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Review Article

Effect of Sex and Age on Knee Strength in Young Athletes: A Systematic Review and Meta-analysis

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ABSTRACT

International Journal of Exercise Science 17(6): 1461-1477, 2024. The purpose was to summarize the studies examining knee strength in young athletes and provide valuable insights into the magnitude of changes in knee flexion and extension strength during the transition from pre-puberty to puberty among male and female athletes. The literature search was conducted through Cochrane Library, Embase, PubMed, Web of Science. Cohen's effect size (ES) and 95% confidence intervals (CIs) were computed using a random effects model. While comparing males and females, as well as pre-puberty and puberty stages, we conducted subgroup analyses for pre-puberty versus puberty and for males versus females respectively. Thirteen studies published between 2003 and 2021 were included in the analysis. In the pre-puberty stage, no statistical difference was observed on knee extensors or flexors between male athletes and female athletes (p=0.695, 0.138); In the puberty stage, males exhibited higher strength relative to weight compared to females for both knee extensors and flexors (SMD=1.36, 1.25). From pre-puberty to puberty, the strength of knee extensors and flexors relative to weight vastly increased for males (SMD=-1.71, -1.86), while no significant change was found for females (p=0.436, 0.071). There were no discernible sex- or age-related differences in the hamstring-quadricep (HQ) ratio (p=0.590, 0.834). The validity of the HQ ratio as a parameter for predicting injury risks was brought into question by the findings of this study. Strength of male athletes started to grow in puberty while the increase in strength for female athletes was not significant, which indicated that more sex-specific training and injury reduction program should be accomplished.

KEY WORDS: Sex, growth, athletes, muscle strength, knee, meta-analysis

INTRODUCTION

There are increasing numbers of children and adolescents participating in athletics globally (4). This increasing participation has resulted in an increase in the number of injuries and recognition of the importance of injury risk reduction strategies (31). Given the fact that knee is one of the most commonly injured body regions in skeletally immature athletes (7, 31), many researchers have focused on providing normative data for knee periarticular muscles by assessing muscle strength at isolated joints with isokinetic testing (5). Varieties of strength parameters have been used to assess knee function and predict potential injury risks. For instance, knee extensors torque asymmetry may play a role in jumper's knee pathology, which is one of the most common overuse injuries in basketball players (15). Weak knee flexors promote excessive and potentially debilitative knee extensor–induced anterior tibial shear loads during landings, which increases the risk of anterior cruciate ligament injury (31). The hamstring-to-quadricep ratio (HQ ratio), which examines the similarity between hamstrings and quadriceps moment-velocity patterns, is considered to be a critical predictor of anterior cruciate ligament deficiency and hamstring strains (20, 35). However, normative data for knee muscles are still limited and conflicted, especially for young athletes for they are in growing ages.

The prevailing notion suggested that sex differences between males and females often do not manifest into altered movement mechanics until the onset of puberty (11, 31). However, However, this concept was contested by a study involving participants in the prepuberty stage (aged 9-10 years), which yielded contrasting findings: most boys exhibited higher mean knee strength values than girls (6). As a result, further investigation is warranted to ascertain whether and to what extent sex-related differences in knee strength exist among youth.

Besides sex-related differences in knee muscle strength, researchers have also focused on age-related differences. Both males and females go through a period of the rapid growth of strength during adolescence (9). Several studies have documented increases in eccentric and concentric peak torque of both knee extensor and flexor in young athletes during maturation (25, 33). However, when the focus shifted to peak torque normalized by body weight, studies yielded various results. An earlier longitudinal study that tested 39 female adolescent football and basketball players demonstrated that although knee extensor strength relative to body weight steadily increased throughout maturation, knee flexor strength remained approximately the same (34). Furthermore, Peek et al. reported decreased knee flexor strength relative to body weight from pre- to post-puberty in girls (31). Hence, the true extent of age-related differences in knee strength in young athletes during maturation, especially for females, remained controversial.

To date, no meta-analysis had systematically investigated the effects of age and sex on knee strength in young athletes under 18 years old. Based on a previous similar study (36), athletes were divided into a pre-puberty group (12 years of age and younger) and a puberty group (older than 12 years of age). This systematic review and meta-analysis aimed to summarize and quantify the effects of age and sex on knee extensors, knee flexors, and HQ ratio in this population.

METHODS

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (30) guidelines when conducting and reporting this systematic review and meta-analysis.

