA-CA (skeletal age-chronological age); whereas one study used ±0.5 years SA-CA.[39] Nine studies[20 22 28 35–39 41] included male athletes and one study included males and females.[40] Eight of the studies involved soccer,[20 22 29 35–39] with single studies in track and field[41] and alpine skiing.[40] Sample sizes ranged n=26[29] to n=233.[38] The methodological quality of the studies was generally low, ranging from poor[29] to fair.[39]

Associations between the timing of maturity and injury were observed across several,[22 29 36 38 39] but not all[20 35 37] studies of male soccer players. The nature and direction of these associations did, however, vary depending on injury type and the age range of the sample. A closer inspection of the findings suggested that the impact of maturity status was more important than the timing of maturity itself when investigating injury susceptibility in young athletes. Consistent with this hypothesis, U14 and U13–U19 players categorised as early-maturing presented a higher incidence of injuries associated with more advanced stages of maturation, including reinjury, injury to ligaments, tendons and muscles and injuries to the groin, head or face, and overall injuries.[36 38] Early-maturing U14 players also reported higher burdens for time loss, muscle, hamstring and joint/ligament-related injuries.[39] In contrast, players categorised as 'on-time', presented higher incidence rates for injuries associated with the early-to-mid stages of adolescence, including lower limb apophyseal injuries, anterior inferior iliac spine avulsions, Osgood-Schlatter's, Sever's and knee-related injuries in on-time than early maturing.[36 38] In comparison to late-maturing players, on-time U14 players presented higher rates of incidence for, groin injuries, tendinopathies and moderate injuries,[36] and higher burdens for joint/ligament, knee, anterior inferior iliac spine, growth-related and time-loss injuries.[22 39] Late-maturing players presented higher incidence rates for osteochondrosis, thigh, growth-related and major injuries than early-maturing players, and a higher incidence of tendinopathies and osteochondral disorder of the knee than early and on-time players.[36 38] Late-maturing track and field athletes also presented a higher incidence for foot, ankle and lower limb injuries compared with their peers.[41] Despite late-maturing alpine skiers presenting a higher prevalence of traumatic and overuse injuries, respectively, these values did not differ statistically from early-maturing skiers.[40]

## Growth and maturity tempo and injury

Nine quantitative studies[19 23 25 27 34 42–45] adopting prospective designs (table 3) and two qualitative studies[32 33] investigated associations between rate of growth and/or maturation and injury. Rate of change in stature (n=9) and leg length (n=5) were the most frequent growth measures. Four studies assessed growth tempo in body mass and mass-for-stature. Singular studies considered growth of the foot,[42] torso[30] and tempo of skeletal maturation.[34] Six studies[19 23 25 43–45] involved male

**Table 3** Associations between growth and maturation indices and injury for all relevant selected studies

| Study | Sport | Growth indices | Injury | Result |
|---|---|---|---|---|
| Bowerman *et al*[42] | Dance | Foot-length | Probability | ↑ Right Foot: ↑ lower extremity overuse Injury |
| Johnson *et al*[19] | Soccer | Height<br>Leg-length | Incidence<br>Burden | ↑ Height: ↑ non-contact injury incidence<br>↑ Height: Non-linear association with non-contact injury burden<br>↑ Leg length: Non-linear association with non-contact injury burden |
| Kemper *et al*[43] | Soccer | Height<br>BMI | Probability | ↑ Height: ↑ Probability of injury<br>↑ BMI: ↑ Probability of injury |
| Monasterio et al[22] | Soccer | Height | Burden | ↑ Height: ↑ overall, growth and knee injuries |
| Rinaldo *et al*[25] | Soccer | Height<br>Mass<br>Leg-length<br>BMI | Injured vs non-injured | ↑ Height in injured players<br>↑ Mass in injured players<br>↑ Mass in players with overuse injuries |
| Rommers *et al*[44] | Soccer | Height<br>Mass<br>Leg-length | Probability<br>Injured vs non-injured | ↑ Height in U10–12's with overuse injuries<br>↑ Leg length in U10–12's with overuse injuries<br>↓ Height in U13–15's with acute injuries<br>↓ Leg length in U13–15's with acute injuries<br>↑Leg length: ↑Probability for overuse injuries in U10–12's<br>↓ Height: ↑ Probability for acute injuries in U13–15's |
| Rommers *et al*[45] | Soccer | Height | Probability | ↑ Height: ↑ Probability of overall injury |
| Steidl-Muller *et al* [27] | Alpine skiing | Height<br>Mass<br>Leg-length<br>BMI | Injured vs Non-injured | ↓ Height in injured skiers<br>↑ Leg length in injured skiers |
| Wik *et al*[34] | Track and field | Height<br>Trunk<br>Leg-length<br>Mass<br>BMI<br>Skeletal age (Fels) | Probability | ↑ Height: ↑ Probability of bone and growth plate injuries<br>↑ Leg length: ↑ Probability of overall, bone and growth plate injuries<br>↑ Skeletal age: ↑ Probability of bone injuries |

