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Sex-Specific Changes in Physical Risk Factors for Anterior Cruciate Ligament Injury by Chronological Age and Stages of Growth and Maturation From 8 to 18 Years of Age

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Objective: To critically assess the literature focused on sex-specific trajectories in physical characteristics associated with anterior cruciate ligament (ACL) injury risk by age and maturational stage.

Data Sources: PubMed, CINAHL, Scopus, and SPORTDiscus databases were searched through December 2021.

Study Selection: Longitudinal and cross-sectional studies of healthy 8- to 18-year-olds, stratified by sex and age or maturation on $\geq$1 measure of body composition, lower extremity strength, ACL size, joint laxity, knee-joint geometry, lower extremity alignment, balance, or lower extremity biomechanics were included.

Data Extraction: Extracted data included study design, participant characteristics, maturational metrics, and outcome measures. We used random-effects meta-analyses to examine sex differences in trajectory over time. For each variable, standardized differences in means between sexes were calculated.

Data Synthesis: The search yielded 216 primary and 22 secondary articles. Less fat-free mass, leg strength, and power and greater general joint laxity were evident in girls by 8 to 10 years of age and Tanner stage I. Sex differences in body composition, strength, power, general joint laxity, and balance were more evident by 11 to 13 years of age and when transitioning from the prepubertal to pubertal stages. Sex differences in ACL size (smaller in girls), anterior knee laxity and tibiofemoral angle (greater in girls), and higher-risk biomechanics (in girls) were observed at later ages and when transitioning from the pubertal to postpubertal stages. Inconsistent study designs and data reporting limited the number of included studies.

Conclusions: Critical gaps remain in our knowledge and highlight the need to improve our understanding of the relative timing and tempo of ACL risk factor development.

Key Words: knee, pediatric, Tanner stage

The incidence of anterior cruciate ligament (ACL) injuries in children and adolescents has steadily increased over the past 30 years[1] and outpaced that of adults.[2] Injury trends relative to sex and age have remained relatively unchanged; ACL injuries are rare before the age of 10 years, followed by a rapid and steady increase from 11 to 17 years that is substantially greater in girls than boys.[1,3–5] When participation rates and athlete-exposures are controlled, by the time female athletes reach high-school age, they have a 1.4 to 1.6 times greater relative risk of ACL injury across all sports and a 3.1 to 4.1 times greater relative risk in similar sports (eg, basketball, soccer, track and field) compared with boys.[6,7] These sex differences persist at the collegiate level (ie, once fully mature).[8–10] Because of the young age at which these injuries are occurring and the well-documented secondary health consequences associated with ACL injury (ie, substantially greater risk of sustaining a second ACL injury,[11,12] high prevalence of early onset of osteoarthritis within 5 to 10 years of the initial injury,[13] reduced quality of life[14]), pediatric ACL injury has become a major health concern.

Adolescence is a time of rapid growth and development when sex differences in physical characteristics begin to emerge, including body composition, muscle strength and power, knee anatomy (ligament size, notch dimensions, joint laxity), and neuromuscular control (balance, biomechanics). Although sex differences in these physical characteristics have often been reported and implicated individually in a female's greater risk for ACL injury (see Shultz et al[15] for review), less is known of the timing (age at onset) and trajectories of these sex-specific physical

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changes relative to one another and how they coincide with the timing of the rapid rise in ACL injury risk. Due to the limitations of hospitalization and insurance records, the literature describing the sex-specific pediatric ACL injury incidence has been related to chronological age.[1–5] However, hormonal and other physiological changes associated with maturation, not chronological age, are the primary drivers of these sex-specific changes in physical characteristics.

With the initiation of puberty (Tanner stage II), sex steroid output by the gonads increase through Tanner stage V, which leads to increasing estradiol levels in girls (the greatest change occurring from Tanner stages II to IV)[16] and increasing testosterone levels in boys (with the greatest increase occurring between Tanner stages III and IV).[17] (For a more in-depth review, see Caldwell et al.[18]) When compared against chronological age, these increases are evident by approximately 10 years of age and rise steeply thereafter.[16,17] Comparatively, the ACL injury risk rises steadily from 11 to 17 years of age. Yet while 11 to 17 years of age generally coincides with the pubertal transition and the time surrounding peak growth (±2 years), the actual age of onset and time between pubertal events varies widely among adolescents.[19–21] For example, menarche occurs on average around 12 to 13 years of age, but the actual age of occurrence normally ranges from 8 to 15 years of age,[22] and the time between thelarche (Tanner stage II breast development signaling the onset of puberty) and menarche can vary as much as 1 to 4 years.[23] Pubertal timing relative to age can also vary by race and ethnicity,[23] and girls generally progress through pubertal stages 1 to 2 years earlier than boys.[20,21] Additionally, female athletes, particularly those involved in sports focused on leanness, aesthetics, or weight classifications, have a higher prevalence of menstrual cycle irregularity and delayed menarche than their nonathletic peers.[24–26] Given all these factors, identifying the timing of sex-specific trajectories in physical risk factor development relative to both pubertal stage and chronological age may enable us to more accurately identify the earliest onset of sex-specific risk factor development and, thus, the best time to screen for and intervene to mitigate that risk at the individual level.

The purposes of this systematic review and meta-analysis were to (1) identify studies that examined sex-specific trajectories in physical characteristics (ie, body composition, leg strength, knee anatomy, laxity and alignment, balance, knee joint neuromechanics) that have been independently associated with or otherwise implicated in ACL injury risk by chronological age (8 to 18 years of age), stages of growth (age relative to peak height velocity [PHV]), and maturation (eg, Tanner stage); (2) examine sex differences in these trajectories over time; and (3) graphically compare the relative timing and tempo of these physical changes with one another within and between sexes.

METHODS

Protocol Registration

The protocol followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).[27] The study protocols were specified in advance and registered in the National Institute for Health Research International Prospective Register of Systematic Reviews (PROSPERO 2021 CRD42021251191, https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=251191).

Eligibility Criteria

Studies were selected based on the Participants, Exposure, Comparator, Outcomes, Study Design (PECOS) guidelines (https://training.cochrane.org/handbook).

Information Sources and Searches

Studies were identified by searching electronic databases (PubMed, CINAHL, Scopus, SPORTDiscus), scanning article reference lists, and coauthors scanning of their own reference databases. The searches were limited to papers published in English, but the dates were not restricted. The full search was conducted on July 6, 2021, and a final search took place on December 3, 2021. We used these terms to search all databases: *fat free mass*, *fat mass*, *anterior cruciate ligament*, *femoral notch width*, *intercondylar notch*, *tibial slope*, *knee laxity*, *balance*, *postural control*, *lower extremity alignment*, *knee strength*, *hip strength*, and *lower extremity biomechanics* were paired with maturation (*maturation*, *puberty*, *sexual development*) and sex (*sex*, *gender*). We added *BMI* (body mass index) and *obesity* as exclusionary terms given the large volume of papers associated with body composition that were not relevant to our search. Although BMI is a known ACL injury risk factor, well-established reference data for this measure were available based on 5 national health surveys of more than 16 000 participants (Centers for Disease Control and Prevention BMI Growth Charts; Table 16: https://www.cdc.gov/nchs/data/series/sr_11/sr11_246.pdf). Additionally, BMI is only a rough estimate of adiposity and does not partition the sex- and age-specific changes in fat mass (FM) and fat-free mass (FFM) that contribute to overall weight. As such, we focused the searches on sex-specific changes in FM and FFM. Appendix A provides an example of the full electronic search strategy used in PubMed.

Study Selection

The search results from the 4 data sources were uploaded to a systematic review management platform (Rayyan Systems Inc). Duplicates were identified, confirmed via visual inspection, and removed. Given the size and breadth of the search, our study selection process consisted of 3 steps. In step 1, all titles and abstracts were independently screened by 2 reviewers (S.J.S. and M.R.C.), guided by the eligibility criteria that had been agreed upon by all coauthors. Discrepancies between the reviewers were resolved with a consensus-based discussion; when questions persisted, the articles were carried forward. The full texts of eligible articles based on the titles and abstracts were then retrieved and independently screened by the same 2 reviewers to further evaluate eligibility criteria, identify secondary citations from reference lists, and code each article based on the risk factor(s) examined (step 2). Articles carried forward from step 2 were entered into a spreadsheet and divided into 6 groups of risk factors (body composition, anatomical factors, balance, muscle strength, leg power, and lower extremity biomechanics). Two coauthors were then assigned to each group of risk factors to perform an in-depth review and quality assessment of each article based on the study criteria to determine final inclusion (step 3). If maturation was relevant to the research question and the outcome data were reported in aggregate (versus stratified by age or maturational stage), we attempted to contact the article's author(s) up to 3 times by email over a 4-week period. If these efforts were unsuccessful, the article was excluded. If, upon in-depth full-text review, a study was found to be ineligible, this was confirmed by both coauthors.

Data-Extraction Process

A data-extraction template was created so that each coauthor used the same standardized system for collecting data for the assigned outcomes. The template was piloted by the coauthors over a 1-week period, all coauthors met to resolve any questions or challenges, and the template was refined accordingly. To avoid double-counting data, we carefully compared articles reporting the same outcomes from the same authors or from the same data set. If the same study data were reported in more than 1 publication, the data were treated as 1 dataset. If the data overlapped, we used either the data with the largest sample or those that provided the more discrete stratification by individual ages or maturational stages. For data that were presented in a figure, we first attempted to contact the authors for the raw data in tabular format. If our efforts to reach the authors were unsuccessful, specialized software (WebPlotDigitizer; Automeris LLC[28]) was used to extract the data from the figure if the clarity was sufficient. All data for each outcome were extracted by a single author.

Data Items

The following data were extracted from each study: (a) author(s); (b) study design (ie, cross-sectional, longitudinal, mixed); (c) sample demographics (ie, sample size [boys, girls, total]), total age range examined, activity level (general population, physically active, athlete, sedentary, not specified), race or ethnicity, and country or origin; (d) manner in which data were stratified (eg, categories of age, Tanner stage, age at PHV, or pubertal stage [prepubertal, pubertal, postpubertal]); (e) risk factor characteristics (ie, measure, method of assessment, unit value); and (f) data (measures of central tendency and dispersion and sample size by each sex and age or maturation category reported).

In addition to the originally planned outcome variables, the search also yielded 34 articles that described total leg power via a single-legged hop or vertical or horizontal jump and 15 articles that addressed flexibility. Because these outcomes are often employed in ACL injury-prevention programs and leg power is used as a performance metric in ACL injury-screening and rehabilitation protocols, we extracted these variables as well. Additionally, we found that leg FFM was reported more often than thigh muscle mass. These factors are assumed to be highly correlated with one another, so we retained both outcomes.

Study Quality of Individual Studies

We assessed the quality of individual studies using the National Institutes of Health Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools). The tool was revised to add 3 questions that were particularly relevant to this review with the ability to reduce bias in the meta-analysis and graphic representation of the data: (1) Was the sample size >10 participants for each sex for each age and maturation category examined? (2) Were both boys and girls assessed at each time point? and (3) Were assessments made across the full range of ages (8–18 years) or the full range of maturational stages (eg, Tanner stages I to V); *yes* was only indicated if the data for each individual age or individual maturational stage were provided. Two reviewers working independently assessed and scored each study. If the final scores differed by >1 point, the reviewers discussed the discrepancies. These data were used to ensure an in-depth review of each article, confirm study eligibility, assist with identification of studies to be included in the meta-analyses and the graphical representation of the data for each outcome, and aid in data interpretation. Studies were not excluded based on quality scores.

Summary of Measures

Our primary interest was in examining the collective sex-specific changes in ACL risk factor outcomes across age, maturational stage, and age of PHV. For aim 1, we examined the results for each risk factor independently. To be included in the summary tables and narrative review, the following criteria had to be met: data for both boys and girls were included and the data were clearly stratified by age or maturation status to represent 2 or more maturity levels (prepubertal, pubertal, postpubertal).

Synthesis of Results

For aim 2, we addressed sex differences in trajectories over time. Random-effects meta-analyses were conducted using the Comprehensive Meta-Analysis application (version 3.3.070; Biostat Inc). Meta-analyses were performed for an outcome if ≥ 2 studies supplied sample sizes and measures of central tendency and dispersion for both boys and girls by chronological age or maturational stage that clearly spanned 2 or more pubertal stages (prepubertal, pubertal, postpubertal). Because all outcome variables were continuous in nature, we used the subgroup (age or maturational stage) sample size, mean, and SD to calculate the standardized difference in means between boys and girls for each outcome. Standardized differences in means were calculated to compare homogeneous outcomes that were measured in a variety of ways or reported in various units.[29,30] We used conversions reported by Wan et al[30] to estimate the means and SDs when the data were given as medians with the interquartile range or range. Equations to convert standard errors or CIs into SDs were provided by the Cochrane handbook.[29] Because most sample sizes for subgroups were <60, we used the formula with the t distribution value as the denominator in calculating the SD.[29] For each outcome, we constructed a forest plot by age or maturity category. The standardized differences in means, standard errors, lower and upper confidence limits, P values, and the studies contributing to each age group were available with each forest plot. For interpretation purposes, a standardized difference in means >0 favored boys and <0 favored girls as having greater values for each outcome. A subgroup was included only if ≥2 studies gave the sample size, mean, and SD for both boys and girls.

For aim 3, we provided an overall summary of the data. We used the standardized point estimates derived from the studies that were eligible for the meta-analysis to create an infographic of the comparative trajectories in outcomes by sex and time (age, maturation). If we were unable to perform a meta-analysis on a particular outcome, we used a single study to represent that risk factor if it was rated as good to high quality, incorporated 80% of the age or pubertal stage categories, and included ≤10 participants for each age or pubertal stage category. When a single study was used, this was clearly noted in the graphic. If the data were insufficient for that risk factor, this was also noted.

Publication Bias

Bias was managed through rigorous searches, and review and scoring of available studies were conducted by ≥2 investigators for each outcome variable. We did not calculate the Egger test for small study bias because a significant number of subgroups across most outcome variables lacked at least 3 studies (≥3 are needed). Therefore, sample sizes, the number of studies, and weight were provided so readers can make informed judgements about the robustness of the meta-analyses. As noted, tests for asymmetry (potential bias) in meta-analyses are generally considered underpowered for ≤10 studies.[29] Hence, any meta-analysis results with <10 studies contributing to a subgroup should be viewed with caution.

RESULTS

The searches yielded a total of 1805 citations, with 1556 unique articles remaining after we removed duplicates. A total of 216 articles from the primary search and 22 articles from the secondary search (ie, screening of reference lists) were carried forward from step 2 and entered in a spreadsheet. The flow diagram in Appendix B.1 shows the number of articles that underwent in-depth review for each group of risk factors. Studies that included outcomes for >1 risk factor group were evaluated separately for each risk factor. Detailed forest plots with individual listings of studies included in the meta-analyses by age and maturity subgroup can be found in Supplemental File 1 (available online at https://doi.org/10.4085/1062-6050-0038.22.S1).

Body Composition

The searches produced 79 papers that addressed sex-specific changes in body composition with specific outcomes of percentage of body fat (%BF), FM and fat mass index (FMI; kg), FFM and fat-free mass index corrected for change in stature (FFM and FFMI, respectively; kg/m^2), and appendicular leg/thigh muscle mass (ALM). We included ALM given the functional importance of the leg musculature in movement control and reported associations between thigh muscle mass and ACL size.[31,32] After in-depth review, 39 articles were excluded for not meeting the eligibility criteria, and 2 papers were excluded for supplying duplicate data. The most common reasons for exclusion were not providing stratified data by sex and age or Tanner stage, the wrong study design or outcome, only reporting 1 sex or age span, or insufficient data to confirm that the age span represented 2 or more pubertal stages. We contacted 12 authors to obtain stratified data by sex and age without success. This left 38 studies that examined 1 or more variables of body composition (Appendices C.1–C.4).[33–70] The majority of articles (27) described sex-specific changes with age, with fewer (14) reporting data by Tanner stage; 2 articles offered data by sex for both age and pubertal stage for select outcomes.[33,54] No investigators stratified data by the age of PHV. The data were insufficient to perform meta-analyses for FMI, FFMI, and ALM by Tanner stage.

The studies of %BF consistently demonstrated increases with each age or Tanner stage in girls, whereas the boys' values either maintained or increased early and then decreased during pubertal development (typically after Tanner stage II and age 12–13 years; Appendix C.1). Meta-analysis revealed greater %BF in girls by age 8 years (Appendix B.2)[41,50,53,63,69] and Tanner stage I (Appendix B.3),[36,44,48,58,60,61] with this sex difference increasing from 11 to 16 years (at which time it begins to plateau) and Tanner stages II to V. The increasing sex difference in %BF results from sex divergence in both FM and FFM. The FM increases similarly in boys and girls up to 12 years of age and Tanner stage IV and then continues to rise in girls, while stabilizing and decreasing in boys (Appendix C.2). Conversely, FFM increases steadily in boys throughout adolescence, while increasing more slowly and plateauing earlier in girls (Appendix C.3). The meta-analyses confirmed these findings, showing increasingly greater FM in girls starting at age 12 years and greater FFM in boys as early as age 8 and Tanner stage I, with girls displaying increasingly greater FM accumulation by 12 years of age (Appendix B.4)[33,34,50,51,69,70] and Tanner stage IV (Appendix B.5)[36,46,47,71] and boys displaying increasingly greater FFM accumulation from age 10 (Appendix B.6)* and Tanner stage I (Appendix B.7)[36,44,46,47,54,61] onward. Fewer researchers reported changes in FMI and FFMI by age (Appendices C.2 and C.3),[38,43,50,51,66] and the findings were similar to those for FM and FFM (see Supplemental File 1).

Sex-specific changes in ALM follow a trend similar to FFM; boys and girls increase similarly up to the age of 13, and boys accumulate more muscle thereafter (Appendix C.4). Increases in leg muscle mass occurred 1 to 2 years earlier in girls than in boys.[34] This is consistent with their earlier pubertal development, as Marwaha et al[54] observed that both boys and girls experienced the largest increases between pubertal stages I and III. Meta-analysis of 5 included studies[34,53,54,56,63] revealed that boys had increasingly greater leg muscle mass than girls from 14 to 17 years of age (Appendix B.8). The data were more variable at age 18 years, given fewer included studies.

Thigh and Hip Strength

The search resulted in 36 articles that described sex-specific changes in knee-extensor, knee-flexor, and hip strength. After in-depth review, we excluded 27 articles for not meeting the inclusion criteria (20 articles, 13 of which only reported 1 sex) and inability to obtain sex-stratified data by age or pubertal stage (7 articles). Thus, 9 studies were included in the current review.[53,72–79] One article

*References 33, 34, 50, 51, 53, 54, 63, 69, 70.

addressed hip-extension, hip-abduction, and hip-rotation strength,[74] and the remaining 8 articles supplied both knee-extensor and knee-flexor strength values. Four articles offered sex-specific changes by pubertal stage, whereas 5 gave changes by age. Because of insufficient data, we were unable to perform a meta-analysis on hip strength by age or maturity level.

Most authors noted linear trends for knee-extensor and knee-flexor strength as age and maturation level increased. In 5 of the 9 studies, knee-extensor strength in boys began to exceed female values by 12 to 15 years or Tanner stages IV and V (Appendix C.5).[73,75,77–79] Conversely, 1 group[74] (of 2 groups who normalized strength to body mass) found greater knee-extensor strength in prepubertal girls compared with prepubertal boys and postpubertal girls. The meta-analysis revealed that knee-extension strength was greater in girls at age 9, similar to boys at age 10, and then less than boys at ages 11 and 12 years, with no differences evident at age 13 years (Appendix B.9).[53,74–76,79] However, when stratified by maturity level, boys demonstrated more knee-extension strength than girls at pubertal and postpubertal stages, with the greatest mean difference occurring at the postpubertal stage (Appendix B.10).[73,74,77,78] For hamstrings strength, 5 of the 7 included studies showed that male strength exceeded female strength between 8 and 12 years or in Tanner stage IV (Appendix C.6). When these studies were combined, the meta-analysis revealed greater knee-flexor strength in boys across all age groups (Appendix B.11)[53,74,76,79] and increasingly greater strength in the pubertal and postpubertal stages (Appendix B.12).[73,74,77] For the 1 included study on hip abduction and external rotation,[74] no changes were present in either sex across pubertal stages (Appendix C.7). However, hip-extension strength (normalized to participant mass and height) tended to decrease linearly in both sexes as the pubertal level increased; no interactions were observed between sex and maturation level.