Search of literature
Two investigators performed a systematic search of PubMed, Embase, Cochrane Library, and Web of Science independently using the following search strategy: ((“age” OR “maturation” OR “gender” OR “sex” OR “children” OR “adolescent” OR “youth” OR “girls” OR “boys” OR “puberty”) AND (“hamstring to quadriceps strength ratio” OR “quadriceps to hamstring

strength ratio" OR "hamstring" OR "quadriceps" OR "flexor" OR "extensor" OR "lower extremity strength" OR "muscle" or "strength") AND ("knee" OR "knee joint" OR "tibiofemoral joint" OR "patellofemoral joint") AND ("athlete" OR "athletes")). An original literature search was conducted in January 2023 to validate the search terms. In addition, the search was limited to cross-sectional studies and longitudinal studies, full-text articles written in English and human species. Publication year of articles was not limited. All titles and abstracts were reviewed by two investigators to remove duplicates and evaluate their relevance. Then investigators further included and excluded articles according to the following selection criteria. This research was carried out fully in accordance with the ethical standards of the *International Journal of Exercise Science* (27).

Criteria for selection

Studies had to meet the following criteria to be eligible for inclusion: (a) participants were healthy young athletes under 18 years old. (b) at least one measure of knee extensors strength, flexors strength, and conventional hamstring to quadriceps ratio was presented in the study (c) either sex difference between boys and girls or age difference between prepuberty and puberty or both sex and age difference should be reported in the included studies. (d) Strength parameter should be peak torque normalized by body weights. (e) cross-sectional studies, longitudinal studies. The exclusion criteria were as follows: (a) participants had any self-reported history of serious lower extremity musculoskeletal injury (such as ligament rupture), musculoskeletal injury within the last six months (b) studies that report only graphic data which could not be extracted by extraction tool, or data only with mean which did not allow for calculation of effect sizes were excluded (c) muscle strength that was not tested by isokinetic dynamometers. (d) intervention studies

Study quality

AXIS critical appraisal tool (12) was used to assess the study quality and risk of biases. Studies were rated based on one 17-item criteria since items 7, 13, and 14 regarding the management of non-responders were not relevant to this investigation. This quality assessment approach was also used in a previous systematic review (29). Quality assessment was performed by two independent reviewers. Discussion was initiated when discrepancies arose. If the respective reviewers did not reach a consensus, an evaluation from a third expert was obtained.

Statistical analyses

When articles only reported confidence interval (CI) instead of standard deviation (SD), we would use the formula provided by Cochrane Handbook for Systematic Reviews of Interventions (18) to calculate standard deviation from confidence interval. In some cases, several ages which fell into the prepuberty group or puberty group were reported respectively in one article. For example, when participants in one study were divided into 11, 15, 16 years old groups, we used the following formula supplied by Cochrane Handbook to combine two subgroups (15 years group and 16 years group) into a single group (puberty group).

$$\sqrt{\frac{(N_1-1)SD_1^2+(N_2-1)SD_2^2+\frac{N_1N_2}{N_1+N_2}(M_1^2+M_2^2-2M_1M_2)}{N_1+N_2-1}}$$

This formula would be applied sequentially when there were more than two groups to combine. If the age group reported in the studies overlaid our cut-off age—12-year-old, we grouped them according to their predominating age. For the continuous variables, standardized mean difference (SMD) with 95% confidence interval (CI) was used to assess the effects of age and sex on knee muscle strength. As the presence of heterogeneity from different speeds of dynamometer tests, and different sports types were assumed priorly, we chose to use the random-effects model in all pooled analyses. According to Cohen (8), in terms of values for SMD, 0.2 represents a small effect, 0.5 a moderate effect and 0.8 a large effect. Heterogeneity calculated in I^2 was classified as being either trivial (0% < I2 >40%), moderate (30% <I2 >60%), substantial (50% <I2 > 90%), or considerable (75% < I2 >100%) (18). If high heterogeneity was present, we would conduct sensitivity analysis by removing studies to evaluate the stability of results. Any *p* value less than 0.05 was considered to be statistically significant. To investigate possible publication bias, Egger's regression test (13) was used. It is a quantitative test with *p*< 0.05 indicating significant publication bias. StataSE 15 was used to do all analyses.

Results

Study characteristics

In total, twelve cross-sectional studies and one longitudinal study published between 2003 and 2021 were included in this analysis. Figure 1 illustrated the process of the systematic literature search. Table 1 presented the characteristics of the selected studies used in the meta-analysis. In the pre-puberty and puberty group categories, the ages and the numbers of males or females in each category were presented. Among a total of 1054 subjects in 12 cross-sectional studies, males were 558 and females were 496, while 341 subjects were categorized in pre-puberty and 713 subjects were in the puberty group. Only one longitudinal study, comprising six males and six females, compared individuals across different age groups.

Study quality

The quality assessment revealed that the majority of included studies complied with most of the criteria of the Appraisal tool for Cross-Sectional studies. In detail, 11 out of 13 studies fulfilled >7 out of 9 criteria regarding the quality of the study method. Moreover, only one study performed a power calculation to justify sample sizes used in the recruitment of sample population. Only 3 out of 13 studies did not get full three scores regarding the quality of study result. 11 out of 13 studies fulfilled >2 out of 4 criteria regarding the quality of study discussion, limitation, and ethical approval. Therefore, all studies met the criteria above average. (See Table 2).