BMI, body mass index.

soccer players with the remaining studies involving male track and field athletes,[34] and dancers[42] and alpine skiers[27] of both sexes. Samples sizes ranged from n=46[42] to n=378.[45] The methodological quality of the studies was generally low, ranging from poor[43] to fair.[34 45]

More rapid gains in stature were associated with a higher incidence and/or probability of overall,[25 43 45] non-contact[19] and overuse[44] injuries in male academy soccer players, and bone and growth plate injuries in male track and field athletes.[34] Greater growth in stature was, however, associated with a reduced probability for acute injuries in U13–15 academy soccer players[44] and overall injuries in male and female alpine skiers.[27] More rapid gains in stature during PHV was associated with a higher burden for overall, knee and growth-related injuries, but not muscle, joint/ligament, knee or ankle injuries in U14 academy soccer players.[22] A non-linear (inverted-U) association between growth in stature and burden for non-contact injuries was reported in U13–U16 male soccer players, with peak estimated injury burden occurring at 4.17 cm per year.[19] More rapid growth of the lower limbs was associated with a higher probability for overall injuries in alpine skiing[27] and track and field,[34] overuse[44] injuries in soccer, and bone and growth plate in track and field.[34] As with stature, a non-linear association was observed between growth rate of the lower limbs with peak estimated injury burden occurring at a growth rate of 5.27 cm per year.[19]

Rate of growth in body mass did not differentiate between injured and non-injured alpine skiers[27] and was not associated with injury probability in track and field athletes[34] and U10–15 soccer players.[44] Greater seasonal gains in body mass were observed in injured vs non-injured Italian soccer players; however, growth in mass did not emerge as a predictor of injury in a subsequent regression model.[25] With respect to mass-for-stature, more rapid gains in body mass index (BMI) were observed between injured vs non-injured Dutch soccer players,[43] but not their Italian counterparts.[25] Rate of change in BMI was unrelated to overall injury risk injury in alpine skiing[27] and overall, gradual and sudden-onset, bone and growth plate injuries in track and field.[34]

In both qualitative studies,[32 33] more rapid gains in stature and mass were perceived as risk factors for injury in young gymnasts, with specific reference to stress fractures, growth-related, shoulder and lower back injuries. The risk was also perceived to be higher when accompanied with high or sudden spikes in training and competition loads, and restricted eating.

Trunk growth was unrelated to probability for overall, gradual onset, sudden onset, bone or growth plate-related injuries in track and field athletes.[34] More rapid growth of the foot was, however, associated with a higher risk for lumbar and lower extremity injury risk in male and female dancers.[42] Finally, more rapid changes in skeletal maturation were associated with an increased risk of bone injuries in a track and field athletes, yet was unrelated to risk of gradual-onset and sudden-onset, growth plate and overall injuries.[34]

## DISCUSSION

This review described contemporary research and emerging evidence related to growth, maturation and injury in youth athletes engaged in elite performance pathways. A total of 30 articles were deemed eligible for inclusion in this review with the majority involving male soccer players. The disparity between sports reflects the popularity of soccer, as a sport, and the significant investment by professional clubs and national governing bodies in the monitoring of physical development and health of young players.[10] Implemented in parallel, injury surveillance and growth and maturity profiling systems have enabled researchers to collect high-quality longitudinal data, consider the implications of growth and maturation across diverse injury types and perform more sophisticated methods of analysis. Those investigating the associations between growth, maturation and injury in young athletes should look to soccer for examples of good practice (see Monasterio,[8 22 23 39] Rommers,[44 45] Materne[38] and Hall[17]), such as the aggregation of data across age groups, clubs and/or multiple seasons and consideration of different injury types and interactional effects. Wik's investigation of both maturity status and tempo as risk factors across multiple injury types in track and field also serves as a good example of innovative practice within this field.[34]