Lower Extremity Power

Our search identified 34 articles describing leg power metrics. After an in-depth review of each, 18 were excluded for not meeting the inclusion criteria (3 articles) or inability to obtain sex-specific stratified data by age or pubertal stage from the authors (15 articles), leaving 16.[52,53,63,80–92] The remaining articles depicted reported sex-specific changes in leg power by age (10 articles) and sexual maturation (6 articles).

Horizontal leg power, including during the standing long jump and single-legged hop, rose to a greater extent in boys versus girls with age and maturation in most studies (Appendix C.8). Performance in the standing long jump improved in boys with age and sexual maturity in all studies except one,[80] in which it was stable between ages 15 and 18. Girls also demonstrated increased standing long-jump distances with increasing age in 2 of 3 studies, but increases based on maturity were observed only between prepubertal and pubertal stages.[91] Single-legged hop performance improved in both boys and girls with age and maturity, with greater increases in boys.[88,90] By maturity, single-legged hop distances were greater in boys during Tanner stages III to IV and V but similar in boys and girls during Tanner stages I to II.[88] The meta-analysis for age (Appendix B.13)[80,84,87,90] and Tanner stage (Appendix B.14)[88,91] confirmed greater horizontal jump distances in boys versus girls at 12 and 13 years and across all pubertal stages. This sex difference increased from 11 to 12 to 13 years and from pubertal (Tanner II to IV) to postpubertal (Tanner V) stages.

Studies of vertical leg power measured via standing vertical jump, countermovement jump, drop jump, or single-legged hop are detailed in Appendix C.9. When compared by age, the findings were inconsistent. In 1 study, vertical jump height was greater in girls 9 to 10 years and 13 to 14 years,[89] whereas some researchers identified equal vertical jump performance by sex across ages,[53,83] and others detected greater increases in boys.[52,63,85] When stratified by maturational status, boys demonstrated increased vertical jump height across maturation while jump height performance in girls remained the same[82,86,92,93] or increased less from prepubertal and postpubertal girls.[81] Similarly, single-legged hop distance increased in both boys and girls from 11 to 16 years; thereafter, hop height continued to increase in boys but decreased in girls from 15 to 16 and 17 to 18 years.[52] Meta-analysis for age[52,53,63,83,85,89] revealed a general trend toward increasing sex differences from 12 to 15 years except for age 13, though findings of the 4 included studies were more variable (Appendix B.15). The meta-analyses for Tanner stage[81,86] were limited to comparisons at the pubertal and postpubertal stages and showed greater vertical height in boys at both stages, with this sex disparity being greatest at the postpubertal stages (Appendix B.16).

Knee-Joint Anatomy

The search yielded 12 articles that explored sex-specific changes in knee-joint anatomy, including notch width (NW), transcondylar width, notch width index (NWI), ACL cross-sectional area (CSA) and width, ACL length, ACL sagittal-inclination angle, ACL coronal-inclination angle, lateral tibial slope, medial tibial slope, intercondylar roof-inclination angle, and medial tibial depth. After an in-depth review, we excluded 4 articles for not meeting the inclusion criteria or an inability to obtain sex-specific data stratified by individual age or pubertal stage from the authors, leaving 8 articles. In 7, sex-specific changes in knee-joint geometry with age were reported; 1 article provided data based on evidence of tibial physis closure. Appendix C.10 supplies the summary findings for 6 studies of outcomes more commonly associated with ACL injury risk: NW, NWI, ACL size (CSA and width), and tibial slope.[94–99] Additional condylar and ACL dimensions obtained in the search are listed in Supplemental File 2 (available online at https://doi.org/10.4085/1062-6050-0038.22.S2). Sufficient data were available to perform meta-analyses for NW, NWI, and ACL size by chronological age. Insufficient data were available to examine tibial slope by age and all outcomes by maturational stage.

Measures of ACL size (ACL CSA and width) generally show similar increases in boys and girls until about 11 to 15 years of age, when boys begin to increase more than girls through age 17 to 18.[95,97] The meta-analyses of 3 included studies[95,97,99] indicated greater ACL size in boys by 15 years of age, with the sex difference increasing from 15 to 17 years (Appendix B.17). Measures of notch geometry generally demonstrated similar increases in boys and girls with growth, but a smaller notch size was evident in some older adolescent girls.[96] Meta-analysis of the absolute NW revealed similar sizes between sexes from age 8 to 12 years; boys had a greater NW from age 13 to 18 years (Appendix B.18).[95,96,98] However, once normalized to condylar width (NWI), no differences were present between sexes throughout the aging process (Appendix B.19).[94–96,98,99]

Knee-Joint Laxity

The searches produced 12 articles on sex-specific changes in joint laxity, most often giving values for general joint laxity (GJL) and anterior knee laxity, with 1 article each reporting sex-specific changes in frontal- and transverse-plane laxity[100] and genu recurvatum.[101] After an in-depth review of each article, we excluded 4 for our inability to obtain sex-specific stratified data by individual age or pubertal stage from the authors and 2 for single-sex data, leaving 6.[100–106] The authors of 4 studies noted sex-specific changes in laxity by maturational status, with 2 studies supplying data by age (Appendix C.11).

Collectively, investigators demonstrated that although anterior knee laxity tended to decrease with maturation in both boys and girls,[101] this decrease was greater in boys than in girls,[101,102,104] ultimately leading to higher values in mature girls versus mature boys in 2 of the 3 studies.[102,104] A meta-analysis performed on the 2 investigations revealed a trend toward greater values in prepubertal boys and greater values in postpubertal girls, but these were not significantly different at any stage (Appendix B.20).[101,104] A general trend of decreasing joint laxity with adolescence also occurred in 1 study each for varus-valgus,[100] internal-external rotation laxity,[100] and genu recurvatum,[101] yet these decreases were similar within the age ranges surveyed (8 to 14 years for varus-valgus and rotational laxity, 9 to 18 years for genu recurvatum). General joint laxity was greater in girls than boys across all maturational stages in 1 study[101] and increased in girls from prematuration to postmaturation with no changes in boys in another.[106] When these studies were combined for the meta-analysis, prepubertal girls had greater GJL than prepubertal boys, and this sex difference progressively increased from prepubertal to pubertal to postpubertal stages (Appendix B.21).

Lower Extremity Alignment

Eight articles described sex-specific changes in lower extremity alignment. After an in-depth review of each article, we excluded 2 for an inability to obtain sex-specific stratified data by individual age or pubertal stage from the authors, leaving 6.[101,107–111] Most researchers (5 articles) observed sex-specific changes in lower extremity alignment with age, whereas a single study provided data by maturational stage (Appendix C.12). Tibiofemoral angle was the most commonly reported variable in the reviewed manuscripts. Other less commonly measured variables were femoral and tibial specific angles and geometries, pelvic angle, standing quadriceps angle, hip anteversion, and tibial torsion.

Studies of valgus knee angulation (tibiofemoral, quadriceps angle) consistently indicated little to no change with age or maturation in girls. Male values may decrease somewhat, ultimately resulting in greater valgus angulation in girls. A meta-analysis of 3 studies by age that captured sufficient data from 10 to 15 years[101,107,108] displayed similar values in boys and girls until age 12, when girls developed increasing values that became significantly different from boys at age 15 (Appendix B.22). Of the 1 study involving tibiofemoral angle by maturational stage, decreases were most pronounced from pubertal to postpubertal stages, and girls had higher values across all maturational stages.[101] Due to the varied methods used to characterize frontal-plane femoral angulations, we did not attempt to combine these variables into a meta-analysis. However, studies of the bicondylar angle of the femur (frontal-plane angle between the long axis of the femoral shaft and a line tangent to the distal femoral condyles) and the collodiaphyseal angle (frontal femoral neck-shaft angle) collectively suggested that even though both angles changed with age in girls and boys, sex differences became apparent around 10 to 12 years of age, when the bicondylar angle increased and the collodiaphyseal angle decreased in girls,[110,111] which could result in a more valgus lower extremity posture. Finally, based on 1 study[101] of comprehensive changes in lower extremity alignment with maturational stage, the quadriceps angle increased from prepubertal to pubertal stages in girls and decreased in boys, yielding greater angles in girls in the pubertal and postpubertal stages. Foot pronation and genu recurvatum decreased and tibial torsion and pelvic angle increased similarly across maturation in boys and girls.

Flexibility

The searches identified 15 articles on sex-specific changes in flexibility, 9 of which were excluded because we were unable to obtain sex-specific stratified data by individual age or pubertal stage from the authors (4 articles), reporting on only a single year of age (1 article), reporting on only 1 sex (1 article), and not measuring actual flexibility (3 articles), leaving 6.[74,84,87,91,112,113] Five of the 6 studies focused on variations of the sit-and-reach test: 4 addressed changes by age or grade level and 1 addressed changes by maturity level (Appendix C.13).

Boys either decreased or maintained their flexibility with age or maturity, whereas girls tended to maintain or increase their flexibility with age or maturity. Meta-analysis of the sit-and-reach test was limited to 2 investigations[84,112] that included the ages of 11 and 14 due to a lack of uniformity in age range and stratification among studies (Appendix C.13). Girls had greater flexibility than boys at both ages, with the mean difference increasing from age 11 to 14 years (Appendix B.23).

Balance

The searches resulted in 34 articles on sex-specific changes in static or dynamic balance. After reviewing each article, we excluded 24 for not meeting the inclusion criteria or our inability to obtain stratified data from the authors. Therefore, 10 studies were included.[76,77,85,89,114–119] Seven of these provided static balance by age (Appendix C.14), and 3 explored dynamic balance by age and 1 assessed maturity status (Appendix C.15). Static balance by maturity was not evaluated in any of the papers.

Static balance was generally better in girls across most studies and age groups.[76,77,116–119] In addition, static balance generally improved at least up to age 12 in both girls and boys. It should be noted that 4 of these investigations consisted only of children up to the age of 12 or 14 years and so barely met the inclusion criteria of including at least 2 potential maturity categories.[76,89,116,118] Nonetheless, our meta-analysis showed better overall static balance in girls, with this difference becoming greater from 14 to 17 years and significantly different at 15 and 16 years, when most girls were nearing the end of puberty and most boys had at least started puberty (Appendix B.24). However, given the small number of articles, most of which did not supply data across the entire age range, we combined eyes-open, eyes-closed, and anterior-posterior and medial-lateral sway under the assumption of independence and because the forest plots with or without ≥ 1 of the directions or conditions did not change directionality. Pletcher et al[77] described static balance by age group, with the ages of 10.8 and 16.8 years roughly corresponding to prepubertal and postpubertal children. If we consider their results in the context of maturity, postpubertal boys had worse balance than prepubertal boys, and girls outperformed boys at both time points.

The few studies of dynamic balance by sex and age were limited to ages 11 to 15 years. Our meta-analyses of 3 of these articles[85,114,115] demonstrated a difference that began favoring boys at age 12 and continued through age 15 (Appendix B.25). Researchers of a single study[85] reported dynamic Y-balance test scores by maturity status. No statistically significant differences were found, but boys improved postpuberty, whereas girls performed less well than their prepubertal and pubertal counterparts.

Knee Biomechanics

A total of 35 articles evaluated sex-specific changes in lower extremity biomechanics. After review of each article, we excluded 22 for not meeting the inclusion criteria. Therefore, 13 articles were included in the current review.[74,77,86,88,120–128] Lower extremity biomechanics were assessed using both 2- and 3-dimensional motion-capture techniques during a variety of tasks, including the drop vertical jump, stop jump, cutting, and unanticipated cutting. Due to this variability, discrete changes in these variables were not provided in the summary tables. Four studies classified participants based on chronological age, 11 by maturational status, and 2 by percentage of predicted adult stature. Within those that classified maturational status, investigators used different tools to estimate pubertal development and stratify their data (ie, Tanner stages I + II, III + IV, V versus Tanner stages I, II + III, IV + V). For the purpose of the meta-analyses, subgroups of prepubertal (Tanner stage I), pubertal (Tanner stages II to IV), and postpubertal (Tanner stage V) participants were operationally defined.

Measures of knee-abduction kinematics and kinetics were the most frequent outcomes, appearing in 11† and 4[121,123,126,127] studies, respectively (Appendix C.16). During dynamic tasks, boys typically demonstrated no maturation-related change in knee-abduction kinematics to slightly decreased knee-abduction angles and motion throughout maturation, while girls consistently displayed increased knee-abduction angles and motion throughout maturation.[74,88,121,122,125,128] Meta-analyses indicated that girls exhibited greater knee-abduction angles during dynamic tasks than boys at age 10 to 14 years (Appendix B.26), though no differences were seen in the maturational analysis (Appendix B.27). Knee-abduction moment was higher in postpubertal girls than boys, with no difference during the prepubertal and pubertal stages (Appendix B.28). During maturation, the knee-abduction moment decreased slightly in boys[121,123,127] and consistently increased in girls.[121,123,126,127] Consistent sex differences in knee-abduction moment emerged in postpubertal participants[121] and those who had reached >92% of adult stature.[123]

Measures of knee-flexion kinematics and kinetics were reported in 5 articles[74,77,121,124,128] and 1 article,[121] respectively (Appendix C.17). Throughout maturation, most authors found minimal changes in knee-flexion kinematics of male participants and relatively consistent evidence of decreasing knee flexion in girls,[74,121,128] especially after the age of 14[128]; however, the meta-analyses by maturation status did not reflect any sex differences (Appendix B.29).

Peak vertical ground reaction force (vGRF) during athletic movements was evaluated in 3 investigations (Appendix C.18).[74,77,86] Generally, mass-normalized vGRF decreases throughout maturation in boys with no corresponding change in girls[74,86]; however, the meta-analysis (Appendix B.30) by subgroup showed no differences among prepubertal, pubertal, or postpubertal boys and girls.

Summary Findings

An overall graphical summary of the individual trajectories for girls and boys and the sex differences in these trajectories for all outcomes by age and maturity level, respectively, based on meta-analysis data, is given in Appendices B.31 and B.32. The data were insufficient to graph trajectories for tibial slope, anterior knee laxity, GJL, flexibility and knee-flexion angle, knee-abduction moment, and VGRF by age and NWI, ACL size, tibial slope, tibiofemoral angle, flexibility, and balance by maturity.

DISCUSSION

Our primary goals were to characterize and compare (1) the sex-specific changes in individual physical risk factors with chronological age and maturity level to better understand the earliest point when sex differences in physical risk factors begin to emerge, (2) the timing and sequencing of these physical changes relative to one another, and (3) how the development of these factors coincides with the time points linked to the increase in ACL injury risk in girls versus boys (approximately 12 to 17 years). Our results indicated marked physical changes occurring throughout adolescence in both boys and girls. Sex differences in FFM, leg strength and power, and GJL were already evident in individuals at 8 to 10 years or in Tanner stage I (or both). Sex differences in FM, FFM, leg strength and power, GJL, and balance became increasingly evident by 11 to 12 years and when transitioning from prepubertal to pubertal stages. Other factors more often emerged at later ages (ACL size and tibiofemoral angle by approximately 13 to 15 years) or when transitioning from

†*References 74, 77, 88, 120–125, 127, 128.*

pubertal to postpubertal stages (anterior knee laxity, knee-joint biomechanics). When we qualitatively compared sex-specific changes by chronological age versus maturity status, the demarcation in sex-specific trajectories over time tended to be more apparent when examined relative to pubertal status than chronological age, with the greatest changes emerging around Tanner stages III to IV.

Body Composition, Thigh Strength, and Leg Power

Sex differences in body composition and muscular strength and power were among the first to appear and were already present at the earliest ages studied and before the time when the ACL injury risk begins to rise.

Body Composition. Multiple researchers[10,129,130] identified higher BMI (weight by stature) as a risk factor for ACL injury, particularly in girls. Despite these findings, the rationale for including BMI in multivariate risk factor models and how it might be theoretically associated with ACL injury is rarely addressed. Although BMI is easy to measure clinically and is commonly used to characterize relative adiposity, it is a poor indicator of body composition in maturing youth because it does not distinguish between the increasing divergence in relative contributions of muscle and fat weight to an individual's overall weight by stature.[131] According to Centers for Disease Control and Prevention reference data,[132] BMI increases linearly with age in a similar manner in both boys and girls from 8 to 18 years of age, and data from our meta-analyses demonstrated an increasingly greater proportion of FM in girls versus a greater proportion of FFM in boys after age 12, the same age when ACL injury begins to disproportionately affect girls. By 14 to 15 years of age, girls have accumulated the majority of their FFM (both overall and leg-specific mass) as male FFM continues to rise; female FM continues to rise while male FM plateaus or decreases. When examined relative to pubertal stage, this sex-specific demarcation is evident as early as pubertal stage II, with a clear shift toward greater accumulation of FM (girls) and FFM (boys) by Tanner stage III.[33,36,46,54] In 1 study of age and Tanner stage,[46] Tanner stage III on average coincided with 13.1 years for girls and 13.6 years for boys (consistent with chronological data), yet the actual ages of participants in this stage ranged from 10 to 15.6 years and 11.7 to 16.1 years in girls and boys, respectively. Thus, if these body composition changes in girls during Tanner stages III to V (driven hormonally to a large extent[131]) are associated with their ACL injury risk, then girls who matured at earlier chronological ages could be at greater risk for ACL injury than those who mature at later chronological ages.

Leg Strength. Consistent with the sex-specific trajectories in FFM and leg muscle mass (increasing in both sexes), boys and girls exhibited increasing knee-extension and knee-flexion absolute torque values with increasing age and maturation levels through 12 to 15 years of age. This increase was slower in girls, resulting in less quadriceps strength compared with boys by age 11 years. When stratified by pubertal stage, these sex differences were evident between Tanner stages II and IV. The consistent finding of less hamstrings strength in girls as early as age 8 years and Tanner stage II is concerning, particularly because we did not identify appreciable sex differences in leg-specific muscle mass until after 14 years of age. This earlier divergence in hamstrings strength perhaps was a function of reduced muscle quality (greater fatty infiltration) in maturing girls. Greater proportions of FM are already present in girls by age 8 and Tanner stage I (Appendices B.2 and B.3), and greater FM was associated with less muscle density in 9- to 12-year-old girls.[133] Although we were unable to find data on sex comparisons of muscle quality in adolescents, less hamstrings muscle density was observed in young female adults than in young male adults, and less muscle density was more strongly associated with less isometric hamstrings strength than with muscle CSA.[134]

It should be noted that, with the exception of DiStefano et al,[74] findings of sex differences were primarily based on absolute torque, and the data were not normalized by body size (mass or height). The increasing sex difference in FFM per body weight (and the earlier acceleration in FFM accumulation in girls with earlier pubertal onset) likely explains the DiStefano et al[74] results of greater knee-extensor strength in prepubertal girls compared with pubertal boys and postpubertal girls and the overall greater knee-extensor strength in girls at 9 years of age in the meta-analysis for age. The evidence is limited to a single study, but hip strength normalized to body size does not appreciably improve in boys or girls over time.

Leg Power. Similar to strength, leg power tended to increase to a greater extent in boys than in girls and increase linearly with age. With respect to strength development, an earlier (by approximately 1 year) and steeper rise in leg power trajectories appeared in both the age and maturity data (Appendices B.31 and B.32). Individual study data and meta-analyses for maturity level also identified sex differences earlier than quadriceps strength, with greater values for horizontal leg power in prepubertal boys (Appendix B.13–B.16). As maturity progressed, boys demonstrated a linear increase in leg power, while power generation more often plateaued or declined in girls from pubertal to postpubertal stages. The increasing sex difference was particularly notable in studies that included boys and girls past the age of 16 years. Along with changes in body composition, increasing sex differences in the ability to generate power during maturation are likely due to the muscular demands associated with a weight-bearing task. Specifically, as girls and boys move from pubertal (Tanner stage III) to postpubertal stages, girls have increasingly less muscle mass to propel the same body weight as boys. Future authors should also consider if plateaus in strength and leg power increase the risk of ACL injury in pubertal and postpubertal girls. Although muscle strength has not been associated with the ACL injury risk in athletes,[10,130,135] isolated muscle testing does not functionally challenge the system as a weight-bearing jump or hop would. Jump and hop performance has been used extensively to examine associations between suboptimal landing mechanics and ACL injury.[136–138] We are not aware of any researchers who examined horizontal or vertical leg power as a prospective risk factor for ACL injury.[135] It may also be useful to establish the extent to which neuromuscular training programs specifically maintain or improve leg power in girls into mid- to late-pubertal development and how this may affect injury risk.