Outcome of meta-analysis

Knee extensors: Figure 2A showed the effect of sex difference on knee extensors. There was no statistically significant difference between girls and boys in the stage of prepuberty (SMD=-0.01, I^2=65.1, p=0.659, 6 studies). A statistically significant difference was found between boys and girls in puberty age and a large effect in favor of boys was indicated by SMD (SMD=1.36, I^2=72.8 %, *p*<0.001, 7 studies). Fig 2B showed the effect of age difference on knee extensors. No statistically significant difference was found in girls from pre-puberty to puberty (SMD=-0.35,

I^2=85.8%, *p*=0.436, 6 studies). Strength of boys grew largely from prepuberty to puberty age (SMD=-1.71, I^2=90.7%, *p*<0.001, 8 studies). Overall heterogeneity was considerable for both two comparisons (I^2=85.3%; I^2=90.3%).

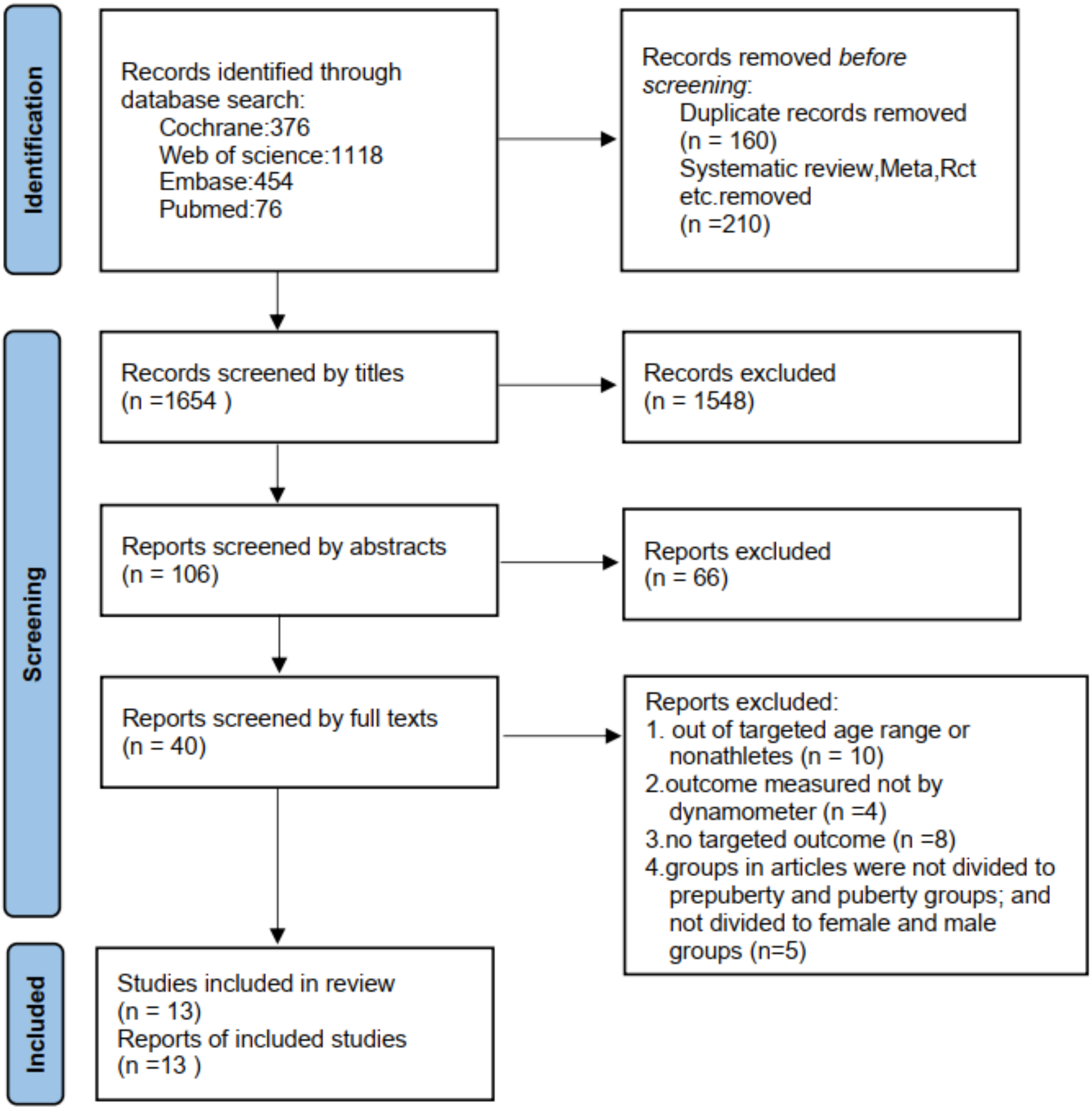

Figure 1. Selection of studies.