The lack of studies involving and/or exclusive to female athletes is a particular concern. The eligible studies that considered physical development and injury in female athletes all had comparatively small sample sizes and, thus, it is difficult to draw firm conclusions from the evidence. Injury research related to male athletes does not always generalise to female athletes.[46] The sex differences in human anatomy and physiology that emerge during puberty may predispose male and female athletes to variable levels of injury risk.[7] Whereas some studies have found female athletes to be at greater or reduced risk for certain types of injury,[46 47] others suggest more comprehensive research and data are still required to effectively inform injury prevention and treatment strategies specific to female athletes.[48] There is a need for sport's national governing bodies to prioritise and invest in research related to physical development and injury in female athletes. Care must, however, be taken in the design and implementation of growth and maturity profiling strategies for female athletes with particular sensitivity around the collection, communication and use of data.[49] Data pertaining to physical development should be used to understand and support the health and development of the athletes and not as a criteria for the selection and exclusion of athletes.[49] Clinicians and researchers should seek to identify those injuries that female and, to a lesser extent, male athletes may be more or less susceptible to at different stages of maturation and consider strategies for the early detection and mitigation of conditions such as relative energy deficiency RED-S which can compromise physical development and the immediate and long-term health of youth athletes.[49] Researchers should also investigate the extent to which the processes of growth and maturation contribute to the elevated risk of medial collateral ligament (MCL) and anterior cruciate ligament (ACL) injuries observed in female athletes during adolescence.[7]

The evidence reviewed suggests that susceptibility to injury in youth athletes varies relative to maturity status. Adopting a broad definition of injury, incidence and burden generally increases with advancing maturation. The nature of the association between maturity status and injury does, however, vary relative to injury type. The adolescent growth spurt signalled a marked increase in the incidence and burden of growth-related injuries, confirming the beliefs and experiences of coaches and medical practitioners.[32 33] Growth-related injuries were most prevalent at the onset and during the growth spurt, with apophyseal, osteochondrosis and avulsion prominent in numerous sport contexts.[8 18 21 22 33 34] Growth-related injuries also followed a distal-to-proximal gradient consistent with the sequential and asynchronous nature of adolescent growth, before declining in both incidence and burden post-PHV. In contrast, the incidence of muscular, cartilaginous and ligamentous injuries generally increased with advancing maturity status and were most prevalent in athletes categorised as mature and/or post-PHV. Increased susceptibility for such injuries post-PHV has been attributed to several factors associated with growth and maturation, including disruptions in neuromuscular control, insufficient muscle capacity, imbalance in muscle and tendon growth, and increase in moments of inertia in athletes' segments.[8] Despite much of the data within the eligible studies being normalised to exposure per 1000 hours, uncertainties remain regarding the standalone impact of maturational status on injury incidence and burden, given the variations in activity content (eg, modality, frequency, intensity, location) that may comprise an individual's exposure hours.

The absence of a consistent pattern of association between timing and injury suggested that maturing in advance or delay of one's peers (ie, timing) was not an inherent risk for injury. Rather, the extent to which timing impacts an athlete's maturational status and/or proximity to PHV appeared to be of greater relevance. Compatible with this logic, early maturing athletes presented a higher incidence and burden for injuries associated with more advanced stages of maturity (eg, tendinopathies, groin strains, joint and ligament injuries, functional muscle disorders).[22 36 38 39] Conversely, on-time and late maturing reported a higher incidence and burden for injuries associated with the earlier stages of the growth spurt (eg, lower limb apophyseal injuries, osteochondrosis, AIIS, Osgood-Schlatter's, Sever's).[22 36 38 39 41] Due to inherent maturity selection biases that exist in sport,[3 50–52] late-maturing athletes were under-represented in several of the eligible studies[22 36 38 39] resulting in insufficient statistical power to make effective comparisons across groups. As late maturing athletes experience the growth spurt at an age when training intensities and volumes are typically higher, they may be more susceptible to injuries associated with growth or overloading.[53] Any elevated injury risk associated with later maturation may, however, be mitigated by a lower rate of growth at PHV. Future studies may need to aggregate data across teams, sport or consecutive seasons to test this hypothesis or focus on sports or activities where late developers are more likely to be represented (ie, gymnastics, ballet, diving).