These data indicate that while BMI changes similarly in boys and girls, girls have increasingly less leg muscle mass, strength, and power to control the same relative body weight during sport activity as maturing boys, particularly as they transition from Tanner stages III to V. In future risk factor studies, as opposed to overall BMI, the FMI and FFMI should be partitioned (ie, FM and FFM adjusted for change in stature) to better elucidate the relationship between body composition and ACL injury risk. More specifically, it is important to determine mechanistically how the lesser proportion of muscle mass per unit body weight influences girls' lower extremity strength and power and, ultimately, neuromuscular control strategies and the internal and external loads placed on the ACL.

Appreciating that both girls and boys can augment muscle development during maturation through training,[139] it is plausible that girls can increase or extend the trajectory of their muscle development and lessen the observed gaps in body composition and muscular strength and power. From this perspective, comparisons of leg muscle mass and strength and power trajectories in athletic and nonathletic populations throughout the entire adolescent growth period (ie, through age 18 years) would be beneficial. As body composition is one of the first factors to change with maturation and some sex differences in strength and power are already evident in prepubertal children, early strength training interventions could be warranted. These sex-specific developmental changes are also important considerations once injury occurs. Quadriceps strength and vertical and horizontal jump performance are used as metrics in determining readiness to return to sport after ACL reconstruction,[140,141] and it is well established that the rate at which girls return to sport after ACL reconstruction is slower than in boys.[142,143] Future researchers should consider sex-specific rehabilitation protocols to address these inherent decrements in leg power in girls and determine if this will enable girls to return to sport more effectively and safely.

Knee-Joint Geometry, Laxity, and Flexibility

Smaller ACLs and notch dimensions and steeper lateral tibial slopes in the contralateral knee were described in studies focused on younger (high school and college-aged) individuals who sustained an ACL injury.[10,144,145] Smaller ACLs are associated with less linear stiffness,[146,147] lower load at failure,[146,147] and greater anterior knee laxity.[148] In turn, greater anterior knee laxity was identified as a strong independent predictor of the ACL injury risk in females.[10,130] Based on the limited evidence available, male participants increased their ACL size and NW (with no difference in NWI) and decreased their lateral tibial slope and anterior knee joint laxity to a greater extent than female students as they matured (Appendices C.10 and C.11; Appendices B.17–B.19).

Although ACL size was not normalized to body dimensions in the included studies, prior work suggested that female adults still had 25% to 30% smaller ACLs, even after body dimensions such as body mass, BMI, and NW were accounted for.[31,149,150] Some data indicated that the sex difference in ACL size could be partly explained by sex differences in muscle size.[31,32] When comparing the sex-specific trajectories in thigh muscle mass with those of ACL size (see Supplemental File 1, Figures 19 and D1), girls accumulated thigh muscle mass and increased ACL size at lower rates (with earlier plateaus) than boys, with sex differences becoming increasingly apparent by approximately 14 years of age (data not available by maturity level). Although we cannot change bone geometry, these findings are potentially promising in that ACL size (and, in turn, anterior knee laxity) could be modifiable to some extent if addressed early. This once again points to the need for continued research examining how these risk factors change relative to one another during pubertal growth to determine what contributes to a smaller and weaker ACL and to examine the effect of early strength training interventions on these outcomes in developing girls.

Adult females were often observed to have greater anterior knee laxity than men,[10,151,152] and this was thought to be mediated to an extent by sex differences in ACL size.[148] From the available data, it is difficult to compare the relative trajectories of ACL size reported by age and anterior laxity reported by pubertal status, other than to note that both trajectories change more in males; sex differences develop at later ages and maturational stages compared with body composition, strength, and leg power. In fact, although all included studies consistently demonstrated greater declines in anterior knee laxity in boys versus girls throughout maturation, sex differences were not always present by late maturational stages within the age ranges assessed. Also, not all girls develop greater magnitudes of knee laxity, and individual variations in other physical factors (eg, sex steroid hormones, lower extremity alignment) that are also changing during this time may contribute to this variability.[152,153] Given the importance of anterior knee laxity as an independent ACL injury risk factor, understanding the factors that promoted the development of greater anterior knee laxity in maturing girls at the individual level is an important direction for future research.

Findings on sex-specific changes in flexibility, genu recurvatum, GJL, and frontal- and transverse-plane knee laxity were more limited. Based on the studies available, frontal- and transverse-plane knee laxity seem to progressively decrease in boys and girls, with no sex differences emerging by 14 years of age (data were not available after this age). Flexibility and GJL either decrease or maintain with increasing age and maturational stage in boys, whereas girls more often increased their values with maturation. This resulted in girls having greater flexibility and GJL as early as age 11 years and Tanner stage I, and this difference became more pronounced at later ages and maturational stages. Greater GJL and genu recurvatum were associated with a greater risk of ACL injury,[10,130,154] yet our knowledge of flexibility relative to ACL injury and prevention is incomplete and equivocal, with 1 study[10] showing a trend toward greater preinjury sit-and-reach scores in patients with ACL injury compared with an uninjured cohort and another[155] suggesting that more emphasis on static stretching in ACL injury-prevention programs may reduce the risk. Further investigations are needed to determine the sequencing of these changes with other risk factors and the timing of ACL injury.

Lower Extremity Alignment

Although sex differences in lower extremity alignment have been examined as ACL injury risk factors, we identified very few studies that examined sex-specific changes in lower extremity alignment during the adolescent years when ACL risk is rising. Given the paucity of research, our analyses were primarily limited to the assessment of frontal-plane knee angles. Salenius and Vankka[156] reported that the natural progression of tibiofemoral angle was a reduction in valgus angulation in children from 2 to 8 years of age. Our meta-analysis suggests a continued progression that is more pronounced in boys throughout adolescence with clear sex differences emerging around 15 years of age. Although greater static frontal alignment measurements have yet to emerge as important predictors of ACL injury[130,157] and are largely nonmodifiable, it is important to understand the development of these alignment patterns and how they may influence other risk factors thought to be associated with ACL injury (eg, dynamic movement patterns[158]), as they may modify our approach to interventions.

Balance

Studies included in this review indicated that balance generally improves at younger ages and then remains stable. Our findings showed that static balance tends to be better overall in girls (less excursion or sway), with this difference more conclusive at ages 15 and 16 years. Conversely, dynamic balance (greater reach distance) seems to favor boys starting around the age of 12. These developmental trends could benefit girls, as poor static balance (greater postural sway) is associated with a greater risk of ACL injury.[135] Dynamic measures such as the Y-Balance or Star Excursion Balance tests have not been specifically associated with ACL injury, but greater reach distances were associated with lower limb injury in general.[135] Additionally, ACL injury-prevention programs that included more balance training were linked with a higher risk of ACL injury.[155] As such, the clinical implications of developmental changes in balance relative to ACL injury risk and prevention are less clear and require further research. Moreover, these studies were primarily based on age and involved younger age ranges: 4 of the 7 demonstrated static balance up to the age of 12 or 14 years (encompassing the early years of ACL risk development), and none included all ages (8 to 18 years). Many of the participants were likely still prepubertal or early pubertal, thus limiting any inferences regarding changes across the full range of maturity.[20,21,159] Moreover, improved balance was not observed until the age of 15, when most girls were near the end of puberty and boys were still developing (Appendix B.24). In this single study,[85] the age span was limited to 12 to 15 years, which yielded a disproportionate number of prepubertal boys and postpubertal girls. Despite this, multiple sex-specific anthropometric (eg, height, BMI) and performance (eg, countermovement jump height, strength) measures were observed to change with maturation, whereas Y-Balance test results did not. Further work is needed to determine if meaningful changes in static and dynamic balance occur across the maturation continuum and how these may be affected by or affect the development of other physical risk factors known to vary by sex.

Lower Extremity Biomechanics

Based on the available evidence from individual studies, knee kinematics and kinetics change very little during maturation in boys performing dynamic tasks, whereas girls increase knee-abduction angles and moments and decrease knee-flexion angles throughout maturation (prepubertal to pubertal to postpubertal). Conversely, mass-normalized vGRF decreases in boys and shows little change in girls. The meta-analysis confirmed greater knee-abduction angles in girls versus boys from 11 to 14 years of age (when the ACL injury risk begins to rise) and in the postpubertal stage (Appendices B.26 and B.27). Similar trends were identified in knee-abduction moment with maturation in 3 of the included studies.[121,123,160] This was an important finding given that knee-abduction moment had been prospectively identified as a risk factor for ACL injury in female athletes.[136] Furthermore, the general consensus is that these collective biomechanical changes pose a greater risk for ACL injury, and improvements in these motion patterns were a primary focus of ACL injury-prevention efforts.[15] The implications of these high-risk movement strategies for ACL loading are particularly concerning for the female ACL, which is proportionally smaller with advancing maturation (Appendix C.10; Appendix B.17).

When considering the overall timing of these changes with respect to other physical changes, our review suggested that sex differences in multiple physical risk factors may precede or coincide with these biomechanical changes and potentially contribute to the development of higher-risk knee biomechanics in girls. Earlier changes observed in body composition (already present at age 8 years and Tanner stage I), leg strength, and power may decrease a girl's ability to stabilize the hip and knee upon landing. In fact, improvements in knee-flexion motion and reductions in knee abduction during the landing phase of a vertical jump were reported after neuromuscular training designed to improve leg strength and power.[161] Although perhaps more difficult to modify, the subsequent sex divergences in frontal-plane knee alignment, ACL size, and knee-joint laxity that become increasingly apparent from pubertal to postpubertal stages may further contribute to the increasing sex difference in high-risk movement patterns from pubertal to postpubertal stages (Appendix B.28). Girls with greater magnitudes of knee laxity landed with greater muscle activation, knee stiffness, and valgus knee motion,[162,163] indicating greater demands to control joint motion when strength capabilities are already disadvantaged. Those with lower extremity alignments characterized by a more rotated and valgus knee posture also displayed more functional knee valgus during landing.[158] A better understanding of these underlying contributions is important, as integrated neuromuscular training programs designed to target these risk factors could be more successful if implemented before these risk factors emerge.[164–166] Screening protocols to identify the earliest emergence of both modifiable and nonmodifiable risk factors and how they contribute to high-risk biomechanics should continue, with attention to the role that maturation and pubertal growth may play. This will lead to continued advancement of targeted interventions to reduce the risk of ACL injury.

Maturational Versus Age-Derived Sex Comparisons

As previously noted, ACL incidence data were primarily based on chronological age, which is not an ideal metric for understanding the development of individual risk factors, given the large variations in ages at which boys and girls begin to mature and progress through puberty.[16,17] Thus, we sought to identify studies that also addressed physical risk development by maturational status in an effort to better clarify when sex differences begin to occur at the individual level and how these may coincide with age-related changes in ACL injury risk. Our search revealed that the majority of risk factors were either mostly described by chronological age (eg, balance, knee-joint geometry, lower extremity alignment) or maturational status (joint laxity, lower extremity biomechanics), making it difficult to qualitatively compare age-related changes with the stages of maturation. However, we did obtain sufficient data on sex-specific trajectories in body composition, muscle strength and power, and, to a lesser extent, lower extremity biomechanics (ie, knee-abduction angle across limited ages) by both chronological age and pubertal status (see Appendices B.31 and B.32). These data seem to support a clearer demarcation (and more consistent reporting) of emerging sex differences by pubertal status. We often had to collapse stages into prepubertal, pubertal, and postpubertal for the meta-analyses due to study inconsistencies in defining pubertal stage, yet individual studies suggested that Tanner stage III and the transition from Tanner stage III to IV were the most sensitive markers of change for these factors, rather than a particular age. Tanner stage III and the transition to stage IV are known to be associated with considerable physiological changes in maturing girls and boys. Tanner stages III and IV represent the time when girls experience an appreciable rise in estradiol levels and most reach menarche and peak growth.[16,20] For boys, increases in testosterone and the time of peak growth most often occur in Tanner stage IV and the transition to stage V.[17,21] Longitudinal investigations assessing the relative timing, tempo, and dependency of collective risk factor changes across discrete pubertal stages (ie, individual Tanner stage, individual ages relative to PHV) in boys and girls would enable us to better determine when risk begins to develop at the individual level. This is particularly critical because the speed at which a boy or girl passes through these stages varies by individual. Additionally, it should be noted that hormonal changes within and across pubertal stages could vary substantially in both boys and girls.[16,17] Because sex hormones can both directly and indirectly influence many of these physical outcomes, future authors should also examine the effects of this individual variability on physical risk-factor development relative to pubertal stage, as well as the potential effects of early versus delayed pubertal onset.

Limitations

The following limitations expose the critical gaps that remain in our knowledge and the need for continued research in this area.

Given the scope of the review and to ensure that we obtained representative data on all relevant risk factors, we chose not to limit the publication dates for included studies. Although age at menarche and the timing of hormonal surges have remained relatively stable for both boys and girls, research suggested that the age of *thelarche* (onset of puberty in girls) had decreased by 0.24 years every decade (approximately 3 months).[167,168] This would likely have had little effect on our findings, as the majority (93%) of the included studies were published in 2000 or later, which would amount to a shift in the data of 6 months or less. Also, the effect of earlier pubertal onset on physical development is uncertain as it is not accompanied by the earlier onset of hormonal changes. Still, these secular trends in age of pubertal development again speak to the need to study trends in risk factor development by maturity stage rather than by age.

Other limitations were based on the characteristics of the studies included. These were largely cross-sectional in nature and often limited to relatively small samples sizes that were not balanced across age groups. Some outcomes were historically stratified by chronological age and others by sexual maturity or growth trajectories. Studies stratified by chronological age were more often based on general populations, whereas those of sexual maturity were more often based on athletic populations. The extent to which physical activity may have collectively influenced these developmental risk factors is unknown. Other study characteristics restricted which studies could be combined in the meta-analysis. Studies that did not provide SDs or sample size per group could not be included in the meta-analyses. Investigations often did not include the entire age range or stages of pubertal development, or data were collapsed across ages or maturational stages in an inconsistent manner. This resulted in insufficient data in some age and maturity groups for drawing inferences across the entire maturation process. We attempted to mitigate this limitation by allowing an age or maturity stage subgroup to be included with only 2 studies supplying data. However, conducting a meta-analysis with only 2 studies in each subgroup was also problematic because at least 3 studies were required to conduct bias analyses, and this factor should be considered when interpreting these results.

CONCLUSIONS

Sex differences in physical characteristics often associated with a girl's greater risk of ACL injury in large part emerge between 11 and 17 years of age, when the ACL injury risk is rising more rapidly in girls than in boys. During this transition, sex differences in body composition emerge first, closely followed by leg strength and power (with differences in these outcomes and GJL already evident by the prepubertal stage). Sex differences in knee anatomy, knee-joint laxity, and lower extremity biomechanics follow and more often emerge between pubertal and postpubertal stages. Our collective findings suggested that initiating interventions as early as 8 to 10 years of age (Tanner stage II) may be beneficial to optimize lean muscle development, strength, and power and potentially affect the subsequent sex-specific development of ACL geometry, joint laxity, and neuromuscular control. Yet considerable gaps remain in our understanding of the specific timing and tempo of these collective changes within an individual relative to the stage of pubertal development and how the timing of these developmental changes coincides with the risk of ACL injury.[16,17] Longitudinal studies that simultaneously examine multiple risk factors across discrete stages of the entire maturation process (eg, individual Tanner stages I to V) would greatly improve our knowledge of the relative timing and tempo of ACL risk factor development. In turn, this understanding would allow us to more accurately identify, at the individual level, the earliest entry point for screening and intervening on relevant risk factors. Our hope is that this review will serve as an effective catalyst to encourage future research in this area.

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S.J. Shultz was responsible for the original concept and oversight of the entire project. All co-first authors met regularly to contribute to the design and conduct of the systematic review, with each responsible for the in-depth review, data extraction, summary analysis, and reporting for 1 or more risk factor sections (Body Composition [S.J. Shultz], Strength [B. Pietrosimone], leg power [E. Casey], Knee-Joint Geometry and Laxity and Lower Extremity Alignment and Flexibility [R.J. Schmitz], Balance [T. Dompier], and Hip and Knee Biomechanics [J.B. Taylor, K.R. Ford]). T. Dompier performed all meta-analyses. All authors contributed to the drafting, review, and final approval of the manuscript.

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SUPPLEMENTAL MATERIAL

Supplemental File 1.
Forest plots with individual study results and weightings. Found at DOI: https://doi.org/10.4085/1062-6050-0038.22.S1

Supplemental File 2.
Additional knee-joint geometry measures reported. Found at DOI: https://doi.org/10.4085/1062-6050-0038.22.S2

Appendix A. PubMed Search Terms

(((1[UID] OR (*fat*[All Fields] AND *free*[All Fields] AND (*molecular weight*[MeSH Terms] OR (*molecular*[All Fields] AND *weight*[All Fields]) OR *molecular weight*[All Fields] OR *mass*[All Fields])) OR (*fat*[All Fields] AND (*molecular weight*[MeSH Terms] OR (*molecular*[All Fields] AND *weight*[All Fields]) OR *molecular weight*[All Fields] OR *mass*[All Fields])) OR (*anterior cruciate ligament*[MeSH Terms] OR (*anterior*[All Fields] AND *cruciate*[All Fields] AND *ligament*[All Fields]) OR *anterior cruciate ligament*[All Fields] OR *ACL*[All Fields]) OR (*anterior cruciate ligament*[MeSH Terms] OR (*anterior*[All Fields] AND *cruciate*[All Fields] AND *ligament*[All Fields]) OR *anterior cruciate ligament*[All Fields]) OR ((*femor*[All Fields] OR *femorals*[All Fields] OR *femur*[MeSH Terms] OR *femur*[All Fields] OR *femoral*[All Fields]) AND (*notch*[All Fields] OR *notch s*[All Fields] OR *notched*[All Fields] OR *notches*[All Fields] OR *notching*[All Fields] OR 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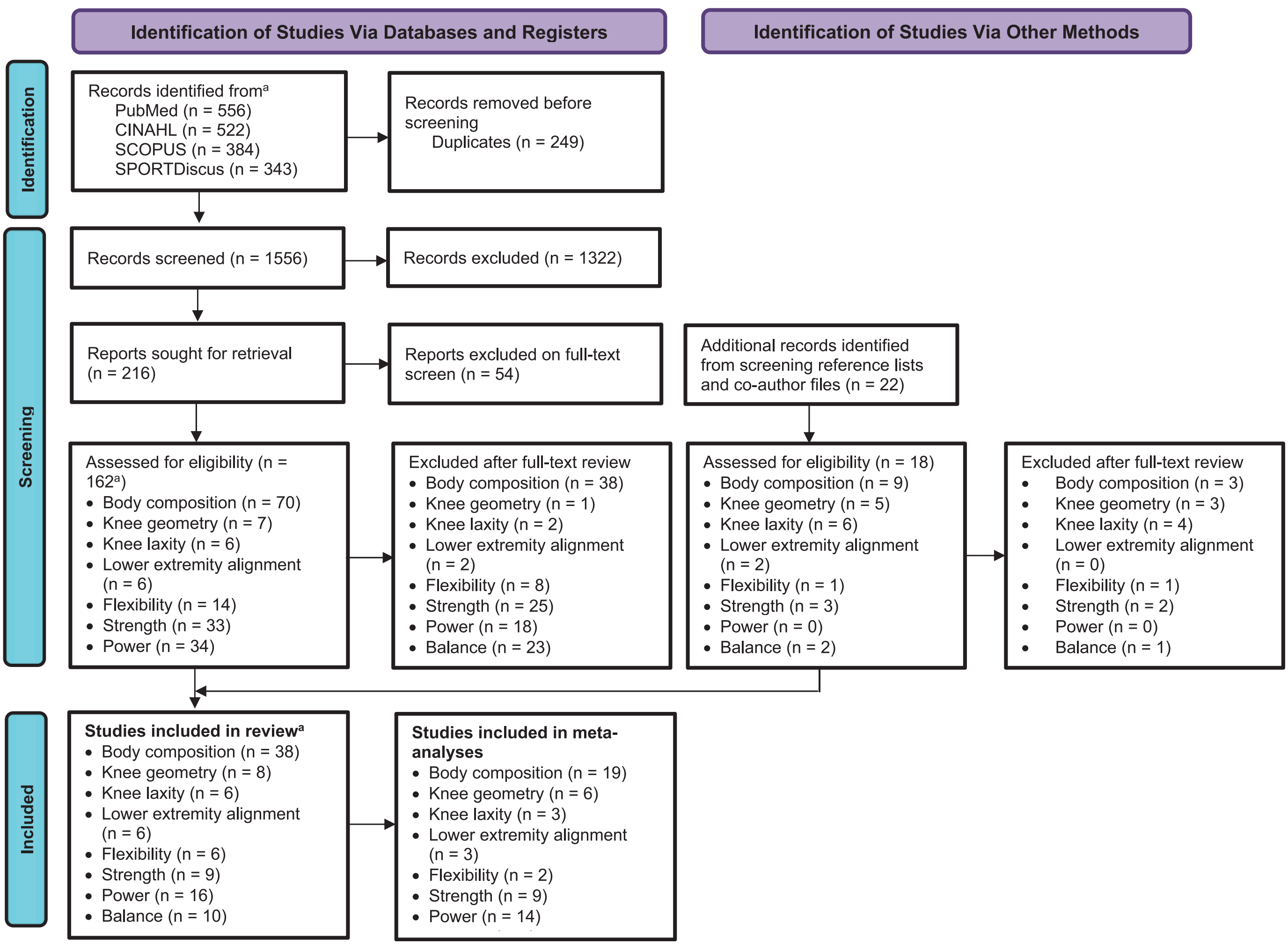
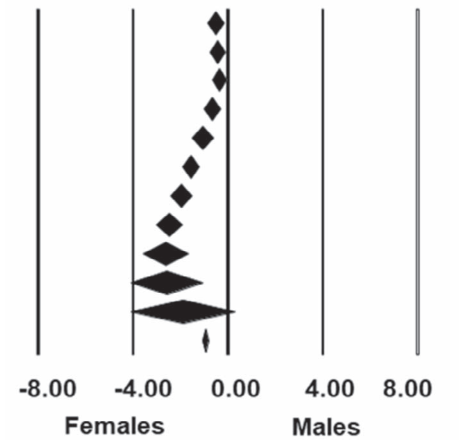
Appendix B



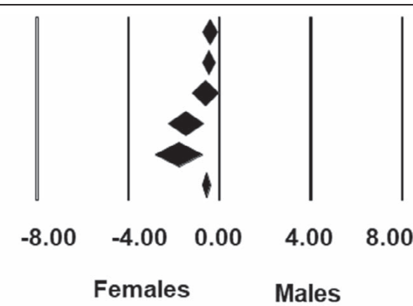
Appendix Figure 1. Flow diagram for included studies (some studies are included in more than 1 risk factor category).