Table1. Characteristics of the studies used in the meta-analysis.

study	study type	sports	Velocity(deg/s)	Outcome(s)	Pre-puberty group	Puberty group	N
Andrade et al. 2021	cross-sectional	soccer	60	HQ	11.83yrs; F(35)	13.72-16.1yrs; F(58)	93
Barber-Westin et al. 2005	cross-sectional	soccer	180	KF, KE, HQ	10 yrs; M(25), F(27)	--	52
Nagai et al. 2021	cross-sectional	basketball	240	KF, HQ	--	14yrs-18yrs; M(64), F(108)	172
Gerodimos et al. 2003	cross-sectional	basketball	60	KF, KE, HQ	12yrs; M(30)	13-17yrs; M(150)	180
Vargas et al. 2020	cross-sectional	soccer	60	HQ	12yrs; F(14)	14,15,18yrs; F(52)	66
Buchanan et al. 2009	cross-sectional	basketball	60	KF, KE, HQ	9-10yrs; M(6), F(7)	12-13yrs; M(11), F(10)	34
Pletcher et al. 2021	cross-sectional	mixed	60	KF, KE, HQ	11 yrs; M(42), F(38)	17 yrs; M(40), F(40)	160
Buchanan et al. 2003	cross-sectional	basketball	60	KF, KE, HQ	11-13yrs; M(10),F(11)	15-17yrs; M(9), F(11)	41
Kalata et al. 2021	cross-sectional	soccer	120	KF, KE	11yrs; M(32)	14,15yrs; M(58)	90
Noyes et al. 2005	cross-sectional	soccer	180	KF, KE	11-13yrs; M(20), F(20)	14-17yrs; M(27), F(27)	94
Hadzić et al. 2013	cross-sectional	basketball	60	KF, KE, HQ	--	15 yrs; M(10), F(14)	24
Kanehisa et al. 2006	longitudinal	tennis	60	KE	12yrs; M(6), F(6)	13,14yrs; M(12), F(12)	12
Zulfikri et al. 2021	cross-sectional	badminton	60	KF, KE, HQ	--	13-14yrs, 15-17yrs; M(24), F(24)	48

HQ: hamstring to quadricep ratio; KF: knee flexors; KE: knee extensors; F: females; M:males: yrs: years old

Table 2. Study quality

study	1.	2.	3.	4	5.	6.	8.	9.	10.	11.	12.	15.	16.	17.	18.	19.	20.	total score
Buchanan et al. 2003	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	0	1	14
Gerodimos et al. 2003	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1	14
Barber-Westin et al. 2005	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Buchanan et al. 2009	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	15
Vargas et al. 2020 *	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	1	1	14
Andrade et al. 2021	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Nagai et al. 2021	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	15
Pletcher et al. 2021	1	1	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	15
Noyes et al. 2005	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	16
Kalata et al. 2021	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Hadzić et al. 2013	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1	14
Kanehisa et al. 2006	1	1	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	15
Zulfikri et al. 2021	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16

*:evaluated by expert (outside researcher).