More rapid gains in stature and length of the lower limbs were associated with a higher incidence of overuse, non-contact and growth-related injuries across several sports. Monasterio *et al*, also observed more rapid growth in stature to be associated with a higher burden for overall and growth-related injuries during PHV.[22] Johnson *et al*, did, however, report a non-linear associations between burden and rate of growth in stature and of the lower limbs, with peak burdens occurring post-PHV and at a rate of approximately 4-to-5 cm per year.[19] The delayed effect of injuries sustained during PHV on injury burden post-PHV may explain the discrepancy in these results. No clear or consistent associations were observed between rate of growth in mass and mass-for-stature with injury. Pubertal gains in mass and mass-for-stature may have greater injury implications for athletes participating sports that involve frequent landing, jumping, pivoting and high intensity accelerations and decelerations.[5] They may also have greater impact for risk in female athletes who experience larger gains in absolute and relative fat-mass, and corresponding smaller gains in absolute and relative strength during puberty.[2 50] Further research on the growth and injury in female athletes is needed with a particular focus on the preventative benefits of targeted functional movement and neuromuscular strength training interventions.[54–56]

Intervention studies designed to mitigate growth-related injuries in young athletes are currently lacking. However, in the interim, growth and maturity profiling can provide valuable information pertaining to maturational status, timing and growth rate of individual athletes, enabling practitioners to identify athletes at heightened risk for specific injuries and adapt their training and conditioning accordingly.[1] For example, the Athletic Skills Model (ASM) describes a maturity-matching strategy whereby athletes identified as circa-PHV are assigned to training groups with an increased emphasis on movement competency, core and lower body strength, mobility, balance, coordination, coupled with reductions training load, intensity and movement repetition.[57] A recent intervention aligned to theASM principles resulted in marked reductions in non-contact injury incidence and burden among academy soccer players identified as circa-PHV and at-risk.[58] Although promising, further encompassing research is required to validate these findings.

## Strengths and limitations

The inclusion of several contemporary studies conducted across multiple clubs or seasons was a strength of this review.[8 17 22 23 36 38 39 44 45] With comparatively large samples and more rigorous approaches to data capture, these studies enabled more comprehensive and detailed investigations of growth, maturation and injury. These studies also provided valuable insight as to the complex, multifaceted and dynamic nature of the relationship between physical development and injury in youth. The myriad of methodological limitations highlighted by Swain *et al*[4] persist, making it challenging to generalise findings or draw firm conclusions from the existing literature on this topic. Although the quality of the two qualitative studies was deemed excellent, the methodological quality of the quantitative studies was generally low, ranging from poor to fair. To improve research quality and robustness, there is a need to develop a contemporary consensus statement on standardised evidence-informed best practices for assessing and estimating growth and maturation in young athletes. This review was commissioned by the IOC as a wider contribution towards a consensus statement, and as such adopted a harmonised methodology. Researchers may wish to consider alternative methodologies in additional future reviews. Building on previews reviews and commentaries,[3 4 59–61] particular attention should be paid to the operationalisation of growth and maturation and the criteria used to determine maturity status, timing and tempo of growth. It is equally important to consider the rationale for measurement, analytical quality control, frequency of measurement, the education of key stakeholders and how data are communicated to athletes, parents/guardians and coaches.[49] The validity and reliability of the various methods used to estimate maturation should also be considered with a particular focus on non-invasive estimates of somatic maturation.[3 62 63]

## Conclusion

The evidence reviewed indicates that variability in growth and maturation plays a contributing role in the risk of injury among youth athletes engaged in high performance pathways. The associations involved are intricate and diverse, requiring further research to comprehend the precursors, mechanisms and contextual factors that may predispose athletes to a higher risk of specific injuries (eg, those related to motor competence, functional capacity, training/competition load and content). It is recommended that sport's governing bodies simultaneously implement comprehensive injury surveillance and growth and maturity profiling systems for youth, along with educational content and a current consensus statement on best/standardised practice in the estimation and monitoring of growth and maturation. Such an approach has the potential to enhance our understanding of the connections between growth, maturation and injury and provide the empirical basis for the subsequent development and implementation of injury prevention programmes.