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	-0.481	0.172	-0.819	-0.144	.005
9	-0.394	0.159	-0.707	-0.082	.013
10	-0.333	0.156	-0.637	-0.028	.032
11	-0.623	0.184	-0.983	-0.263	.001
12	-1.015	0.227	-1.459	-0.571	.000
13	-1.529	0.176	-1.874	-1.183	.000
14	-1.932	0.223	-2.369	-1.494	.000
15	-2.436	0.277	-2.979	-1.893	.000
16	-2.580	0.482	-3.525	-1.635	.000
17	-2.550	0.770	-4.060	-1.040	.001
18	-1.909	1.116	-4.097	0.279	.087
Overall	-0.935	0.065	-1.063	-0.807	.000



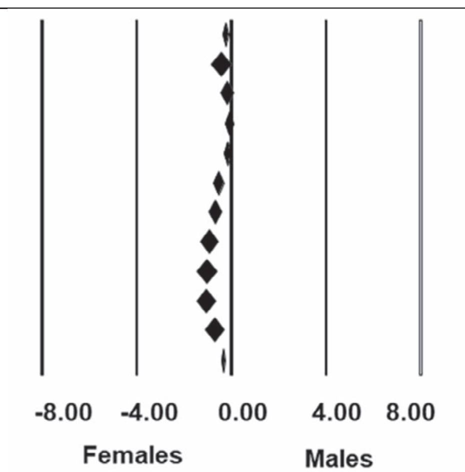
Appendix Figure 2. **Meta-analysis of percentage of body fat by sex and chronological age. Abbreviation: Std Diff, standard differential**

Tanner Stage	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
I	-0.395	0.174	-0.736	-0.055	.023
II	-0.438	0.142	-0.717	-0.159	.002
III	-0.597	0.287	-1.161	-0.034	.038
IV	-1.457	0.393	-2.227	-0.687	.000
V	-1.766	0.523	-2.791	-0.741	.001
Overall	-0.552	0.098	-0.744	-0.361	.000



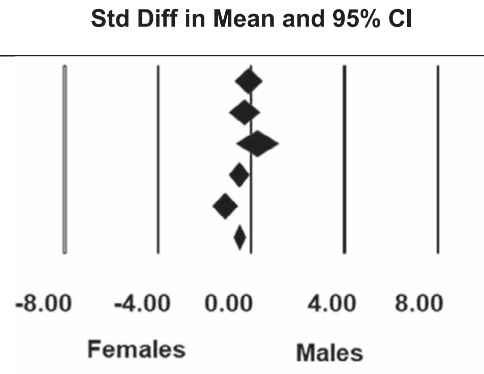
Appendix Figure 3. **Meta-analysis of percentage of body fat by sex and maturity level.**

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	-0.227	0.067	-0.358	-0.096	.001
9	-0.414	0.218	-0.842	0.015	.058
10	-0.143	0.150	-0.437	0.152	.342
11	-0.064	0.094	-0.247	0.120	.496
12	-0.164	0.075	-0.310	-0.018	.028
13	-0.543	0.116	-0.771	-0.315	.000
14	-0.647	0.133	-0.908	-0.385	.000
15	-0.912	0.196	-1.296	-0.527	.000
16	-1.003	0.208	-1.411	-0.594	.000
17	-1.044	0.204	-1.443	-0.644	.000
18	-0.675	0.193	-1.054	-0.296	.000
Overall	-0.331	0.035	-0.399	-0.262	.000



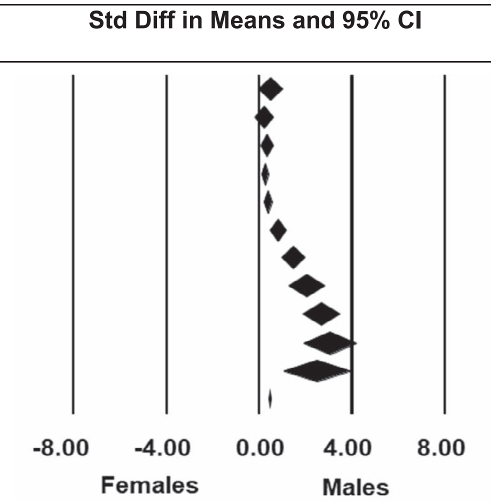
Appendix Figure 4. **Meta-analysis of fat mass by sex and chronological age.**

Tanner Stage	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
I	-0.086	0.286	-0.645	0.474	.764
II	-0.280	0.332	-0.932	0.371	.399
III	0.280	0.465	-0.631	1.190	.547
IV	-0.488	0.209	-0.897	-0.078	.020
V	-1.091	0.275	-1.630	-0.552	.000
Overall	-0.449	0.127	-0.698	-0.201	.000



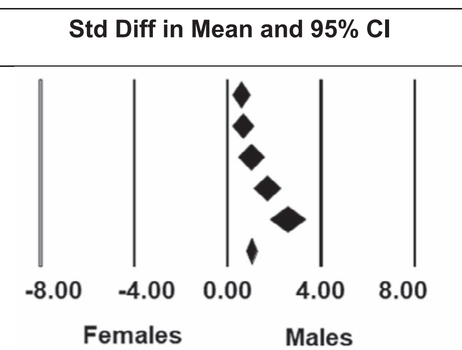
Appendix Figure 5. Meta-analysis of fat mass by sex and maturity level.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	0.521	0.275	-0.019	1.061	.059
9	0.234	0.195	-0.147	0.616	.229
10	0.352	0.131	0.096	0.608	.007
11	0.280	0.078	0.127	0.432	.000
12	0.389	0.088	0.217	0.561	.000
13	0.852	0.170	0.519	1.186	.000
14	1.507	0.249	1.020	1.995	.000
15	2.081	0.387	1.322	2.840	.000
16	2.696	0.413	1.887	3.506	.000
17	3.078	0.577	1.948	4.208	.000
18	2.493	0.725	1.072	3.914	.001
Overall	0.494	0.047	0.403	0.585	.000



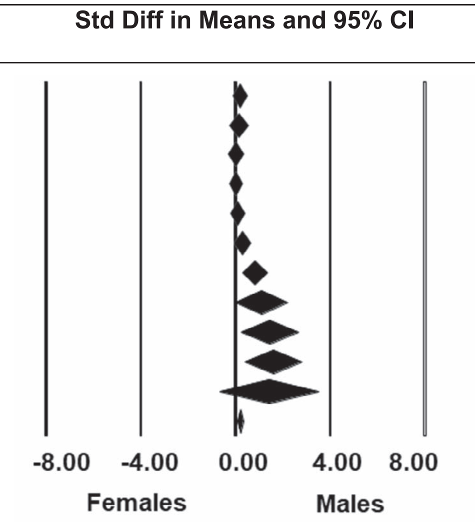
Appendix Figure 6. Meta-analysis of fat-free mass by sex and chronological age.

Tanner Stage	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
I	0.599	0.189	0.228	0.970	.002
II	0.702	0.233	0.246	1.158	.003
III	1.035	0.284	0.478	1.591	.000
IV	1.712	0.298	1.127	2.296	.000
V	2.600	0.392	1.833	3.368	.000
Overall	1.028	0.114	0.804	1.252	.000



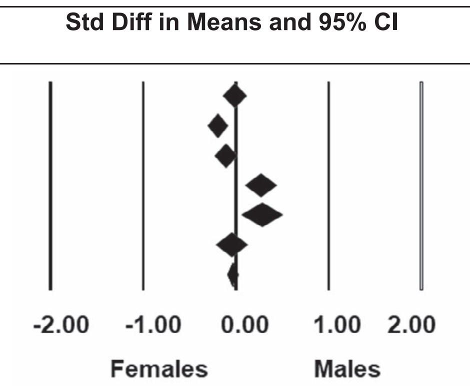
Appendix Figure 7. Meta-analysis of fat-free mass by sex and maturity level.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	0.222	0.159	-0.089	0.534	.161
9	0.169	0.197	-0.218	0.556	.393
10	0.063	0.160	-0.251	0.376	.696
11	0.055	0.141	-0.221	0.331	.695
12	0.121	0.159	-0.190	0.432	.446
13	0.344	0.183	-0.014	0.701	.060
14	0.844	0.267	0.320	1.368	.002
15	1.120	0.558	0.027	2.213	.045
16	1.477	0.611	0.281	2.674	.016
17	1.593	0.615	0.387	2.798	.010
18	1.437	1.064	-0.650	3.523	.177
Overall	0.235	0.064	0.111	0.360	.000



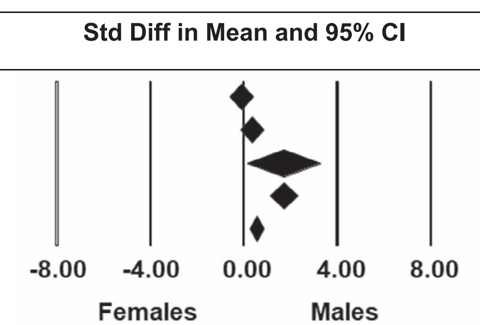
Appendix Figure 8. Meta-analysis of leg muscle mass by sex and chronological age.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	-0.006	0.061	-0.125	0.113	.924
9	-0.189	0.055	-0.296	-0.082	.001
10	-0.095	0.060	-0.213	0.024	.117
11	0.274	0.087	0.104	0.444	.002
12	0.291	0.114	0.067	0.514	.011
13	-0.033	0.086	-0.202	0.136	.699
Overall	-0.030	0.029	-0.086	0.026	.300



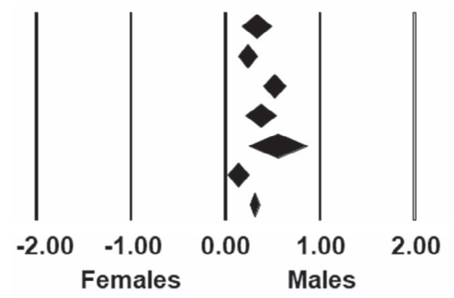
Appendix Figure 9. Meta-analysis of knee-extension strength by sex and chronological age.

Tanner Stage	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
I	-0.068	0.254	-0.565	0.429	.788
II	0.405	0.255	-0.096	0.906	.113
IV	1.726	0.782	0.194	3.258	.027
V	1.739	0.308	1.135	2.343	.000
Overall	0.611	0.152	0.312	.909	.000



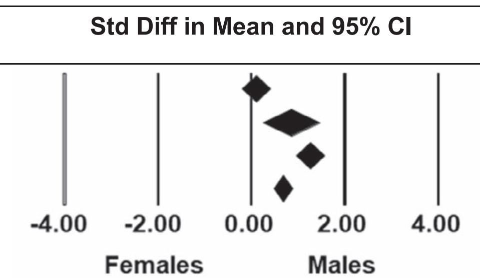
Appendix Figure 10. Meta-analysis of knee-extension strength by sex and maturity level.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	0.344	0.078	0.190	0.498	.000
9	0.245	0.049	0.148	0.342	.000
10	0.530	0.063	0.407	0.653	.000
11	0.384	0.081	0.226	0.543	.000
12	0.557	0.156	0.250	0.863	.000
13	0.150	0.057	0.039	0.261	.008
Overall	0.315	0.027	0.261	0.369	.000



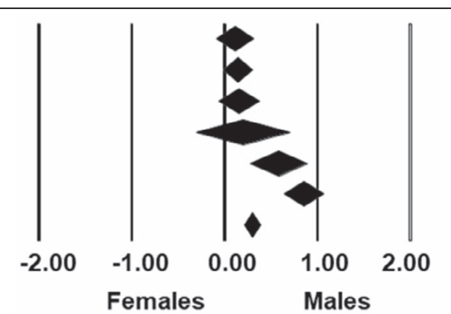
Appendix Figure 11. Meta-analysis of knee-flexion strength by sex and chronological age.

Tanner Stage	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
I	0.111	0.154	-0.190	0.413	.470
III	0.864	0.312	0.252	1.476	.006
V	1.270	0.156	0.965	1.575	.000
Overall	0.704	0.103	0.501	0.906	.000



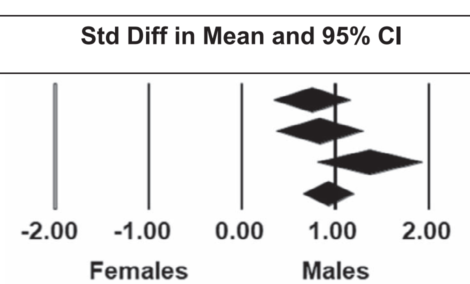
Appendix Figure 12. Meta-analysis of knee-flexion strength by sex and maturity level.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	0.119	0.104	-0.085	0.324	.253
9	0.146	0.080	-0.011	0.303	.068
10	0.163	0.113	-0.058	0.383	.149
11	0.201	0.256	-0.301	0.703	.433
12	0.590	0.156	0.284	0.896	.000
13	0.864	0.111	0.647	1.080	.000
Overall	0.311	0.046	0.220	0.402	.000



Appendix Figure 13. Meta-analysis of horizontal leg power by sex and chronological age.

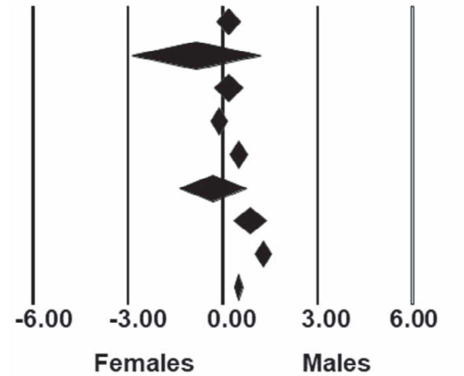
Tanner Stage	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
I–II	0.753	0.208	0.346	1.160	.000
III–IV	0.836	0.239	0.368	1.303	.000
V	1.371	0.284	0.813	1.928	.000
Overall	0.924	0.137	0.655	1.193	.000



Appendix Figure 14. Meta-analysis of horizontal leg power by sex and maturity level.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	0.202	0.197	-0.184	0.588	.305
9	-0.838	1.041	-2.878	1.202	.421
10	0.220	0.228	-0.226	0.666	.334
11	-0.097	0.131	-0.353	0.159	.459
12	0.537	0.138	0.267	0.806	.000
13	-0.302	0.539	-1.360	0.755	.575
14	0.882	0.265	0.362	1.402	.001
15	1.317	0.136	1.050	1.584	.000
Overall	0.497	0.066	0.367	0.626	.000

Std Diff in Means and 95% CI



Appendix Figure 15. Meta-analysis of vertical leg power by sex and chronological age.

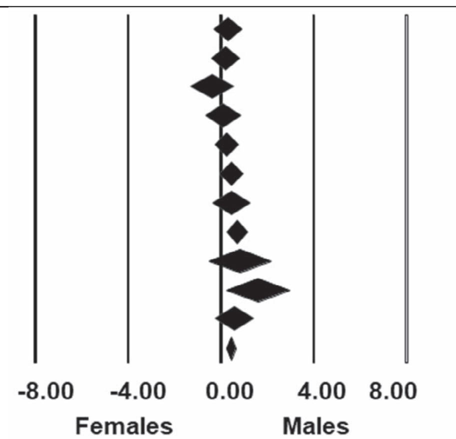
Maturity Status[a]	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
Pubertal	1.088	0.246	0.606	1.569	.000
Postpubertal	2.354	0.476	1.422	3.285	.000
Overall	1.354	0.218	0.927	1.782	.000

Std Diff in Mean and 95% CI

Appendix Figure 16. Meta-analysis of vertical leg power by sex and maturity level. [a] Defined by age from peak height velocity and Pubertal Maturation Observational Scale.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	0.328	0.300	-0.260	0.916	.275
9	0.220	0.301	-0.370	0.811	.465
10	-0.368	0.472	-1.293	0.556	.435
11	0.144	0.388	-0.616	0.904	.710
12	0.287	0.262	-0.227	0.802	.274
13	0.501	0.257	-0.004	1.005	.052
14	0.480	0.413	-0.329	1.290	.245
15	0.739	0.232	0.284	1.194	.001
16	0.841	0.680	-0.491	2.173	.216
17	1.594	0.692	0.237	2.951	.021
18	0.599	0.419	-0.222	1.419	.153
Overall	0.434	0.101	0.235	0.632	.000

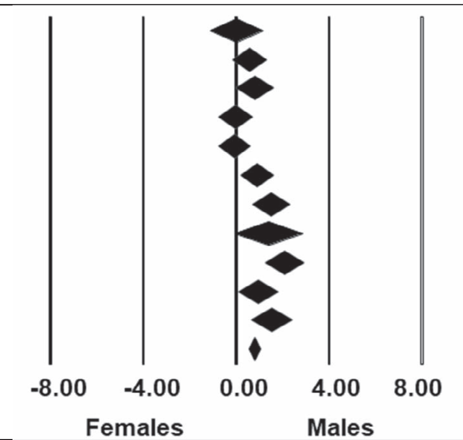
Std Diff in Means and 95% CI



Appendix Figure 17. Meta-analysis of anterior cruciate ligament size by sex and chronological age.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	0.013	0.576	-1.116	1.142	.982
9	0.600	0.374	-0.132	1.332	.108
10	0.846	0.411	0.040	1.652	.040
11	0.002	0.368	-0.720	0.724	.996
12	-0.040	0.346	-0.718	0.637	.907
13	0.936	0.351	0.247	1.624	.008
14	1.528	0.415	0.715	2.342	.000
15	1.406	0.742	-0.048	2.861	.058
16	2.112	0.416	1.297	2.928	.000
17	0.979	0.441	0.116	1.843	.026
18	1.585	0.445	0.713	2.457	.000
Overall	0.838	0.125	0.593	1.084	.000

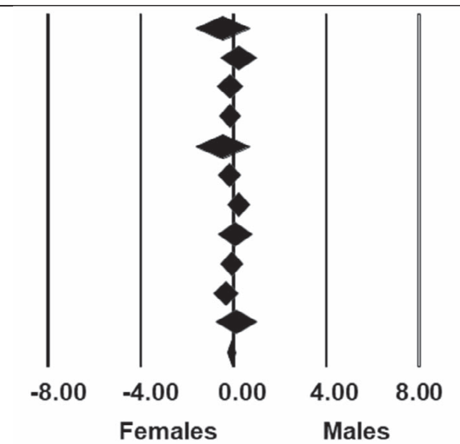
Std Diff in Means and 95% CI



Appendix Figure 18. Meta-analysis of absolute notch width by sex and chronological age.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	-0.441	0.597	-1.610	0.728	.460
9	0.251	0.391	-0.515	1.018	.521
10	-0.132	0.283	-0.687	0.422	.640
11	-0.117	0.232	-0.572	0.338	.613
12	-0.425	0.589	-1.580	0.730	.471
13	-0.133	0.240	-0.604	0.338	.581
14	0.263	0.249	-0.226	0.752	.292
15	0.083	0.372	-0.646	0.812	.823
16	-0.047	0.242	-0.521	0.428	.848
17	-0.289	0.264	-0.807	0.228	.274
18	0.155	0.445	-0.718	1.027	.728
Overall	-0.052	0.091	-0.231	0.126	.567

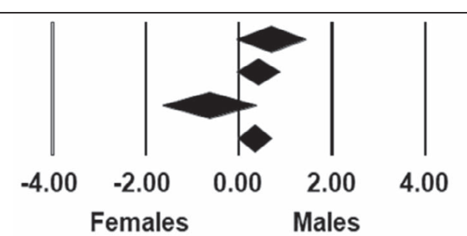
Std Diff in Means and 95% CI



Appendix Figure 19. Meta-analysis of notch width index by sex and chronological age.