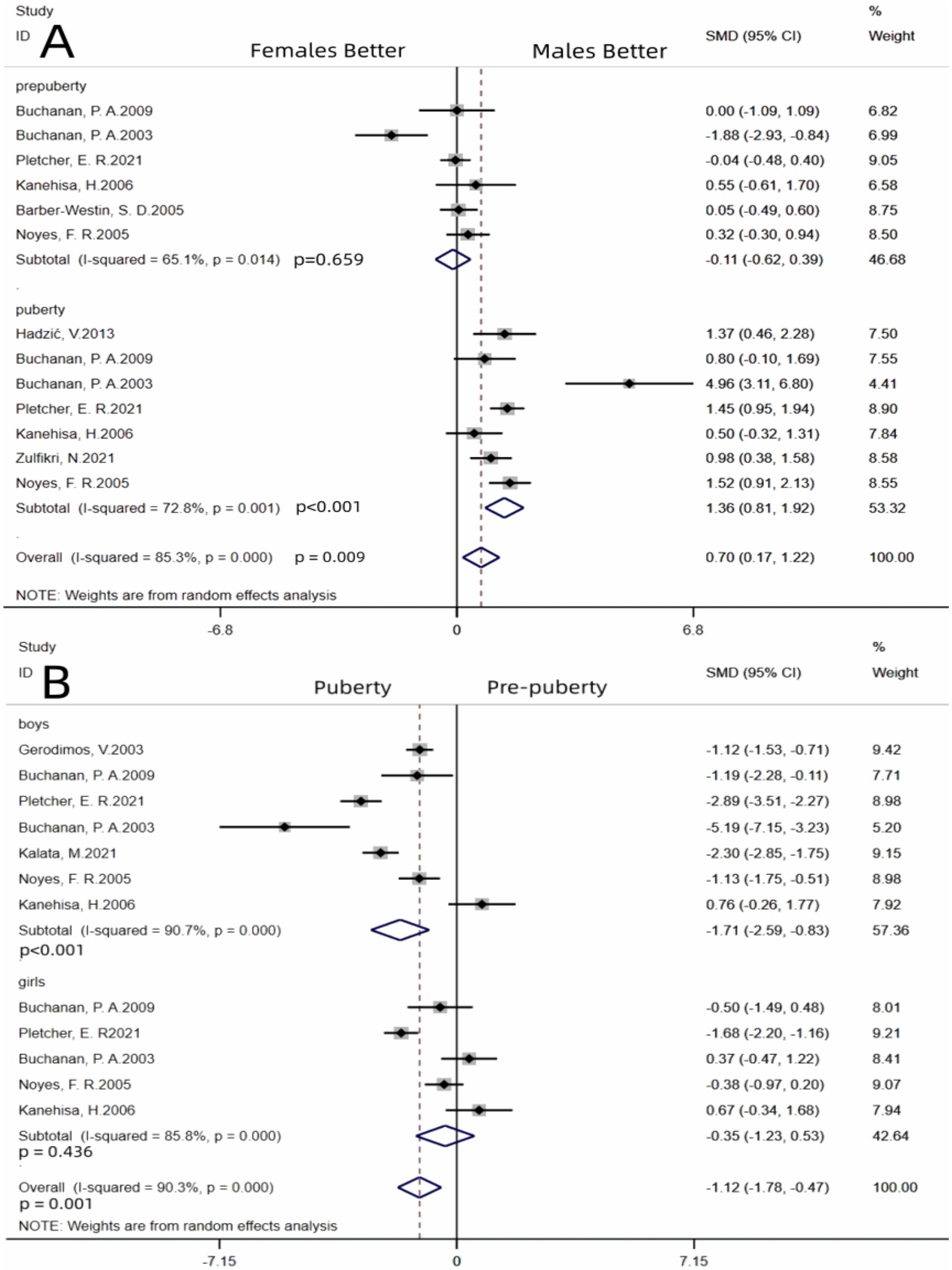

Figure 2 A. Effect of sex difference on knee extensors; B: Effect of age difference on knee extensors.

Knee flexors: Figure 3A showed the effect of sex difference on knee flexors. Strengths of boys and girls were similar in prepuberty stage (SMD=0.1, I^2=0.0%, p=0.487, 5 studies). However, in puberty stage, boys had much stronger knee flexors than girls (SMD=1.28, I^2=45.6%, p<0.001, 7 studies). In Figure 3B, no statistically significant difference was found in girls from prepuberty to puberty (SMD=-1.86, I^2=88.9%, p=0.071, 4 studies) while a large- sized effect in favor of puberty over prepuberty in boys group was found (SMD=-1.86, I^2=83.9%, p<0.001, 6 studies).

Overall heterogeneity for knee flexors was considerable for both sex difference(I^2=76.8%) and age difference(I^2=87%).