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## REFERENCES

1 Jayanthi N, Schley S, Cumming SP, *et al*. Developmental Training Model for the Sport Specialized Youth Athlete: a Dynamic Strategy for Individualizing Load-Response During Maturation. *Sports Health* 2022;14:142–53.
2 Malina RM, Bouchard C, Bar-Or O. *Growth, maturation, and physical activity*. 2nd edn. Human Kinetics, 2004:712.Available: https://www.humankineticslibrary.com/encyclopedia?docid=b-9781492596837
3 Malina RM, Rogol AD, Cumming SP, *et al*. Biological maturation of youth athletes: assessment and implications. *Br J Sports Med* 2015;49:852–9.
4 Swain M, Kamper SJ, Maher CG, *et al*. Relationship between growth, maturation and musculoskeletal conditions in adolescents: a systematic review. *Br J Sports Med* 2018;52:1246–52.
5 McKay D, Broderick C, Steinbeck K. The Adolescent Athlete: a Developmental Approach to Injury Risk. *Pediatr Exerc Sci* 2016;28:488–500.
6 Kerssemakers SP, Fotiadou AN, de Jonge MC, *et al*. Sport injuries in the paediatric and adolescent patient: a growing problem. *Pediatr Radiol* 2009;39:471–84.
7 McKay CD, Cumming SP, Blake T. Youth sport: friend or Foe? Best Pract Res Cl Rh. *Feb* 2019;33:141–57.
8 Monasterio X, Gil SM, Bidaurrazaga-Letona I, *et al*. Injuries according to the percentage of adult height in an elite soccer academy. *J Sci Med Sport* 2021;24:218–23.