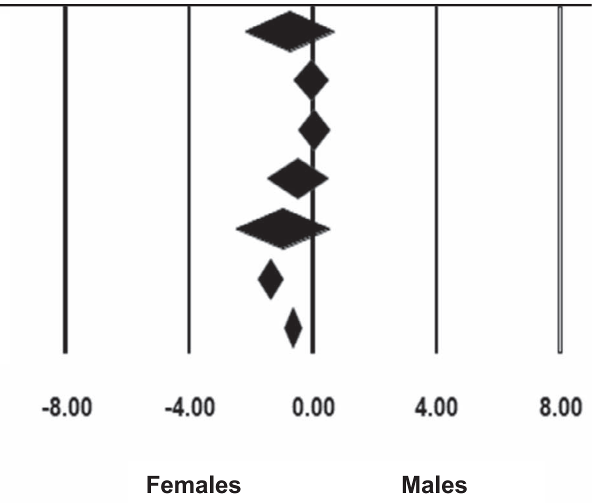
Tanner Stage	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
I	0.695	0.381	-0.053	1.442	.069
II–IV	0.435	0.242	-0.039	0.910	.072
V	-0.623	0.514	-1.631	0.384	.225
Overall	0.355	0.190	-0.017	0.727	.061

Std Diff in Mean and 95% CI



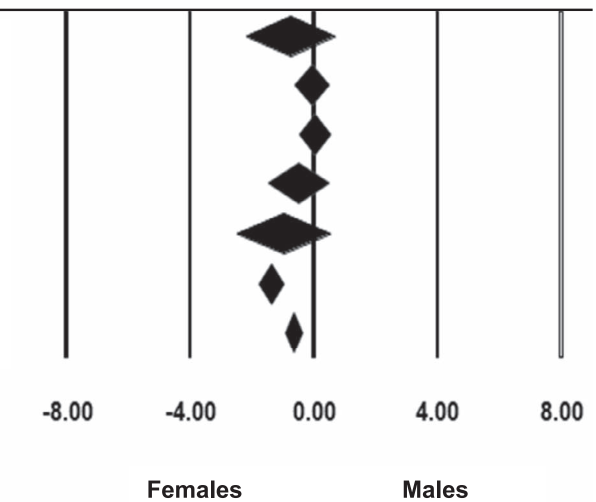
Appendix Figure 20. Meta-analysis of anterior knee laxity index by sex and maturity level.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
10.00	-0.715	0.733	-2.152	0.723	.330
11.00	-0.027	0.285	-0.586	0.532	.924
12.00	0.085	0.253	-0.411	0.581	.737
13.00	-0.457	0.503	-1.443	0.529	.364
14.00	-0.975	0.768	-2.480	0.531	.204
15.00	-1.321	0.204	-1.722	-0.920	.000
Overall	-0.596	0.130	-0.851	-0.342	.000



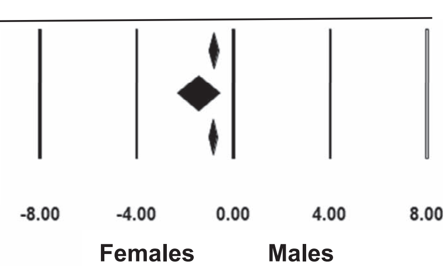
Appendix Figure 21. Meta-analysis of general joint laxity by sex and maturity level.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
10.00	-0.715	0.733	-2.152	0.723	.330
11.00	-0.027	0.285	-0.586	0.532	.924
12.00	0.085	0.253	-0.411	0.581	.737
13.00	-0.457	0.503	-1.443	0.529	.364
14.00	-0.975	0.768	-2.480	0.531	.204
15.00	-1.321	0.204	-1.722	-0.920	.000
Overall	-0.596	0.130	-0.851	-0.342	.000



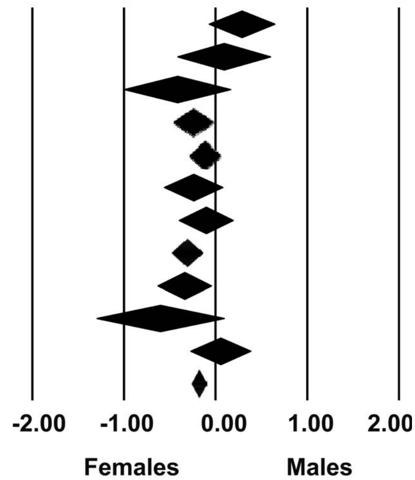
Appendix Figure 22. Meta-analysis of tibiofemoral angle by sex and chronological age.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
11.00	-0.801	0.094	-0.986	-0.617	.000
14.00	-1.424	0.446	-2.298	-0.550	.001
Overall	-0.828	0.092	-1.008	-0.647	.000



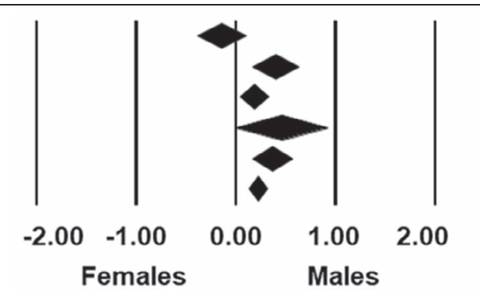
Appendix Figure 23. Meta-analysis of hamstrings flexibility by sex and chronological age.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
8	0.288	0.182	-0.069	0.645	.114
9	0.093	0.258	-0.413	0.598	.719
10	-0.415	0.295	-0.994	0.164	.160
11	-0.245	0.111	-0.462	-0.028	.027
12	-0.116	0.086	-0.284	0.053	.180
13	-0.241	0.161	-0.557	0.076	.136
14	-0.102	0.150	-0.395	0.192	.498
15	-0.313	0.085	-0.480	-0.145	.000
16	-0.337	0.148	-0.627	-0.048	.022
17	-0.602	0.354	-1.295	0.091	.089
18	0.055	0.167	-0.271	0.382	.740
Overall	-0.180	0.041	-0.262	-0.099	.000



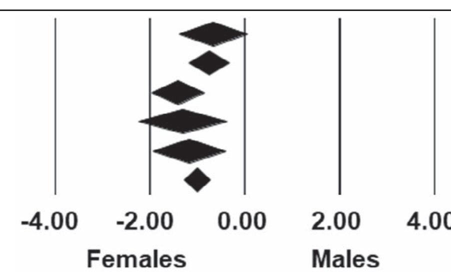
Appendix Figure 24. Meta-analysis of static balance by sex and chronological age.

Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
11	-0.133	0.127	-0.382	0.115	.293
12	0.415	0.119	0.182	0.647	.000
13	0.193	0.073	0.051	0.335	.008
14	0.468	0.236	0.007	0.930	.047
15	0.379	0.104	0.175	0.583	.000
Overall	0.234	0.048	0.140	0.328	.000



Appendix Figure 25. Meta-analysis of dynamic balance by sex and chronological age.

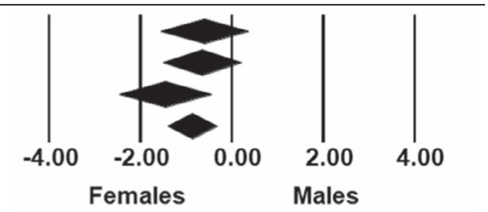
Age	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
10	-0.687	0.368	-1.410	0.035	.062
11	-0.761	0.216	-1.185	-0.337	.000
12	-1.416	0.280	-1.965	-0.867	.000
13	-1.322	0.471	-2.245	-0.398	.005
14	-1.185	0.391	-1.951	-0.419	.002
Overall	-1.010	0.138	-1.281	-0.740	.000



Appendix Figure 26. Meta-analysis of knee-abduction angles during dynamic activities (jumping, cutting) by sex and chronological age.

Maturity Status[a]	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
Prepubertal	-0.589	0.488	-1.545	0.366	.227
Pubertal	-0.648	0.438	-1.507	0.212	.140
Postpubertal	-1.440	0.514	-2.447	-0.433	.005
Overall	-0.857	0.275	-1.396	-0.317	.002

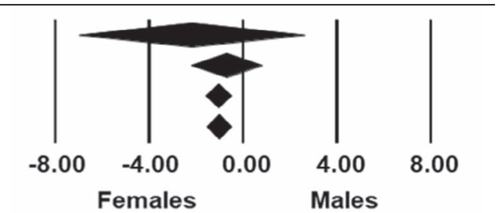
Std Diff in Mean and 95% CI



Appendix Figure 27. Meta-analysis of knee-abduction angles during dynamic activities (jumping, cutting) by sex and maturity level.
[a] Defined by either the Pubertal Maturation Observational Scale or Tanner stage.

Maturity Status[a]	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
Pre-Pub	-2.164	2.456	-6.977	2.650	.378
Pubertal	-0.687	0.771	-2.198	0.824	.373
Post-Pub	-1.010	0.284	-1.567	-0.454	.000
Overall	-0.985	0.265	-1.504	-0.466	.000

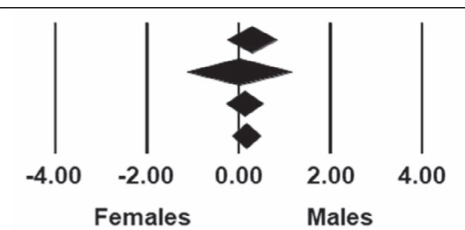
Std Diff in Mean and 95% CI



Appendix Figure 28. Meta-analysis of knee-abduction moment during dynamic activities (jumping, cutting) by sex and maturity level.
Abbreviations: post, postpubertal; pre, prepubertal; pub, pubertal.
[a] Defined by the Pubertal Maturation Observational Scale.

Maturity Status[a]	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
Prepubertal	0.315	0.275	-0.224	0.855	.252
Pubertal	0.024	0.588	-1.129	1.178	.967
Postpubertal	0.146	0.206	-0.258	0.549	.480
Overall	0.193	0.159	-0.118	0.505	.224

Std Diff in Mean and 95% CI

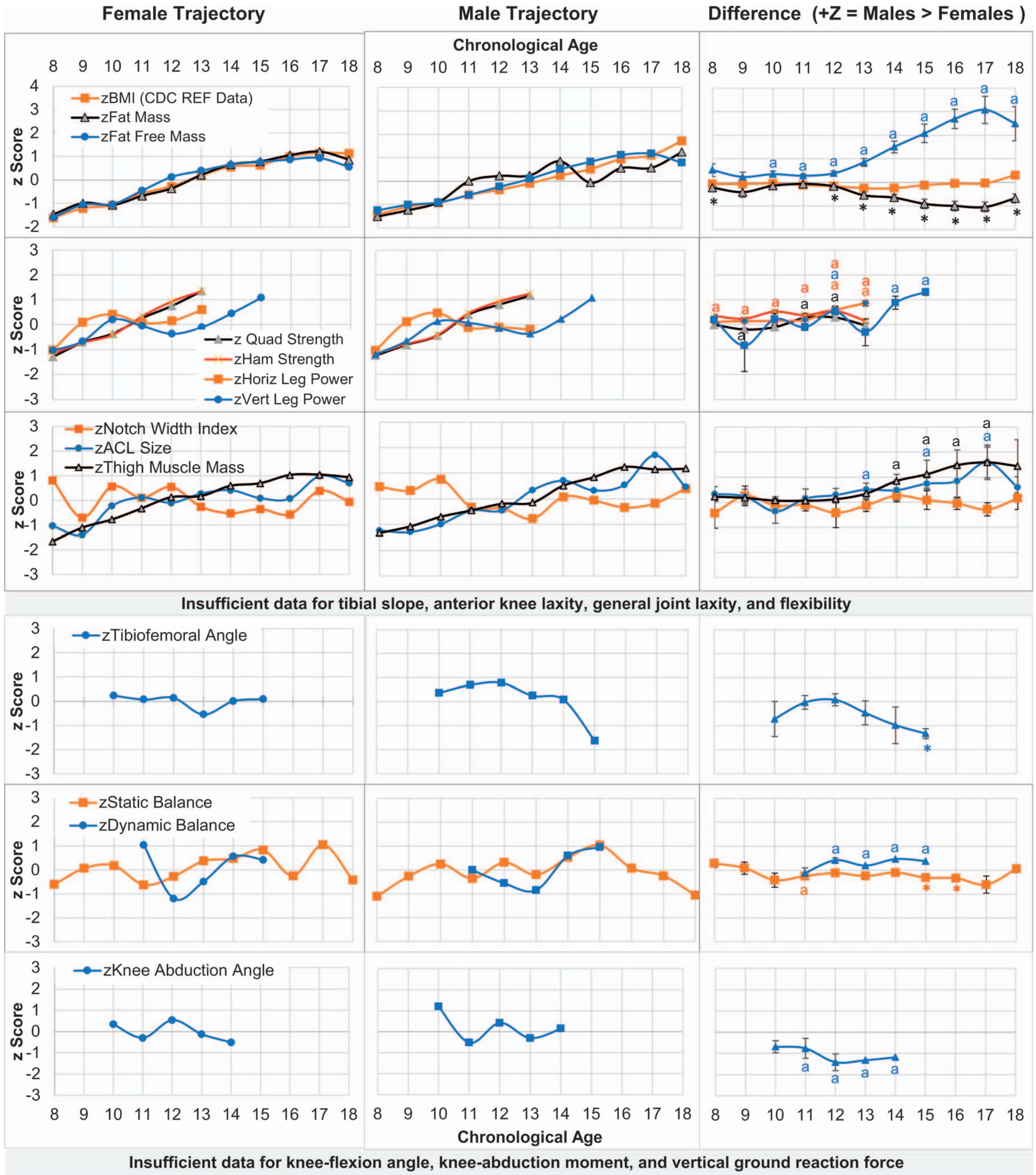


Appendix Figure 29. Meta-analysis of knee-flexion angles during dynamic activities (jumping, cutting) by sex and maturity level.
[a] Defined by the Pubertal Maturation Observational Scale or Tanner stage.

Maturity Status[a]	Std Diff in Means	SE	Lower Limit	Upper Limit	*P* Value
Prepubertal	0.327	0.199	-0.062	0.717	.100
Pubertal	0.095	0.324	-0.539	0.730	.768
Postpubertal	-0.129	0.417	-0.946	0.688	.757
Overall	0.208	0.157	-0.100	0.516	.185

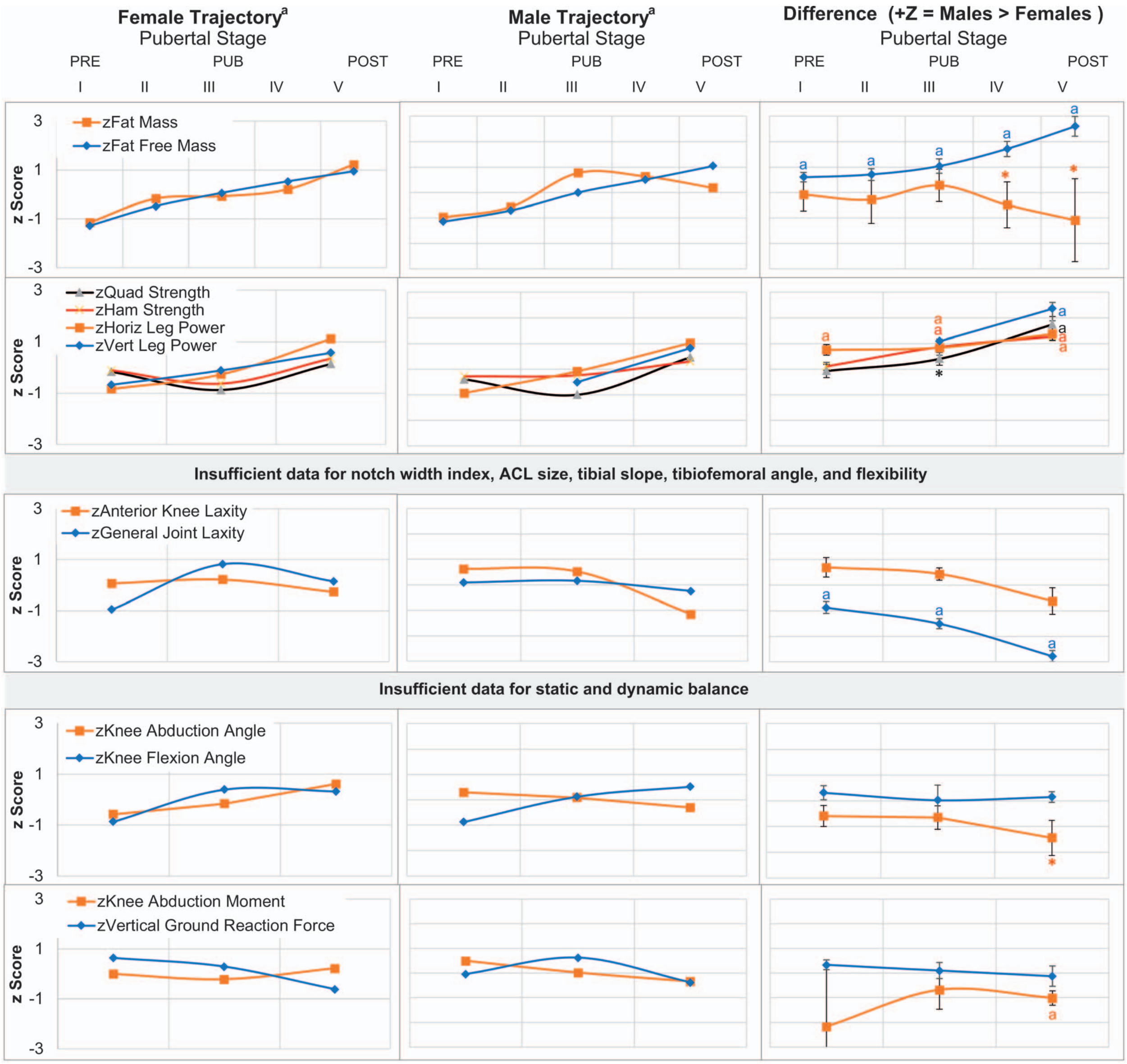
Std Diff in Mean and 95% CI

Appendix Figure 30. Meta-analysis of vertical ground reaction force during dynamic activities (jumping, cutting) by sex and maturity level.
[a] Defined by the Pubertal Maturation Observational Scale or Tanner stage.



*Each dotted line represents a single study with insufficient data for a meta-analysis.

Appendix Figure 31. Overall summary of male and female trajectories in physical risk factor development by chronological age (body mass index data obtained from https://www.cdc.gov/nchs/data/series/sr_11/sr11_246.pdf). Abbreviations: ACL, anterior cruciate ligament; BMI, body mass index.



Appendix Figure 32. Overall summary of male and female trajectories in physical risk factor development by maturity level. Abbreviation: ACL, anterior cruciate ligament.