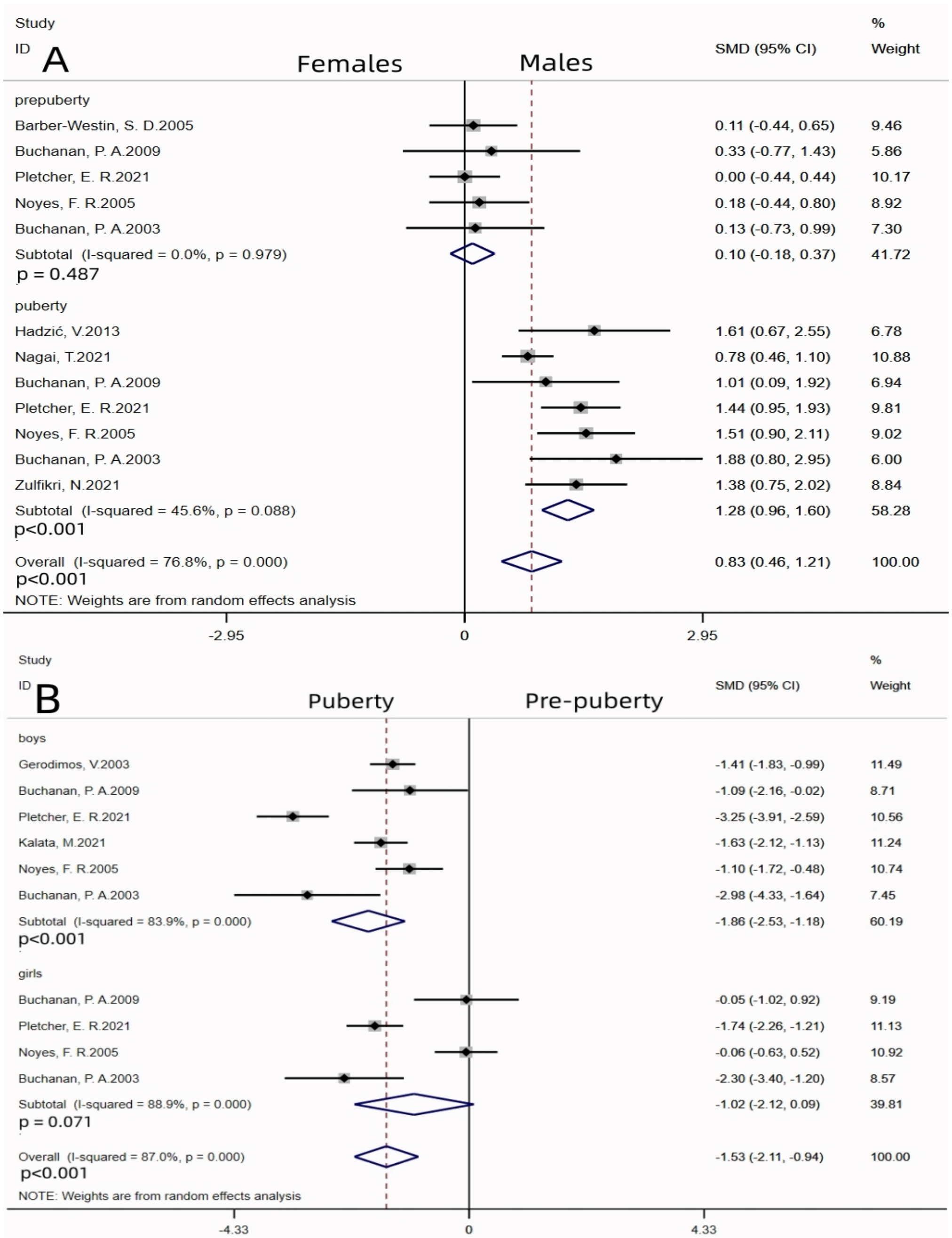

Figure 3 A. Effect of sex difference on knee flexors; B: Effect of age difference on knee flexors.

HQ ratio: Figure 4A and B showed there is no statistically significant difference among any subgroup in neither age difference nor sex difference comparison (p=0.590 in sex difference comparison and p=0.834 in age difference). Besides, the effect size of each subgroup in each of the two comparisons was small (In sex difference comparison, SMD=0.13 for pre-puberty and

0.02 for puberty; in age difference comparison, SMD=-0.25 for males and 0.06 for females). Heterogeneity was trivial for sex difference (I^2=0) and considerable for age difference (I^2=76.9).