9 Price RJ, Hawkins RD, Hulse MA, *et al*. The Football Association medical research programme: an audit of injuries in academy youth football. *Br J Sports Med* 2004;38:466–71.
10 Cumming SP. A game plan for growth: how football is leading the way in the consideration of biological maturation in young male athletes. *Ann Hum Biol* 2018;45:373–5.
11 Bergeron MF, Cote J, Cumming SP, *et al*. IOC Consensus Statement on Elite Youth Athletes Competing at the Olympic Games – Essentials to a Healthy, Safe and Sustainable Paradigm. *Brit J Sport Med* 2024;58:1–20.
12 McKay AKA, Stellingwerff T, Smith ES, *et al*. Defining Training and Performance Caliber: a Participant Classification Framework. *Int J Sports Physiol Perform* 2021;17:317–31.
13 Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Health* 1998;52:377–84.
14 Pearson A, Field J. JBI critical appraisal checklist for qualitative research. 2011.
15 Lockwood C, Munn Z, Porritt K. Qualitative research synthesis: methodological guidance for systematic reviewers utilizing meta-aggregation. *Int J Evid Based Hea Sep* 2015;13:179–87.
16 Bult HJ, Barendrecht M, Tak IJR. Injury Risk and Injury Burden Are Related to Age Group and Peak Height Velocity Among Talented Male Youth Soccer Players. *Orthop J Sports Med* 2018;6:2325967118811042.
17 Hall ECR, Larruskain J, Gil SM, *et al*. Injury risk is greater in physically mature versus biologically younger male soccer players from academies in different countries. *Phys Ther Sport* 2022;55:111–8.
18 Horobeanu C, Johnson A, Pullinger SA. The Prevalence of Musculoskeletal Injuries in Junior Elite Squash Players. *Asian J Sports Med* 2019;10:e84495.
19 Johnson DM, Cumming SP, Bradley B, *et al*. The influence of exposure, growth and maturation on injury risk in male academy football players. *J Sports Sci* 2022;40:1127–36.
20 Johnson DM, Williams S, Bradley B, *et al*. Growing pains: maturity associated variation in injury risk in academy football. *Eur J Sport Sci* 2020;20:544–52.
21 Mónaco M, Rincón JAG, Ronsano BJM, *et al*. Injury incidence and injury patterns by category, player position, and maturation in elite male handball elite players. *Biol Sport* 2019;36:67–74.
22 Monasterio X, Gil SM, Bidaurrazaga-Letona I, *et al*. The burden of injuries according to maturity status and timing: a two-decade study with 110 growth curves in an elite football academy. *Eur J Sport Sci* 2023;23:267–77.
23 Monasterio X, Gil S, Bidaurrazaga-Letona I, *et al*. Peak Height Velocity Affects Injury Burden in Circa-PHV Soccer Players. *Int J Sports Med* 2023;44:292–7.
24 Patel TS, McGregor A, Williams K, *et al*. The influence of growth and training loads on injury risk in competitive trampoline gymnasts. *J Sports Sci* 2021;39:2632–41.
25 Rinaldo N, Gualdi-Russo E, Zaccagni L. Influence of Size and Maturity on Injury in Young Elite Soccer Players. *Int J Environ Res Public Health* 2021;18:3120.
26 Read PJ, Oliver JL, De Ste Croix MBA, *et al*. A prospective investigation to evaluate risk factors for lower extremity injury risk in male youth soccer players. *Scand J Med Sci Sports* 2018;28:1244–51.
27 Steidl-Müller L, Hildebrandt C, Müller E, *et al*. 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. *Int J Environ Res Public Health* 2020;17:364.
28 van der Sluis A, Elferink-Gemser MT, Coelho-e-Silva MJ, *et al*. Sport injuries aligned to peak height velocity in talented pubertal soccer players. *Int J Sports Med* 2014;35:351–5.
29 van der Sluis A, Elferink-Gemser MT, Brink MS, *et al*. Importance of peak height velocity timing in terms of injuries in talented soccer players. *Int J Sports Med* 2015;36:327–32.
30 Wik EH. Growth, maturation and injuries in high-level youth football (soccer): a mini review. *Front Sports Act Living* 2022;4:975900.
31 Rudavsky A, Cook JL, Docking S. Proximal patellar tendon pathology can develop during adolescence in young ballet dancers—A 2-year longitudinal study. *Scand Med Sci Sports* 2018;28:2035–41.
32 Fawcett L, Heneghan NR, James S, *et al*. Perceptions of low back pain in elite gymnastics: a multi-disciplinary qualitative focus group study. *Phys Ther Sport* 2020;44:33–40.
33 Patel TS, McGregor A, Fawcett L, *et al*. Coach awareness, knowledge and practice in relation to growth and maturation and training load in competitive, young gymnasts. *Int J Sports Sci Coach* 2021;16:528–43.
34 Wik EH, Martínez-Silván D, Farooq A, *et al*. Skeletal maturation and growth rates are related to bone and growth plate injuries in adolescent athletics. *Scand Med Sci Sports* 2020;30:894–903.
35 Johnson A, Doherty PJ, Freemont A. Investigation of growth, development, and factors associated with injury in elite schoolboy footballers: prospective study. *BMJ* 2009;338:b490.