Appendix C

Appendix Table 1. Included Studies for Percentage of Body Fat **Continued on Next Page**

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Chronological age				
Escobar-Cardozo et al[41]: 2016 (XS)[a]	3324/2526	General population, 9–18 y	%BF (BIA)	G: ↑ steadily (1.5%) 9–17.9 y B: ↓ 5.5% 9–17.9 y; ↓ to 14 y, then plateaued Sex × age: G > B at all ages; G 35% > B at 17 y
Guo et al[45]: 1997 (L)	114/130	General population, 8–20 y	%BF (hydrostatic weighing)	G: ↑ 5% 8–18 y B: ↓ 3.4% 8–18 y Sex × age: G > B at all ages
Kang et al[50]: 2016 (XS)[a]	578/632	General population, 10–19 y	%BF (DXA)	G: ↑ rapidly 10–15 y, then plateaued B: ↓ 10–15 y, then plateaued Sex × age: NR
Laffaye et al[52]: 2016 (XS)	147/148	Nonathletes, 11–20 y	%BF (BIA)	G: 11–12 y = 13–14 y < 15–16 y < 17–18 y B: 11–12 y > 13–14 y < 15–16 y > 17–18 y Sex × age: age-related ↑ in G; no linear trend in B
Landgraff and Hallén[55]: 2020 (L)	29/47	Athletes, 12, 13, 15 y	kg (BIA)	G: ↑ ∼4% 12–15 y B: ↓ 1%–5% 12–15 y Sex × age: G > B at 13–15 y
Lundgren et al[53]: 2011 (XS)[a]	190/246	General population, 6–12 y	% (DXA)	G: ↑ 3.1% 8–12 y B: ↑ 5.9% 8–12 y Sex × age: NR, used in MA
McCarthy et al[67]: 2006 (XS)	869/1116	General population, 5–18 y	%BF (BIA); 50th percentile	G: gradual ↑ 21.2%–24.6% 8–18 y B: 15%–18% over entire age range with peak at 11 y, then ↓ Sex × age: G similar to B until 10 y; G 60% > B at 18 y
Mølgaard and Michaelsen[59]: 1998 (MX)[b]	201/142	General population, 5–19 y	kg (DXA)	G: ↑ 2.7% from 7–17 y B: ↓ 7.7% from 7–17 y Sex × age: B < G throughout age range
Mueller et al[69]: 2004 (MX)[a]	2229/2264[c]	General population, non-Black, 8–18 y	%BF (BIA); 50th percentile	G: gradual 3.3% ↑ 11.5–17.5 y B: gradual 6.9% ↓ 9.5–17.5 y Sex × age: NR, reference values used in MA
Mueller et al[69]: 2004 (MX)[a]	500/439[c]	General population, Black, 8–15 y	%BF (BIA); 50th percentile	G: ↑ 2.9% 8.5–14.5 y B: ↑ 4.2% 8.5–11.5 y then ↓ 4.2% 11.5–14.5 y Sex × age: NR, reference values used in MA
Tabin et al[62]: 1985 (XS)	30/30	Physically active, 10–15 y	%BF (skinfolds) TS I vs IV/V	G: ↑ 3.2% pre- to postpubescent B: No change Sex × age: not statistically compared
Temfemo et al[63]: 2009 (XS)[a]	239/240	General population, 11–16 y	dm^3 (anthropometry); leg lean mass	G: ↑ 5.3% 11–16 y B: ↑ 2.9% 11–16 y Sex × age: G > B all ages
van der Sluis et al[64]: 2002 (MX)[b]	370/372	Not specified, 4–25 y	Ln% (DXA); mean by age based on fitted line from graph	G: ↑ linearly with age B: remained constant 8–18 y Sex × age: NR
Wang et al[65]: 2007 (XS)	1165/1328	General population, 6–18 y	%BF (DXA)	G: ↑ 8–12 y, then accelerated 12–18 y B: ↑ 6–12 y, ↓ thereafter Sex × age: substantial divergence from 12 y on
Tanner stage (I, PRE; II–IV, PUB; V, POST)				
Bitar et al[35]: 1999 (XS)	39/44	General population, 12–16 y	%BF (BIA)	G: no difference among pubertal stages B: PRE < PUB < POST; overall 49% ↓ Sex × age: G > B at POST only

Appendix Table 1. Continued From Previous Page

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Boot et al[36]: 1997 (XS)[a,c]	234/169	General population, 4–20 y	%BF (DXA)	G: ↑ with each TS ↑ B: ↑ I–III, ↓ III–V Sex × TS: G > B at all stages
Frignani et al[43]: 2015 (XS)	2556/2130	General population, 10–15 y	kg/m² (anthropometrics) TS I, II–IV, V	G: I < II–IV < V B: I = II–IV = V Sex × TS: B < G at II–IV, V
Fukunaga et al[44]: 2013 (XS)[a]	207/245	After-school sports, 12–15 y	cm (US); muscle thickness, anterior thigh	G, B: no change with TS Sex × age: NR, data used in MA
Janz et al[48]: 1993 (XS)[a]	55/67	General population, 9–15.1 y	%BF (skinfolds)	G: ↑ I–II, then plateaued III–V B: ↑ I–II, then ↓ II–V Sex × TS: NR, data used in MA
Mihalopoulos et al[58]: 2010 (MX)[a,b]	337/341	General population, 8–18 y	%BF (BIA)	G: no change I–V B: ↓ I–V Sex × TS: NR, overall median = 18.8% (B), 24.3% (G)
Mota et al[60]: 2002 (XS)[a]	240/254	General population, 8–16 y	%BF (skinfolds)	G: ↑ 3.4% I–V B: ↑ 2% I–II, then ↓ 8.7% II–V Sex × TS: NR, data used in MA
Rico et al[61]: 1993 (XS)[a]	68/86	Not specified, 5–18 y	kg (DXA)	G: I, II < IV, V; ↑ 192% I–V B: I, II < IV, V; ↑ 100% I–V Sex × TS: B = G at I, II; G > B at IV, V

Abbreviations: %BF, percentage of body fat; B, boys; BIA, bioelectrical impedance; dm³, leg muscle volume; DXA, dual-energy x-ray absorptiometry; G, girls; L, longitudinal design; MA, meta-analysis; MX, mixed cross-sectional and longitudinal design; NR, not reported; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; US, ultrasound; XS, cross-sectional design; %ln, percentage of lean tissue.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).
[b] Data extracted using WebPlotDigitizer[28] (Automeris LLC).
[c] Number reflects the total observations if the design was mixed cross-sectional and longitudinal.

Appendix Table 2. Included Studies for Fat Mass (FM) and Fat Mass Index (FMI) Continued on Next Page

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Chronological age				
Alvim et al[33]: 2020 (XS)[a,b]	324/417	General population, 6–19 y	FM; kg (BIA)	G: ↑ 8.4 kg steadily 8–16 y of age B: ↑ 4.0 kg 8–11 y of age, then plateaued Sex × age: similar until 12 y, then G > B (G continued to ↑, B ↓ and stabilized)
Alwis et al[34]: 2010 (XS)[a]	499/539	General population, 6–30 y	FM; kg (DXA)	G: ↑ steadily 8–18 y B: ↑ 8–14 y, then ↓ Sex × age: G > B at all ages; different ↑s starting at 12 y (early puberty) when G ↑ > B through age 18
Foley et al[42]: 2009 (L)	67/116	General population, 8 & 16 y	FM; kg (DXA)	G ↑ 222% 8–16 y B: ↑ 172% 8–16 y Sex × age: NR
Guo et al[45]: 1997 (L)	114/130	General population, 8–20 y	FM; kg (hydrostatic weighing)	G: ↑ 137% 8–18 y B: ↑ 69% 8–16 y Sex × age: G > B at all ages
Kang et al[50]: 2016 (XS)[a]	578/632	General population, 10–19 y	FM; kg (DXA)	G: ↑ rapidly 10–15 y, then plateaued B: ↑ more gradually through 18 y Sex × age: NR
Kang et al[50]: 2016 (XS)[a]	578/632	General population, 10–19 y	FMI; kg/m² (DXA)	G: ↑ 10–15 y, then plateaued B: ↓ 10–15 y, then slowly ↑ to 18 y Sex × age: NR
Kim et al[51]: 2016 (XS)[a]	895/1024	General population, 10–18 y	FM; kg (DXA)	G: ↑ 69% 10–17 y, then stabilized B: ↑ 25% to 14 y, then stabilized Sex × age: NR

Appendix Table 2. Continued From Previous Page

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Kim et al[51]: 2016 (XS)[a]	895/1024	General population, 10–18 y	FMI; kg/m^2 (DXA)	G: rapidly ↑ 10–14 y, then stabilized at higher level B: peaked at 11 y, then ↓ to 15 y and stabilized at lower level Sex × age: NR
McCarthy et al[67]: 2013 (XS)	869/1116	General population, 5–18 y	FM; kg (BIA)	G: ↑ 79% 8–12 y B: ↑ 65% 8–18 y Sex × age: NR
Mølgaard and Michaelsen[59]: 1998 (MX)[b]	201/142	General population, 5–19 y	FM; kg (DXA)	G: ↑ 115% 7–17 y B: ↑ 56% 7–17 y (not significant) Sex × age: near-consistent ↑ in G, no change in B
Mueller et al[69]: 2004 (MX)[a]	2229/2264[d]	General population, non-Black, 8–18 y	FM; kg (BIA); 50th percentile	G: ↑ 8.5 kg 8.5–17.5 y B: ↑ gradually 3.8 kg 8.5–14.5 y, then plateaued and ↓ Sex × age: NR, reference values used in MA
Mueller et al[69]: 2004 (MX)[a]	500/439[d]	General population, non-Black, 8–18 y	FM; kg (BIA); 50th percentile	G: ↑ 6.2 kg 8.5–13.5 y B: ↑ 3.4 kg 8.5–14.5 y Sex × age: NR, data used in MA
Wang et al[65]: 2007 (XS)[b]	1165/1328	General population, Black, 8–15 y	FM; kg (DXA)	G: ↑ throughout age range, accelerated after age 12 B: ↑ throughout age range Sex × age: diverged ~12 y when FM ↑ more rapidly in G vs B
Weber et al[66]: 2013 (XS)	3766/5195	General population, 8–18 y	FMI; kg/m^2 (DXA); based on median values	G: ↑ 57% 8–18 y B: ↑ 9% 8–18 y Sex × age: NR
Zanchetta et al[70]: 1995 (XS)[a]	332/256	General population, 2–20 y	FM; kg (DXA)	G: ↑ 13 kg (70%) 8–14 y, then stabilized B: ↑ 31 kg (147%) 8–18 y Sex × age: NR, data used in MA
Tanner stage (I, PRE; II–IV, PUB; V, POST)				
Alvim et al[33]: 2020 (XS)[c]	324/417	General population, 6–19 y	FM; kg (BIA)	G: ↑ 12.6 kg PRE to POST B: ↑ 2.5 kg PRE to POST Sex × TS: G > B in PUB and POST
Bitar et al[35]: 1999 (XS)	39/44	General population, 12–16 y	FM; kg (BIA)	G: PRE = PUB < POST B: no difference by stage Sex × TS: G > B at POST only
Boot et al[36]: 1997 (XS)[a]	234/169	General population, 4–20 y	FM; kg (DXA)	G: ↑ I–II and IV–V B: ↑ I–II, then stabilized Sex × TS: NR
Clark et al[37]: 2009 (XS)	1810/1585	General population, 9.9 y	FM; kg (DXA)	G: ↑ 4.2% I–II B: ↑ 0.7% I–II Sex × TS: NR, data used in MA
Csakvary et al[38]: 2012 (XS)	133/104	General population, 7–16 y	FMI; kg/m^2 (DXA) TS I–IV	G: ↑ PRE to PUB B: no change Sex × TS: G = B at I, II; G > B at III, IV
Frignani et al[43]: 2015 (XS)	2556/2130	General population, 10–15 y	FMI; kg/m^2 (anthropometrics) TS I, II–IV, V	G: I < II–IV < V B: I > II–IV = V Sex × TS: B < G at II–IV, V
Horlick et al[46]: 2000 (XS)[a]	49/53	General population, 6–19 y	FM; kg (DXA)	G: ↑ I–II, ~ stable II–IV, then ↑ IV–V; peak V B: ↑ I/II–III/IV; ↓ IV–V; peak 3 Sex × TS: NR
Hui et al[47]: 2003 (XS)[a]	117/115	General population, 4–16 y	FM; kg (DXA)	G: I < II & III < IV & V; 287% ↑ I–IV/V B: I < II & III > IV, V; 76% ↑ I–II/III Sex × TS: NR, included in MA, overall G = B

Abbreviations: B, boys; BIA, bioelectrical impedance; DXA, dual-energy x-ray absorptiometry; G, girls; L, longitudinal design; MA, meta-analysis; MX, mixed cross-sectional/longitudinal design; NR, not reported; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).
[b] Data extracted using WebPlotDigitizer[28] (Automeris LLC).
[c] Received raw data from authors.
[d] Number reflects the total observations if the design was mixed cross-sectional and longitudinal.

Appendix Table 3. Included Studies for Fat-Free Mass (FFM) and Fat-Free Mass Index (FFMI) Continued on Next Page

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Chronological age				
Alvim et al[33]: 2020 (XS)[a]	324/417	General population, 6–19 y	FFM; kg (BIA)	G: ↑ 10.0 kg 8–16 y B: ↑ 17.3 kg 8–16 y Sex × age: similar until 12.5 y, then B > G (G stabilized, B continued to ↑)
Alwis et al[34]: 2010 (XS)[a]	499/539	General population, 6–30 y	FFM; kg (DXA)	G: ↑ 8–14 y, then more gradual and plateaued to 18 y B: ↑ 8–18 y, with more rapid ↑ 12–14 y Sex × age: B = G in ↑ up to 10–11 y; rapid ↑ 1–2 y earlier G vs B; peaks in G at 17 y, B continued to ↑ 18 y on
Foley et al[42]: 2009 (L)	67/116	General population, 8 & 16 y	FFM; kg (DXA)	G: ↑ 107% 8–16 y B: ↑ 156 % 8–16 y Sex × age: NR
Guo et al[45]: 1997 (L)	114/130	General population, 8–20 y	FFM; kg (hydrostatic weighing)	G: ↑ 134% 8–18 y B: ↑ 82% 8–18 y Sex × age: B > G 14 y on
Kang et al[50]: 2016 (XS)[a]	578/632	General population, 10–19 y	FFM; kg (DXA)	G: ↑ 10–15 y, then plateaued 16–17 y B: ↑ 10–18 y Sex × age: B > G 10 y on
Kang et al[50]: 2016 (XS)[a]	578/632	General population, 10–18 y	FFMI; kg/m^2 (DXA)	G: ↑ rapidly 10–15 y, then ↑ more gradually up to 18 y B: ↑ rapidly 10–15 y, then ↑ more gradually up to 18 y Sex × age: B > G 10 y on
Kim et al[51]: 2016 (XS)[a]	895/1024	General population, 10–18 y	FFM; kg (DXA)	G: ↑ 44% 10–17 y, then plateaued B: ↑ 89.5% 10–17 y, then plateaued Sex × age: NR
Kim et al[51]: 2016 (XS)[a]	895/1024	General population, 10–18 y	FFMI; kg/m^2 (DXA)	G: ↑ from 10–13 y, then stabilized B: lowest at 10 y and ↑ throughout adolescence Sex × age: NR
Landgraff and Hallén[55]: 2020 (L)	29/47	Athletes, 12, 13, 15 y	FFM; kg (BIA)	G: ↑ 27%–37% 12–15 y B: ↑ 48%–57% 12–15 y Sex × age: G > B at 13 and 15 y
Lundgren et al[53]: 2011 (XS)[a]	190/246	General population, 6–12 y	FFM; kg (DXA)	G: ↑ 43% 8–12 y B: ↑ 32% 8–12 y Sex × age: NR, used in MA
Marwaha et al[54]: 2017 (XS)[a,b]	577/826	General population, 5–18 y	FFM; kg (DXA)	G: ↑ up to 14 y, then plateaued[e] B: ↑ 8–16 y, then plateaued[e] Sex × age: age associated with ↑ greater in B (∼25 kg; 130%) than G (∼14 kg; 83%) from 8–18 y
McCarthy et al[68]: 2013 (XS)	869/1116	General population, 5–18 y	FFM; kg (BIA)	G: ↑ 72% 8–12 y B: ↑ 124% 8–18 y Sex × age: NR
Mølgaard and Michaelsen[59]: 1998 (MX)[c]	201/142	General population, 5–19 y	FFM; kg (DXA)	G: ↑ 90% 7–15 y, then plateaued B: ↑ 159% 7–17 y Sex × age: earlier flattening of age-related change in G vs B
Mueller et al[69]: 2004 (MX)[a]	2229/2264[d]	General population, non-Black, 8–18 y	FFM; kg (BIA); 50th percentile	G: ↑ 22.6 kg 8.5–16.5 y B: ↑ 35.3 kg 8.5–17.5 y Sex × age: NR, reference values used in MA
Mueller et al[69]: 2004 (MX)[a]	500/439[d]	General population, Black, 8–15 y	FFM; kg (BIA); 50th percentile	G: ↑ 17.2 kg 8.5–14.5 y B: ↑ 22.4 kg 8.5–14.5 y Sex × age: NR, reference values used in MA
Temfemo et al[63]: 2009 (XS)[a]	239/240	General population, 11–16 y	FFM; dm^3 (anthropometry); lean mass, leg	G: ↑ 26% 11–16 y B: ↑ 45% 11–16 y Sex × age: B = G 11–12 y; B > G 13 y and on
van der Sluis et al[64]: 2002 (MX)	370/272[d]	Not specified, 4–25 y	FFM; kg (DXA)	G: ↑ with age B: ↑ with age Sex × age: ↑ B > G; peaked age 13 y in G and 15 y in B; maximum rate of change at 11.5 y in G, 14.2 y in B

Appendix Table 3. Continued From Previous Page

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Weber et al[66]: 2013 (XS)	3766/5195	General population, 8–18 y	FFMI; kg/m^2 (DXA)	G: age-related ↑ (3.4 kg/m^2; 30%) 8–18 y; greatest ↑ 8–12 y B: age-related ↑ (5.6 kg/m^2; 45%) 8–18 y; greatest ↑ 11–16 y Sex × age: age-related ↑ steeper in B vs G; B > G after 13 y
Zanchetta et al[70]: 1995 (XS)[a]	332/256	General population, 2–20 y	FFM; kg (DXA)	G: ↑ 17 kg (247%) 8–16 y, then stabilized B: ↑ 6.8 kg (50%) 8–14 y, then stabilized until ↑ 18+ Sex × age: NR, data used in MA
Tanner stage (I, PRE; II–IV, PUB; V, POST)				
Alvim et al[33]: 2020 (XS)[b]	324/417	General population, 6–19 y	FFM; kg (BIA)	G: ↑ 11 kg PRE to POST B: ↑ 15.1 kg PRE to POST Sex × TS: B > G all pubertal stages with difference ↑ POST
Bitar et al[35]: 1999 (XS)	39/44	General population, 12–16 y	FFM; kg (BIA)	G: PRE < PUB < POST; 59% ↑ PRE to POST B: PRE < PUB = POST; 69% ↑ PRE to POST Sex × age: G > B at PUB and POST
Boot et al[36]: 1997 (XS)[a]	234/169	General population, 4–20 y	FFM; kg (DXA)	G: ↑ I–IV, then plateaued B: ↑ with increasing TS Sex × TS: ↑ greater in B vs G after 2
Clark et al[37]: 2009 (XS)	1810/1585	General population, 9.9 y	FFM; kg (DXA)	G: ↑ 2.0 kg I–II B: ↑ 0.6 kg I–II Sex × TS: NR, data used in MA
Csakary et al[38]: 2012 (XS)	133/104	General population, 7–16 y	FFMI; kg/m^2 (DXA) TS I–IV	G: ↑ 12% PRE (I) to PUB (II–IV) B: ↑ 16% PRE (I) to PUB (II–IV) Sex × TS: B > G at I, III, IV
Fukunaga et al[44]: 2013 (XS)[a]	207/245	After-school sports, 12–15 y	FFM; cm (US); muscle thickness, anterior thigh	G: No change by TS B: I, II < II–V; III < V; 31% ↑ I–V Sex × age: NR
Horlick et al[46]: 2000 (XS)[a]	49/53	General population, 6–19 y	FFM; kg (DXA)	G: ↑ with each pubertal stage; ↑ 22.6 kg (101%) I–V B: ↑ with each pubertal stage; ↑ 31.2 kg (120%) I–V Sex × TS: NR, data used in MA
Hui et al[47]: 2003 (XS)[a]	117/115	General population, 4–16 y	FFM; kg (DXA)	G: I < II & III < IV & V; ↑ 92% I–IV/V B: I < II & III < IV & V; ↑ 94% I–IV/V Sex × TS: NR, used in MA; overall B > G
Marwaha et al[54]: 2017 (XS)[a]	577/826	General population, 5–18 y	FFM; kg (DXA)	G: ↑ with each pubertal stage; 12.8 kg (73%) ↑ from II–V B: ↑ with each pubertal stage; 22.8 kg (100%) ↑ from II–V Sex × TS: ↑ each pubertal stage B, G; B > G at each pubertal stage; 57% (B) and 60% (G) of ↑ occurred between I and III
Rico et al[61]: 1993 (XS)[a]	68/86	Not specified, 5–18 y	FFM; kg (DXA)	G: I = II < IV < V; ↑ 59% I–V B: I = II < IV < V; ↑ 117% I–V Sex × TS: B = G at I, II; B > G at IV, V

Abbreviations: B, boys; BIA, bioelectrical impedance; dm^3, leg muscle volume; DXA, dual-energy x-ray absorptiometry; G, girls; L, longitudinal design; MA, meta-analysis; MX, mixed cross-sectional/longitudinal design; NR, not reported; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; US, ultrasound; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).
[b] Received raw data from authors.
[c] Data extracted using WebPlotDigitizer[28] (Atomeris LLC).
[d] Number reflects the total observations if the design was mixed cross-sectional and longitudinal.
[e] Results based on raw data by each year of age provided by the author.