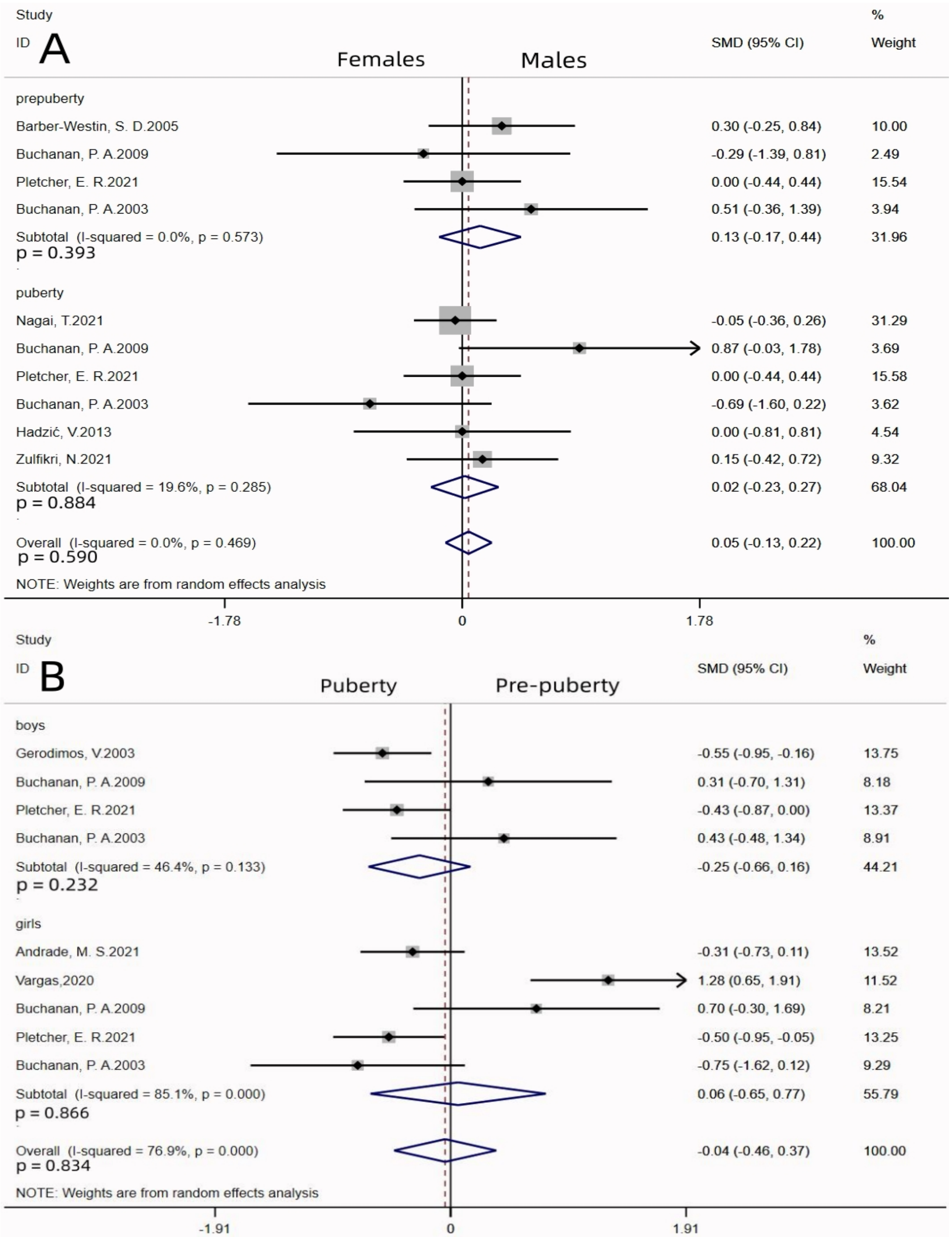

Figure 4 A. Effect of sex difference on HQ ratio; B: Effect of age difference on HQ ratio.

Sensitivity analysis and publication bias: Overall heterogeneity in our study was high thus we conducted sensitivity analysis. Most participants in included studies were test in 60 degree per second as angular velocity. Therefore, we excluded 4 studies (3, 21, 26, 28) with different angular velocities to eliminate one heterogenous factor. Heterogeneity and effect sizes were consistent without apparent fluctuation in most our corresponding comparisons. It only differed on knee flexors between prepuberty females and puberty females, which showed a statistical difference (SMD=-1.37, I^2=82.6%, p=0.022). The p-value of Egger's regression test for every comparison was >0.05. Therefore, Publication bias was not found for studies included in the quantitative synthesis.

DISCUSSION

To the best of our knowledge, the present systematic review and meta-analysis is the first article which characterize and quantify age and sex differences in knee strength in young athletes. The most important finding from this study was that female athletes did not have an increase in knee flexor or extensor strength relative to body weight from prepuberty to puberty. This finding was uniquely different from their male counterparts. In addition, no difference in knee strength between boys and girls was found in prepuberty stage. The finding of this analysis may support the sex-specific exercise program to prevent female athletes' potential sports injuries as they transit into puberty.

The finding of no difference between male athletes and female athletes in knee extensor and knee flexor in the prepuberty stage (under 12 years of old) was consistently identified in studies by Barber-Westin et al. (3) and Sunnegårdh J et al. (38). One study by Kellis et al. (23), demonstrated that body mass and age are the primary variables that explain concentric moment variance. Therefore, the absence of body weight disparity between boys and girls in prepuberty stage may be partly responsible for the lack of difference in knee flexor and extensor strength between sexes. In addition to body weight, similar serum testosterone levels between girls and boys during this period may also contributed to the lack of difference in knee strength before puberty. Senefeld et al. (37) found that males and females between the age of 6 and 10 had similar testosterone levels, which had been demonstrated to be strongly associated with sex differences in athletic performance. Testosterone levels between sexes fully diverged by the age of 12, thereby substantiating the legitimacy for using 12 years old as the cut-off age for further study.

This study also found that males had stronger knee strength than females in puberty. Additionally, there was a significant difference for males between the pre- and puberty group. Maturation for males will include a period of muscle mass and strength that is promoted by increasing testosterone concentrations (16). Generally, testosterone concentrations increase from around 13.3 ng/dL at age 11 to 516 ng/dL at age 20 (37). Meanwhile, from age 11 to 20, the testosterone level of females only increases from around 14.2 ng/dL to 29.5 ng/dL (37). The difference in testosterone levels between males and females appears to correlate with the difference of knee extensor and flexor strength. Hence, the reason for the selection of peak torque normalized by body weight as our outcome was that it not only allows age to provide a reasonable and nonintrusive approximation of maturational/pubertal status but also controls for much of the hormonally mediated gender differences in strength that appear with puberty (10). Based on our finding, those theories were also applicable when muscle strength was normalized by body weight. No difference in either knee extensors or knee flexors between female athletes from prepuberty to puberty was identified in this current analysis, where most controversies was presented. Peek et al. (31) reported an increase in knee extensor strength but a decrease in knee flexor strength (relative to body weight) in females between pre- and post-puberty. Opposite findings were noted in another study (5). They found that the relative strength of females at 15–17 years of age was greater in the hamstrings but not in the quadriceps when compared with girls at 11–13 years of age. The contradiction between the two studies may come from the difference in dynamometer testing speeds. The angular velocity of the Peek et al. study (31) was 300 deg/s, while Buchanan and Vardaxia's study (5) was 60 deg/s. The opposite growth patterns between knee flexors and extensors in either boys or girls posed a challenge for explanation and interpretation because physiologic changes associated with puberty, including those mediated by increasing levels of testosterone that are typically greater for boys than girls, would seemingly have similar effects on the mass and strength of both hamstrings and quadriceps (5, 22). The same growth pattern between knee flexor and extensor strength in our study (no increase in either knee flexor or extensor strength in females and significant increases in both knee flexor and extensor strength in males) can support the above statement. This was also consistent with other studies (17, 28). Given girls gained lesser strength than boys during maturation in terms of peak torque (1, 39), no significant increase in knee strength relative to weight in females may be explained by the fact that the increasing rate of strength in females, as they progress from pre-puberty into puberty, might not have been as great as their increase in body weight, making statistically difference of relative strength unfounded.