36 Le Gall F, Carling C, Reilly T. Biological maturity and injury in elite youth football. *Scand Med Sci Sports* 2007;17:564–72.
37 Light N, Johnson A, Williams S, *et al*. Injuries in youth football and the relationship to player maturation: an analysis of time-loss injuries during four seasons in an English elite male football academy. *Scand Med Sci Sports* 2021;31:1324–34.
38 Materne O, Chamari K, Farooq A, *et al*. Association of Skeletal Maturity and Injury Risk in Elite Youth Soccer Players: A 4-Season Prospective Study With Survival Analysis. *Orthop J Sports Med* 2021;9.
39 Monasterio X, Bidaurrazaga-Letona I, Larruskain J, *et al*. Relative skeletal maturity status affects injury burden in U14 elite academy football players. *Scand Med Sci Sports* 2022;32:1400–9.
40 Müller L, Hildebrandt C, Müller E, *et al*. 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 J Sports Med* 2017;8:113–22.
41 Fourchet F, Horobeanu C, Loepelt H, *et al*. Foot, Ankle, and Lower Leg Injuries in Young Male Track and Field Athletes. *Int J Athl Ther Train* 2011;16:19–23.
42 Bowerman E, Whatman C, Harris N, *et al*. Are maturation, growth and lower extremity alignment associated with overuse injury in elite adolescent ballet dancers? *Phys Ther Sport* 2014;15:234–41.
43 Kemper GLJ, van der Sluis A, Brink MS, *et al*. Anthropometric Injury Risk Factors in Elite-standard Youth Soccer. *Int J Sports Med* 2015;36:1112–7.
44 Rommers N, Rössler R, Goossens L, *et al*. Risk of acute and overuse injuries in youth elite soccer players: body size and growth matter. *J Sci Med Sport* 2020;23:246–51.
45 Rommers N, Rössler R, Shrier I, *et al*. Motor performance is not related to injury risk in growing elite-level male youth football players. A causal inference approach to injury risk assessment. *J Sci Med Sport* 2021;24:881–5.
46 Lin CY, Casey E, Herman DC, *et al*. Sex Differences in Common Sports Injuries. *PM R* 2018;10:1073–82.
47 Zech A, Hollander K, Junge A, *et al*. Sex differences in injury rates in team-sport athletes: a systematic review and meta-regression analysis. *J Sport Health Sci* 2022;11:104–14.
48 Stephenson SD, Kocan JW, Vinod AV, *et al*. A Comprehensive Summary of Systematic Reviews on Sports Injury Prevention Strategies. *Orthop J Sports Med* 2021;9.
49 Mountjoy M, Sundgot-Borgen J, Burke L, *et al*. The IOC consensus statement: beyond the Female Athlete Triad--Relative Energy Deficiency in Sport (RED-S). *Br J Sports Med* 2014;48:491–7.
50 Baxter-Jones ADG, Thompson AM, Malina RM. Growth and Maturation in Elite Young Female Athletes. *Sports Med Arthrosc* 2002;10:42–9.
51 Hill M, Scott S, Malina RM, *et al*. Relative age and maturation selection biases in academy football. *J Sports Sci* 2020;38:1359–67.
52 Johnson A, Farooq A, Whiteley R. Skeletal maturation status is more strongly associated with academy selection than birth quarter. *Sci Med Football* 2017;1:157–63.
53 Mitchell SB, Haase AM, Malina RM, *et al*. The role of puberty in the making and breaking of young ballet dancers: perspectives of dance teachers. *J Adolesc* 2016;47:81–9.
54 Radnor JM, Moeskops S, Morris SJ, *et al*. Developing Athletic Motor Skill Competencies in Youth. *Str Cond J* 2020;42:54–70.
55 Moeskops S, Oliver JL, Read PJ, *et al*. Practical Strategies for Integrating Strength and Conditioning Into Early Specialization Sports. *Str Cond J* 2022;44:34–45.
56 Myer GD, Ford KR, Palumbo JP, *et al*. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res* 2005;19:51–60.
57 Wormhoudt R, Savelsbergh GJP, Teunissen JW, *et al*. The athletic skills model: optimizing talent development through movement education. *Routl* 2018.:xxii.
58 Johnson D, Williams S, Bradley B, *et al*. Can we reduce injury risk during the adolescent growth spurt? An iterative sequence of prevention in male academy footballers. *Ann Hum Biol* 2023;50:452–60.
59 Malina RM, Beunen G. Growth and maturation: methods of monitoring. In: *The young athlete*. 2008: 430–42.
60 Caine DJ, Broekhoff J. Maturity Assessment: a Viable Preventive Measure Against Physical and Psychological Insult to the Young Athlete? *Phys Sportsmed* 1987;15:67–80.
61 Hume PA, Stewart AD. Physique assessment in youth sports for talent identification and development. In: *Best practice protocols for physique assessment in sport*. 2018: 3–10.
62 Malina RM, Kozieł SM, Králik M, *et al*. Prediction of maturity offset and age at peak height velocity in a longitudinal series of boys and girls. *Am J Hum Biol* 2021;33:e23551.
63 Fransen J, Skorski S, Baxter-Jones ADG. Estimating is not measuring: the use of non-invasive estimations of somatic maturity in youth football. *Sci Med Football* 2021;5:261–2.