Appendix Table 4. Included Studies for Leg or Thigh Muscle Mass

Authors: Year (Design)[a]	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Chronological age				
Alwis et al[34]: 2010 (XS)[b]	499/539	General population, 6–30 y	kg (DXA); lean mass, leg	G: ↑ 8–17 y, more rapid ↑ 10–12 y B: ↑ 8–18 y, more rapid ↑ 12–14 y Sex × age: B = G up to 10–11 y; rapid ↑ 1–2 y earlier G vs B; peaked in G at 17 y, continued to ↑ B well beyond 18 y
De Ste Croix et al[39]: 2001 (L)	19/15	General population, 10–12 y	Liter (MRI); muscle volume, thigh	G: ↑ 25% 9.9–11.6 y B: ↑ 27% 10.2–11.9 y Sex × age: NR; all but 2 classified as I at first time point; at time point 2, G more mature than B
Doré et al[40]: 2005 (XS)[c]	583/530	General population, 8–20 y	Liter (anthropometry); lean volume, leg	G: ↑ 112% 8–18 y B: ↑ 175% 8–18 y Sex × age: B = G up to 14 y; B > G after 14 y
Kanehisa et al[49]: 1994 (XS)[d]	138/166	General population, 8–18 y	cm^2 (US); cross-sectional area, thigh muscle	G: ↑ 79% 8–18 y B: ↑ 108% 8–18 y Sex × age: ↑ with age similar in B and G up to 13 y, then B ↑ > G from 13–18 y; B > G from 11 y on
Lundgren et al[53]: 2011 (XS)[b]	190/246	General population, 6–12 y	kg (DXA)	G: ↑ 55% 8–12 y B: ↑ 44% 8–12 y Sex × age: NR, data used in MA
Martin et al[56]: 2004 (MX)[b]	100/109	General population, 8–17 y	Liter (anthropometry); lean volume, leg	G: ↑ 157% 8–17 y; plateaued at 14 y B: ↑ 261% 8–17 y; plateaued at 16 y Sex × age: NR, data used in MA
Marwaha et al[54]: 2017 (XS)[b,c]	577/826	General population, 5–18 y	kg (DXA); lean mass, leg	G: ↑ up to 13 y, stable 13–15 y, then ↑ 15–17 y B: ↑ up to 16 y, then plateaued Sex × age: age associated with ↑ greater in B (9.4 kg; 138%) than G (5.2 kg; 100%) 8–18 y[e]
Temfemo et al[63]: 2009 (XS)[b]	239/240	General population, 11–16 y	dm^3 (anthropometry); leg lean mass	G: ↑ 36% 11–16 y B: ↑ 64% 11–16 y Sex × age: B = G 11–13 y; B > G 14–16 y
Tanner stage (I, PRE; II–IV, PUB; V, POST)				
Fukunaga et al[44]: 2013 (XS)	207/245	After-school sports, 12–15 y	cm (US); muscle thickness, anterior thigh	G: II < I, IV, V (no ↑ with maturation) B: II < IV, V (12% ↑) Sex × age: NR
Marwaha et al[54]: 2017 (XS)	577/826	General population, 5–18 y	kg (DXA); lean mass, leg	G: ↑ each pubertal stage; ↑ 4.92 kg (92%) I–V B: ↑ each pubertal stage; ↑ 8.2 kg (114%) I–V Age × TS: steeper ↑ B vs G; largest % ↑ at II in G and III in B

Abbreviations: B, boys; dm^3, leg muscle volume; DXA, dual-energy x-ray absorptiometry; G, girls; L, longitudinal design; MA, meta-analysis; MRI, magnetic resonance imaging; MX, mixed cross-sectional/longitudinal design; NR, not reported; TS, Tanner stage; US, ultrasound; XS, cross-sectional design.

[a] If the design was MX, the number reflects the total observations.
[b] Used in meta-analysis and infographic (see Appendices B.31 and B.32).
[c] Received raw data from authors.
[d] Data extracted using WebPlotDigitizer[28] (Atomeris, LLC).
[e] Results based on raw data by each year of age provided by the author.

Appendix Table 5. Included Studies for Knee-Extensor Strength

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Age				
Lundgren et al[53]: 2011 (XS)[a]	190/246	General population, 6–12 y; TS I–II	Nm (concentric, isokinetic 60°/s)	G: linear ↑ 167% B: linear ↑ 192% Sex × age: No interaction
Holm and Vøllestad[76]: 2008 (XS)[a]	184/184	General population, 7–12 y	Nm (concentric, isokinetic 60°/s)	G: linear ↑ 154% B: linear ↑ 149% Sex × age: no interaction
De Ste Croix et al[72]: 2002 (L)[a]	21/20	General population, 10–14 y	Nm (concentric, isokinetic 0.52 rad °/s)	G: linear ↑ 89% B: linear ↑ 87% Sex × age: no interaction
Wiggin et al[79]: 2006 (XS)[a]	2030/1557	General population, 6–13 y	Nm (concentric, isokinetic 60, 120°/s)	G: linear ↑ 244% B: linear ↑ 274% Sex × age: no difference until age 12 when B > G
Ervin et al[75]: 2014 (XS)[a]	617/607	General population, 6–15 y	kg (isometric, HHD)	G: linear ↑ 161% B: linear ↑ 286% Sex × age: B > G at 15 y
Sexual maturation				
Ahmad et al[102]: 2006 (XS)[a]	53/70	Athletes G: premenarche or postmenarche B: mature ≥ 14 y; immature ≤ 13 y	kg (isometric, HHD)	G: ↑ 44% immature to mature B: ↑ 148% immature to mature Sex × maturation: 3× greater ↑ with maturity in B vs G
DiStefano et al[74]: 2015 (XS)[a]	54/59	Youth athletes, PMOS PRE vs PUB vs POST	$kg \cdot kg^{-1} \cdot m^{-1}$ (isometric, HHD)	G: ↓ between PRE and POST by 24% B: no change Sex × maturation status: PRE G > PRE B and POST G
Pletcher et al[77]: 2021 (XS)[a]	78/82	Athletes, TS I vs IV	Nm (concentric, isokinetic 60°/s)	G: ↑ 108% B: ↑ 175% Sex × maturation status: B > G at TS IV
Dipla et al[73]: 2009 (XS)[a]	30/30	Physically active B: TS II, IV, V G: TS II, IV/V, V	Nm (concentric, isokinetic 120°/s)	G: ↑ more between TS II and IV/V by 63% B: ↑ more between TS II and IV by 163% Sex × maturation status: B > G at TS IV and V
Ramos et al[78]: 1998 (XS)[a]	27/30	General population, 11–17 y G: TS III, IV/V, V B: TS II, IV, V	Nm·kg (concentric, isokinetic 60°/s)	G: no change B: ↑ linearly by 28% Sex × maturation status: B > G at TS V

Abbreviations: B, boys; G, girls; HHD, handheld dynamometer; L, longitudinal design; Nm, Newton meters; PMOS, Pubertal Maturation Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

Appendix Table 6. Included Studies for Knee-Flexor Strength

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Age				
Lundgren et al[53]: 2011 (XS)[a]	190/246	General population, 6–12 y, TS I–II	Nm (concentric, isokinetic 60°/s)	G: linear ↑ 162% B: linear ↑ 170% Sex × age: B > G at 8 y only
Holm and Vøllestad[76]: 2008 (XS)[a]	184/184	General population, 7–12 y	Nm (concentric, isokinetic 60°/s)	G: linear ↑ 148% B: linear ↑ 155% Sex × age: B > G at 12 y
De Ste Croix et al[72]: 2002 (L)[a]	21/20	General population, 10–14 y	Nm (concentric, isokinetic 0.52 rad °/s)	G: ↑ more at early and later time points than mid time point; overall ↑ of 81% B: linear ↑ 73% Sex × age: no interaction
Wiggin et al[79]: 2006 (XS)[a]	2030/1557	General population, 6–13 y	Nm (concentric, isokinetic 60, 120°/s)	G: linear ↑ 361% B: linear ↑ 405% Sex × age: B > G by 12 y
Sexual maturation				
Ahmad et al[102]: 2006 (XS)[a]	53/70	Athletes G: premenarche or postmenarche B: mature ≥ 14 y; immature ≤ 13 y	kg (isometric, HHD)	G: ↑ 27% immature to mature B: ↑ 179% immature to mature Sex × maturation: ↑ with maturity B > G
DiStefano et al[74]: 2015 (XS)[a]	54/59	Youth athletes, PMOS PRE vs PUB vs POST	$kg \cdot kg^{-1} \cdot m^{-1}$ (isometric, HHD)	G: ↓ linearly 33% B: ↓ linearly 30% Sex × maturation: no interaction
Pletcher et al[77]: 2021 (XS)[a]	78/82	Athletes, TS I vs IV	Nm (concentric, isokinetic 60°/s)	G: ↑ 122% B: ↑ 197% Sex × maturation: B > G at TS IV
Dipla et al[73]: 2009 (XS)[a]	30/30	Physically active G: TS II, IV/V, V B: TS II, IV, V	Nm (concentric, isokinetic 120°/s)	G: ↑ linearly 63% B: ↑ linearly 161% Sex × maturation: B > G at TS IV and V

Abbreviations: B, boys; G, girls; L, longitudinal design; PMOS, Pubertal Maturation Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

Appendix Table 7. Included Studies for Hip Strength

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/Method	Findings
Sexual Maturation				
Hip extension				
DiStefano et al[74]: 2015 (XS)	54/59	Youth athletes, PMOS PRE vs PUB vs POST	$kg \cdot kg^{-1} \cdot m^{-1}$ (isometric, HHD)	G: ↓ more between PRE and PUB B: ↓ more between PUB and POST Sex × maturation: no interaction
Hip abduction				
DiStefano et al[74]: 2015 (XS)	54/59	Youth athletes, PMOS PRE vs PUB vs POST	$kg \cdot kg^{-1} \cdot m^{-1}$ (isometric, HHD)	G: no change B: no change Sex × maturation: no interaction
Hip external rotation				
DiStefano et al[74]: 2015 (XS)	54/59	Youth athletes, PMOS PRE vs PUB vs POST	$kg \cdot kg^{-1} \cdot m^{-1}$ (isometric, HHD)	G: no change B: no change Sex × maturation: no interaction

Abbreviations: B, boys; G, girls; HHD, handheld dynamometer; PMOS, Pubertal Maturation Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; XS, cross-sectional design.

Appendix Table 8. Included Studies for Leg Power: Horizontal Distance

Authors: Year (Design)	G/B	Sample Characteristics	Variable (Unit)/ Method	Findings
Age				
Agostinis-Sobrinho et al[80]: 2017 (XS)[a,b]	267/262	General population, 12–18 y	SLJ distance, cm	G: stable across age groups B: ↑ 29% from 12–15 y but stable 15–18 y Sex × age: greater in B at each age
Katić et al[84]: 2012 (XS)[a]	162/134	General population, 10–14 y	SLJ distance, cm	G: ↑ 1.7% between 10–12 y and 13–14 y B: ↑ 10.3% between 10–12 y and 13–14 y Sex × age: greater in B at each age
Tveter and Holm[90]: 2010 (XS)[a,b]	165/176[c]	School children, 7–12 y	SLH distance, cm	G: ↑ linearly with age (30.8%) B: ↑ linearly with age (43.3%) Sex × age: no difference between sexes
Roth et al[87]: 2018 (L)[a]	915/853[c]	General population, 5–11 y	SLJ distance, cm	G: ↑ linearly with age (22.9%) B: ↑ linearly with age (22%) Sex × age: no difference between sexes
Sexual maturation				
Schmitz et al[88]: 2009 (XS)[a]	78/79	Athletes, 9–18 y; TS I–II, III–IV, V	SLH distance, cm	G: ↑ 22% TS I/II–V; larger ↑ TS III/IV–V B: ↑ 42% TS I/II–V Steady ↑ with maturation Sex × maturation: no difference TS I–II; B > in TS III–IV and V
Ulbrich et al[91]: 2007 (XS)[a]	79/196	Athletes, 6–16 y; TS I–IV	SLJ distance, cm	G: ↑ linearly 33% from TS I–III; stable III–IV B: ↑ linearly 48% with maturation Sex × maturation: greater in B across each TS

Abbreviations: B, boys; G, girls; L, longitudinal; SLH, single-legged hop; SLJ, standing long jump; TS, Tanner stage; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).
[b] Received raw data from authors for inclusion in meta-analysis.
[c] Number reflects the total observations if the design was mixed cross-sectional and longitudinal.

Appendix Table 9. Included Studies for Leg Power: Vertical Distance

Authors: Year (Design)	G/B	Sample Characteristics	Variable (Unit)/Method	Findings
Age				
Jones et al[83]: 2020 (XS)[a]	80/80	General population, 7–11 y	CMJ; peak force, newton	G: ↑ linearly 50% with age B: ↑ linearly 52% with age Sex × age: no difference
Laffaye et al[52]: 2016 (XS)[a]	147/148	General population, 11–20 y	SLH; vertical distance, cm	G: stable 11–13 y, ↑ (28%) 13–16 y, ↓ (17%) 17–18 y B: stable 11–13 y, ↑ (45%) 13–14 y and 17–18 y Sex × age: no differences 11–16 y, B > G 17–18 y
Lesinski et al[85]: 2020 (XS)[a]	283/420	Athletes, 8–18 y	CMJ; vertical distance, cm	G: ↑ linearly 16% with age B: ↑ linearly 39% with age Sex × age: B > G at all age groups
Lundgren et al[53]: 2011 (XS)[a]	190/56	General population, 6–12 y	VJ; vertical distance, cm	G: ↑ linearly 20% with age B: ↑ linearly 20.6% with age Sex × age: no difference
Temfemo et al[63]: 2009 (XS)[a]	239/240	General population, 11–17 y	CMJ; vertical distance, cm	G: ↑ linearly 45.4% with age B: ↑ linearly 94.4% with age Sex × age: B > G at ≥14 y
Tompsett et al[89]: 2015 (XS)[a]	52/52	General population, 9–14 y	VJ; vertical distance, m	G: stable 9–14 y B: stable 9–14 y Sex × age: G > B 9–10 y and 13–14 y, but G = B 11–12 y
Sexual maturation				
Hewett et al[82]: 2006 (XS)	87/188	Athletes, TS II–V	DVJ (31 cm); jump vertical distance, cm	G: no change with maturation B: ↑ linearly with maturation Sex × maturation: B > G TS III–V
Quatman et al[86]: 2006 (L)[a]	16/17	Basketball players, 12–16 y; TS II–III vs IV–V	DVJ (31 cm); jump vertical distance, cm	G: no change with maturation B: ↑ (52%) between TS II–III and IV–V Sex × maturation: B > G at both maturational stages
Age relative to PHV				
Birat et al[81]: 2020 (XS)[a,b]	92/85[c]	Athletes, 7–16 y; pre- vs circa- vs post-PHV	CMJ; vertical distance, cm	G: ↑ 30% pre- to circa-PHV but no ↑ post-PHV B: ↑ linearly 35% with maturation Sex × maturation: greater in B across maturational stages
Lesinski et al[85]: 2020 (XS)[a]	283/420	Athletes, 8–18 y; PRE (<1 y), PUB (±1 y), POST (>1 y) PHV	CMJ; vertical distance, cm	G: ↑ 9% PUB to POST (no PRE data) B: ↑ 50% with greatest ↑ PUB to POST Sex × maturation: B 42% > G at POST vs 17% > at PUB
Veligekas and Bogdanis[92]: 2013 (XS)	89/83	Physically active, 9–12 y; pre- vs post-PHV	CMJ; vertical distance, cm	G: stable with maturation B: stable with maturation Sex × maturation: no difference

Abbreviations: B, boys; CMJ, countermovement jump; DVJ, drop vertical jump; G, girls; L, longitudinal design; PHV, peak height velocity; PRE, prepubertal; PUB, pubertal; POST, postpubertal; SLH, single-legged hop; TS, Tanner stage; VJ, vertical jump; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).
[b] Received raw data from authors.
[c] Number reflects the total observations if the design was mixed cross-sectional and longitudinal.

Appendix Table 10. Included Studies for Knee-Joint Geometry

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Age: Bony measures				
Domzalski et al[94]: 2015 (XS)[a]	43/33	General population, 7–17 y	Ratio/NWI	G: ↓ ∼15% 7–14 y B: ↓ ∼15% 7–14 y Sex × age: not performed
Edmonds et al[95]: 2015 (XS)[a,b]	60/48	General population, 8–18 y	Ratio/NWI	G: ↓ with age, plateaued ∼0.25 around 10 y B: ↓ with age, plateaued ∼0.25 around 10 y Sex × age: no differences by sex
Hosseinzadeh and Kiapour[96]: 2020 (XS)[a,b]	110/109	General population, 8–18 y	Ratio/NWI	G: no change with age B: no change with age Sex × age: no differences
Hirtler et al[98]: 2016 (XS)[a,b]	28/29	General population, 8–18 y	Ratio/NWI	G: no change with age B: no change with age Sex × age: not analyzed
Putur et al[99]: 2020 (XS)[a]	160/162	General population, 8–18 y	Ratio/NWI	G: no change with age B: no change with age Sex × age: not analyzed
Edmonds et al[95]: 2015 (XS)[a,b]	60/48	General population, 8–18 y	mm/notch width	G: ↑ until 10–12 y B: ↑ until 13–15 y Sex × age: B > G (∼3 mm) across ages
Hosseinzadeh and Kiapour[96]: 2020 (XS)[b]	110/109	General population, 8–18 y	mm/notch width	G: no change with age B: ↑ with age, plateaued ∼20 mm around 14 y Sex × age: no differences
Hirtler et al[98]: 2016 (XS)[a,b]	28/29	General population, 8–18 y	mm/notch width	G: ∼4 mm ↑ 12–18 y B: ∼5 mm ↑ 12–18 y Sex × age: not analyzed
Hosseinzadeh and Kiapour[96]: 2020 (XS)[a]	110/109	General population, 8–18 y	Lateral tibial slope/MRI	G: no change with age B: ↓ with age Sex × age: B 7–18 y ∼2–4 mm < G
Hosseinzadeh and Kiapour[96]: 2020 (XS)[a]	110/109	General population, 8–18 y	Medial tibial slope/MRI	G: no change with age B: ↓ ∼2° at 13 y Sex × age: not analyzed
Hosseinzadeh and Kiapour[96]: 2020 (XS)[a]	110/109	General population, 8–18 y	Medial tibial depth/MRI	G: ↑ 11–14 y, then plateaued B: ↑ with age Sex × age: B > G medial tibial depth at all ages
Age: Ligamentous measures				
Hosseinzadeh and Kiapour[97]: 2021 (XS)[a,b]	110/109	General population, 8–18 y	mm^2/ACL CSA	G: ↑ ∼10 mm^2 10–18 y B: ↑ ∼20 mm^2 10–18 y Sex × age: B > G 11–14 y, 15–18 y (↑ with age)
Edmonds et al[95]: 2015 (XS)[a,b]	60/48	General population, 8–18 y	mm/ACL width	G: ↑ ∼2 mm 10–18 y B: ↑ ∼2 mm 10–18 y Sex × age: no difference between sexes
Putur et al[99]: 2020 (XS)[b]	160/162	General population, 8–18 y	mm/ACL width	G: ↑ ∼2 mm 8–14 y, then plateaued B: ↑ ∼3 mm 8–15 y, then plateaued Sex × age: no difference in growth rate

Abbreviations: ACL, anterior cruciate ligament; B, boys; CSA, cross-sectional area; G, girls; MRI, magnetic resonance imaging; NWI, notch width index; XS, cross-sectional design.

[a] Received raw data from authors.

[b] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

Appendix Table 11. Included Studies for Joint Laxity

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Age				
Jansson et al[105]: 2004 (XS)	895/950	General population, 9, 12, 15 y	Points/GJL	G: ↑ ∼2 points 12–15 y B: highest at 9 y, then ↓ ∼1 points at 12 y Sex × age: G > B at all ages
Baxter[100]: 1988 (XS)	122/110	General population, 7–14 y	mm/AKL (arthrometer)	G: ↓ 8–5 mm 8–14 y B: ↓ 8–4 mm 8–14 y Sex × age: not analyzed
Baxter[100]: 1988 (XS)	122/110	General population, 7–14 y	°/varus-valgus (arthrometer)	G: ↓ 17°–10° 8–14 y B: ↓ 18°–10° 8–14 y Sex × age: not analyzed
Baxter[100]: 1988 (XS)	122/110	General population, 7–14 y	°/internal-external (arthrometer)	G: ↓ ∼65°–∼53° 8–12 y, then plateaued B: ↓ ∼57°–48° 8–12 y, then plateaued Sex × age: not analyzed
Sexual maturation				
Ahmad et al[102]: 2006 (XS)	53/70	Athletes G: premenarche or postmenarche B: mature ≥ 14 y; immature ≤ 13 y	mm/AKL (arthrometer)	G: no difference across maturity level B: immature > mature Sex × maturation: mature B < mature G
Falciglia et al[104]: 2009 (XS/L)[a]	80/92	General population, 10.5–14.5 y; TS II–V	mm/AKL (arthrometer)	G: ↑ I–II, then progressive ↓ II–IV B: ↑ I–II, then progressive ↓ II–IV Sex × maturation: ↓ II–IV > in B; B < G at IV
Shultz et al[101]: 2008 (XS)[a,b]	85/88	Athletes, 9–18 y; TS I/II, III/IV, V	mm/AKL (arthrometer)	G: ↓ 1.6 mm early to mid-maturation, then plateaued B: ↓ 3.2 mm across maturational stages Sex × maturation: B continued to ↓ from III/IV–V, G did not
Quatman et al[106]: 2008 (XS)[a]	275/143	Athletes, 11–18 y; PMOS I, II/III, IV/V	Points/GJL	G: ↑ ∼1 PRE to PUB, then plateaued B: ↓ ∼0.5 PRE to PUB, then plateaued Sex × maturation: G > B at PUB and POST
Shultz et al[101]: 2008 (XS)[a,b]	85/88	Athletes, 9–18 y; TS I/II, III/IV, V	Points/GJL	G: I/II < III/IV > V B: no change across maturation Sex × maturation: G > B across all stages
Shultz et al[101]: 2008 (XS)[a]	85/88	Athletes, 9–18 y; TS I/II, III/IV, V	Genu recurvatum active, °	G: III/IV> V B: III/IV > V Sex × maturation: no sex effect

Abbreviations: AKL, anterior knee laxity; B, boys; G, girls; GJL, generalized joint laxity; L, longitudinal design; PMOS, Pubertal Maturation Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

[b] Received raw data from authors to include in meta-analyses.

Appendix Table 12. Included Studies for Lower Extremity Alignment

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/Method	Findings
Age				
Pujol et al[110]: 2014 (XS)	181/0	General population, 9–14 y	°/femoral bicondylar angle	G: ↑ ~4° until 13 y
Pujol et al[111]: 2016 (XS)	0/240	General population, 9–16 y	↑ angle = ↑ knee valgus	B: ↑ 4° until 16 y Sex × age: B < G 10 y+
Pujol et al[110]: 2014 (XS)	181/0	General population, 9–14 y	°/neck–shaft angle	G: ↓ ~15° 9–15 y
Pujol et al[111]: 2016 (XS)	0/240	General population, 9–16 y	↑ angle = ↑ knee valgus	B: ↓ ~8° 9–16 y Sex × age: B > G 10 y+
Popkov et al[109]: 2014 (XS)	62/72	General population, 8–16 y	°/medial proximal femoral angle ↓ angle = ↑ hip adduction	G: ↓ ~0.5°/y 8–16 y B: ↓ ~0.5°/y 8–16 y Sex × age: not analyzed
Popkov et al[109]: 2014 (XS)	62/72	General population, 8–16 y	°/anatomic lateral distal femoral angle ↓ angle = ↑ knee valgus	G: no change with age B: no change with age Sex × age: not analyzed
Popkov et al[109]: 2014 (XS)	62/72	General population, 8–16 y	°/anatomic medial proximal tibial angle ↑angle = ↑ knee valgus	G: no change with age B: no change with age Sex × age: not analyzed
Popkov et al[109]: 2014 (XS)	62/72	General population, 8–16 y	°/angle between anatomic and mechanical axes of femur radiograph ↑ angle = ↑ knee valgus	G: no change with age B: no change with age Sex × age: not analyzed
Cahuzac et al[108]: 1995 (XS)[a]	215/212	General population, 10–15 y	°/TFA	G: no change with age B: at 15 y ↓ ~1° decrease in TFA Sex × age: not analyzed
Arazi et al[107]: 2001 (XS)[a]	214/214	General population, 8–17 y	°/TFA	G: no change with age B: no change with age Sex × age: not analyzed
Shultz et al[101]: 2008 (XS)[a,b]	85/88	Athletes, 8–18 y	°/TFA	G: no clear trend 9–15 y B: progressive ↓ with age (~3°), > after 14 y Sex × age: not reported, used in MA
Sexual maturation				
Shultz et al[101]: 2008 (XS)	85/88	Athletes, TS I/II, III/IV, V	°/TFA	G: ↓ III/IV–V B: ↓ III/IV–V Sex × maturation: G > B across all maturational stages
Shultz et al[101]: 2008 (XS)	85/88	Athletes, TS I/II, III/IV, V	°/standing Q angle	G: no change across maturational stages B: ~3° ↓ I/II–III/IV Sex × maturation: G ~5° > B in later maturational stages
Shultz et al[101]: 2008 (XS)	85/88	Athletes, TS I/II, III/IV, V	°/pelvic angle/inclinometer	G: ↑ III/IV–V B: ↑ III/IV–V Sex × maturation: none
Shultz et al[101]: 2008 (XS)	85/88	Athletes, TS I/II, III/IV, V	°/hip anteversion/goniometer	G: I/II < III/IV > V B: PRE I/II < III/IV Sex × maturation: G > B
Shultz et al[101]: 2008 (XS)	85/88	Athletes, TS I/II, III/IV, V	°/tibial torsion/goniometer	G: ↑ across maturational stages B: ↑ across maturational stages Sex × maturation: none

Abbreviations: B, boys; G, girls; MA, meta-analysis; PRE, prepubertal; TS, Tanner stage; TFA, tibiofemoral angle; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).
[b] Received data from authors for individual age and TS.

Appendix Table 13. Included Studies for Flexibility

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/Method	Findings
Age				
Katić et al[84]: 2012 (XS)[a]	163/134	General population, 11 & 14 y	cm/seated straddle stretch	G: ↑ with age B: no change with age Sex × age: overall, G ~15 cm > B
Mădălina et al[113]: 2015 (XS)	83/90	General population, grades 5–8	cm/sit and reach	G: ↑ 5 cm in G grades 5–6, then plateaued B: ↓ to steady values grade 5 Sex × age: not performed
Bustamante et al[112]: 2015 (XS)[a]	1995/1669	General population, 11–17 y	cm/sit and reach	G: steadily ↓ log-transformed values with age B: steadily ↓ log-transformed values with age Sex × age: not performed
Roth et al[87]: 2018 (L)	116/137	General population, 8–10 y	cm/stand and reach	G: no change with grade level B: no change with grade level Sex × age: not performed
Sexual maturation				
Ulbrich et al[91]: 2007 (XS)	79/196	General population, TS I–IV	Wells' seat flexibility, cm	G: TS III, IV ~3.5 cm > II B: no change across maturation Sex × maturation: not performed
DiStefano et al[74]: 2015 (XS)	54/59	Physically active, 10–18 y (PMOS)	°/ankle dorsiflexion (knee extended)	G: no change across maturation B: no change across maturation Sex × maturation: none
DiStefano et al[74]: 2015 (XS)	54/59	Physically active, 10–18 y (PMOS)	°/ankle dorsiflexion (knee flexed)	G: POST < PUB and PRE B: POST < PUB and PRE Sex × maturation: none
DiStefano et al[74]: 2015 (XS)	54/59	Physically active, 10–18 y (PMOS)	°/hip abduction	G: ↓ across maturation B: ↓ across maturation Sex × maturation: none
DiStefano et al[74]: 2015 (XS)	54/59	Physically active, 10–18 y (PMOS)	°/hip internal rotation	G: no change across maturation B: no change across maturation Sex × maturation: G > B across all maturity levels

Abbreviations: B, boys; G, girls; L, longitudinal design; PMOS, Pubertal Maturation Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

Appendix Table 14. Included Studies for Static Balance

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/Method	Findings
Age				
Holm and Vøllestad[76]: 2007 (XS)[a]	165/144	General population, 7–12 y	Kinesthetic Ability Trainer 2000 (Breg, Inc), °/s	G: no change across ages B: no change across ages Sex × age: G generally performed better than B, significantly so at 7 & 11 y
Pletcher et al[77]: 2021 (XS)[a]	78/82	School and high school-aged athletes, 10.8, 16.8 y	Ground reaction force, force plates 1200 Hz	G: no difference B: worse balance at 16.8 y than 10.8 y Sex × age: at 10.8 y, G performed better than B in anterior-posterior and medial-lateral directions; at 16.8 y, G performed better than B in all conditions
Raschner et al[119]: 2017 (XS)[a]	222/291	Elite ski racers, 11–18 y	Stability score, MFT S3-Check (MFT Bodyteamwork GmbH), dimensionless score	G: no significant changes B: no significant changes Sex × age: G had better balance than B at 15 y but no other ages
Peterson et al[118]: 2006 (XS)[a]	74/80; adults = 20	General population, 8–12 y, adults	Sensory Organization Test composite equilibrium score	G: improved with age; balance at 11–12 y similar to adults B: improved with age; balance at 11–12 y similar to adults Sex × age: overall, G outperformed B
Behan et al[116]: 2019 (XS)[a]	986/1112	General population, 5–12 y	Fundamental movement skills, balance subtest score	G: ↑ 5–9 y B: ↑ 5–9 y Sex × age: G outperformed B at 5, 6, 8, 9 y
Nolan et al[117]: 2005 (XS)[a]	90/90	General population, 9–16 y	Force plate: center of pressure, anterior-posterior, medial-lateral, mm/s	G: no difference B: improved with age Sex × age: G outperformed B 9–10 y
Tompsett et al[89]: 2015 (XS)[a]	52/51	General population, 9–14 y	Fundamental movement skills, balance subtest score	G: no change B: no change Sex × age: no difference
Sexual maturation				
None reported				

Abbreviations: B, boys; G, girls; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

Appendix Table 15. Included Studies for Dynamic Balance (Reach Distance)

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/Method	Findings
Age				
Lesinski et al[85]: 2020 (XS)[a]	283/420	Elite youth athletes, 12–15 y	Y-balance composite score; % normalized on leg length	G: no difference B: no difference Sex × age: no difference
Holden et al[114]: 2016 (L)	80/90 at baseline	General population, 13–15 y	Star Excursion Balance test; % leg length	G: ↑ 13–14 y but not at 15 y in posterolateral direction B: Linear ↑ 13–15 y in anterior, posterolateral directions Sex × age: G performed better in anterior, B better in posterolateral, posteromedial directions
Schwiertz et al[115]: 2020 (XS)[a]	286/383	General population, 10–17 y	Y-Balance composite score; % normalized on leg length	G: younger performed better B: improved with age Sex × age: oldest B performed better than oldest G
Sexual maturation				
Lesinski et al[85]: 2020 (XS)	283/420	Elite youth athletes, PMOS PRE vs PUB vs POST	Y-Balance composite score; %	G: no change B: no change Sex × maturation: no difference

Abbreviations: B, boys; G, girls; L, longitudinal design; PMOS, Pubertal Maturation Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

Appendix Table 16. Included Studies for Knee-Abduction Biomechanics During Dynamic Tasks

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/ Method	Findings
Age				
Barber-Westin et al[120]: 2006 (XS)[a]	916/224	Youth athletes, multiple sports, 10–18 y	DVJ (2D) K_{ABD} angle (normalized knee-separation distance)	G: no change B: no change Sex × age: none
Lucarno et al[124]: 2021 (XS)[a]	57/132	Youth soccer players, 9–16 y	DVJ (3D) K_{ABD} (peak)	G: no clear trend B: no clear trend Sex × age: none
Sasaki et al[125]: 2013 (L)[a]	29/25	Youth athletes, 10–15 y	DVJ (2D) K_{ABD} (knee : hip distance) at IC and peak	G: IC and peak ratios consistently smaller with ↑ age B: no clear trend Sex × age: not analyzed
Yu et al[128]: 2005 (XS)[a]	30/30	Youth soccer athletes, 11–16 y	Stop jump (3D) K_{ABD} angle (IC) K_{ABD} angle (excursion)	G: K_{ABD} at IC: no change; K_{ABD} excursion ↑ with ↑ age B: K_{ABD} at IC ↓ after age 12; no change in K_{ABD} excursion Sex × age: no difference in K_{ABD} at IC; divergence in K_{ABD} excursion at 13 y
Sexual maturation				
Pletcher et al[77]: 2021 (XS)[a]	78/82	High school athletes, TS I vs IV	Stop jump (3D) K_{ABD} angle (IC)	G: no change B: no change Sex × maturation: none
Schmitz et al[88]: 2009 (XS)[a]	78/79	Youth athletes, TS I + II vs III + IV vs V	DVJ (2D) K_{ABD} angle (excursion)	G: ↑ PRE to POST B: ↓ PRE to PUB/POST Sex × maturation: similar at I + II; G > B at III + IV, IV + V
DiStefano et al[74]: 2015 (XS)[a]	59/54	Youth athletes, PMOS PRE vs PUB vs POST	DVJ (3D) K_{ABD} angle (IC) K_{ABD} angle (peak)	G: no clear trend in K_{ABD} at IC; slight ↑ in K_{ABD} excursion PRE/PUB to POST B: no clear trend in K_{ABD} at IC or K_{ABD} excursion Sex × maturation: no difference in IC or excursion
Hewett et al[122]: 2004 (XS)[a]	100/81	Youth basketball and soccer players, TS I vs II + III vs IV, V	DVJ (3D) K_{ABD} angle (excursion, medial knee motion, 2D) K_{ABD} angle (IC) K_{ABD} angle (peak)	G: all outcomes ↑ I/II–III to IV/V B: no change in any outcome Sex × maturation: all outcomes diverged at IV/V
Sigward et al[127]: 2012 (XS)[a]	45/44	Youth soccer players, TS I vs II–IV vs V	DVJ (3D) K_{ABD} moment (peak: normalized)	G: ↑ PRE to PUB/POST B: no clear trend Sex × maturation: none
Ford et al[121]: 2010 (L)[a]	265/50	Youth basketball and soccer athletes, PMOS PUB vs POST	DVJ (3D) K_{ABD} angle (peak) K_{ABD} moment (normalized to mass)	G: K_{ABD} peak angle and moment ↑ PUB to POST B: K_{ABD} peak angle and moment ↓ PUB to POST Sex × maturation: longitudinal ↑ in K_{ABD} peak angle in G with ↓ in B; G > B in K_{ABD} moment at POST
Sigward et al[126]: 2012 (XS)[a]	60/56	Youth soccer athletes, PMOS PRE vs PUB vs POST	Cutting (3D) K_{ABD} angle (peak) K_{ABD} moment (normalized to mass and height)	G: K_{ABD} peak angle: no change; K_{ABD} moment ↓ PRE to PUB to POST B: K_{ABD} peak angle: no change; K_{ABD} moment ↓ PRE/PUB to POST Sex × maturation: none identified
Age from PHV				
Hewett et al[123]: 2015 (XS)	1387/376	Middle and high school basketball and soccer players, % of predicted adult stature (82%–100%)	DVJ (3D) K_{ABD} angle (peak) K_{ABD} moment (peak)	G: K_{ABD} peak angle: no clear trend; K_{ABD} moment ↑ throughout growth B: K_{ABD} peak angle ↓ throughout growth (especially >92% of adult stature); K_{ABD} moment: no clear trend Sex × maturation: G > B in K_{ABD} peak angle and moment in groups >92% of adult stature

Abbreviations: 2D, 2-dimensional; 3D, 3-dimensional; B, boys; DVJ, drop vertical jump; G, girls; IC, initial contact; K_{ABD}, knee abduction; L, longitudinal design; PHV, peak height velocity; PMOS, Pubertal Maturational Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

Appendix Table 17. Included Studies for Knee-Flexion Biomechanics During Dynamic Tasks

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/Method	Findings
Age				
Lucarno et al[124]: 2021 (XS)	57/132	Youth soccer players, 9–16 y	Drop vertical jump (3D) K_{FLEX} angle (peak)	G: no clear trend B: no clear trend Sex × age: no clear trend
Yu et al[128]: 2005 (XS)	30/30	Youth soccer athletes, 11–16 y	Stop jump (3D) K_{FLEX} angle (peak) K_{FLEX} angle (IC)	G: ↓ K_{FLEX} angle at IC and peak, especially after 14 y B: no change at IC or peak Sex × age: divergence in K_{FLEX} angle at 15 (IC) and 16 (peak) y
Sexual maturation				
Pletcher et al[77]: 2021 (XS)[a]	78/82	High school athletes, TS II vs IV	Stop jump (3D) K_{FLEX} angle (IC) K_{FLEX} angle (peak)	G: no change in IC or peak B: no change in IC or peak Sex × maturation: no difference
DiStefano et al[74]: 2015 (XS)[a]	59/54	Youth athletes, PMOS PRE vs PUB vs POST	Drop vertical jump (3D) K_{FLEX} angle (IC) K_{FLEX} angle (excursion)	G: K_{FLEX} at IC ↓ from PRE/PUB to POST; K_{FLEX} excursion ↑ slightly from PRE to PUB to POST B: no clear trend Sex × maturation: ↓ K_{FLEX} at IC in G at POST vs no change in B; no difference in K_{FLEX} excursion
Ford et al[121]: 2010 (L)[a]	265/50	Youth athletes, PMOS PUB vs POST	Drop vertical jump (3D) K_{FLEX} angle (IC) K_{FLEX} angle (peak) K_{FLEX} moment (peak: normalized)	G: no change in K_{FLEX} at IC; slight ↓ K_{FLEX} peak from PUB to POST; K_{FLEX} moment ↑ PUB to POST B: K_{FLEX} at IC ↑ slightly from PUB to POST; K_{FLEX} moment ↑ PUB to POST; no change K_{FLEX} peak Sex × maturation: none observed

Abbreviations: 3D, 3-dimensional; B, boys; G, girls; IC, initial contact; K_{FLEX}, knee flexion; L, longitudinal design; PMOS, Pubertal Maturational Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).

Appendix Table 18. **Included Studies for Peak Vertical Ground Reaction Force During Dynamic Tasks**

Authors: Year (Design)	G/B	Sample Characteristics	Unit Measure/Method	Findings
Sexual maturation				
Pletcher et al[77]: 2021 (XS)[a]	78/82	High school athletes, TS I vs IV	Stop jump (3D) vGRF (peak: normalized)	G: no change B: ↑ PUB to POST B: ↑ PUB to POST Sex × maturation: G < B at I, G > B at IV
Quatman et al[86]: 2006 (L)[a]	16/17	Middle and high school athletes, multiple sports; TS II + III vs IV + V	Drop vertical jump (3D) vGRF (peak: normalized) vGRF (loading rate: normalized)	G: ↓ normalized loading rate PUB to POST; no change in peak vGRF B: ↓ peak vGRF and loading rate PUB to POST Sex × maturation: G < B at II + III, then G > B at IV + V in peak vGRF; no difference in normalized loading rate
DiStefano et al[74]: 2015 (XS)[a]	59/54	Youth athletes, PMOS PRE vs PUB vs POST	Drop vertical jump (3D) vGRF (peak: normalized)	G: no change B: ↓ PUB to POST Sex × maturation: ↓ vGRF in B POST, G: no change

Abbreviations: 3D, 3-dimensional; B, boys; G, girls; L, longitudinal design; PMOS, Pubertal Maturational Observation Scale; PRE, prepubertal; PUB, pubertal; POST, postpubertal; TS, Tanner stage; vGRF, vertical ground reaction force; XS, cross-sectional design.

[a] Used in meta-analysis and infographic (see Appendices B.31 and B.32).