The strength balance of knee flexors and extensors has been considered an important variable in assessing joint stability as they play a crucial role in affecting anterior tibial translation and anterior cruciate ligament (ACL) strain (2). However, we didn't find the effects of neither age difference nor sex difference in hamstring to quadricep ratio in young athletes. It seemed that although males in puberty group were stronger than their female counterparts, they didn't have superiority on knee muscle strength balance. Due to the similar effect sizes of age difference on both knee flexors and extensors reported in male athletes in our study (for knee extensors SMD=-1.71; for flexors SMD=-1.86), we speculated that for young male athletes, the increasing rates of knee flexors and extensors strength during maturation are similar and proportional, which made this ratio stable. Females and males under 18 years of age do not have a difference in HQ ratio throughout maturation, but there is a distinct shift to females demonstrating a higher incidence of ligament injuries than boys after age 12 years of age (19). Therefore, the sensitivity and validity of using the HQ ratio as a parameter to predict injury risks are questionable. Other factors such as muscle co-contraction pattern, joint stability and structure alignment should be considered to explain the higher injury rates for females after pre-puberty age.

High heterogeneities were found in all our comparisons, with the exception of the comparison of sex differences in HQ ratio. The disparity of testing speeds in included studies might be responsible for this. As the angular velocity of the isokinetic dynamometer gets slower, muscle contraction is closer to isometric contraction, which produces higher peak torque. However, when peak torque is normalized by body weight, whether different velocities can still have such an impact, is still unknown. In our study, no substantial difference was found after removing studies with different velocities, which might indicate that peak torque normalized by body weight was relatively stable even with testing velocities being changed. Therefore, the results of this study were cautiously considered stable and high heterogeneity was caused by other factors such as sports types. However, due to the limited number of studies included, subgroup analysis for determining the effect of sports types on relative strength could not be done.

The findings of this study had several clinical implications. Coach, trainers, and physical therapists should emphasize the importance of sex-specific injury reduction programs, given the fact that female athletes and male athletes have different growth patterns during maturation and training. It has been proposed that differences in muscular strength and sex-specific neuromuscular activation patterns play roles in a greater risk of noncontact ACL injury in females (32) after age 12. Ford et al. (14) found during the preparatory phase in one action girls preferentially rely on increased quadriceps activation but not the hamstring with increased plyometric intensity. Considering the absence of an increase in relative strength among females during the transition from pre-puberty to puberty as observed in this study, further studies are needed to unfold if activation patterns play a more prominent role than knee strength for these higher injury rates in puberty. In this study, relative strength was the only parameter showing the difference in comparisons, while the HQ ratio did not show any significant changes during maturation. Therefore, relative strength might be more informative than the ratio of athletes' strength profiles. This was also supported by Buchanan (5). In physical examinations, relative strength should be a more important parameter to examine athletes' overall profiles.

One limitation of the present systematic review and meta-analysis was that the analysis of differences in knee strength was limited to the factors of chronological age instead of the maturational process. Tanner scale by a trained healthcare professional has long been the medical standard to determine physical development as children transition into adolescence and then adulthood (24). However, because of limited studies using tanner stage, we weren't able to compare knee strength with respect to biological age. Additionally, it couldn't be ruled out that differences in sports between subjects might have influenced our results. Therefore, more studies are needed to study the effect of various sports on knee strength in young athletes. Overall, we observed considerable heterogeneity in most of our comparisons. Thus, conclusions should be made cautiously.

No difference in knee flexors, extensors and the ratio between males and females in prepuberty stage was found. The muscle strength of knee extensors and flexors in male athletes exhibited substantial growth, whereas no significant difference was observed in female athletes during maturation. The findings of this study support the implementation of a strengthening program focused on the knee strength for female athletes as they undergo the transition into puberty. Increasing knee flexor or extensor strength relative to body weight in females may play an essential role in injury prevention. HQ ratio might be a questionable predictor for injury as it remained unchanged throughout maturation in our study. We speculated that other factors, such as muscle activation, may contribute to the higher risk of ligament injuries in females after reaching puberty. Further researches are needed to determine differences in knee strength by additional factors (e.g., angular velocity, maturation, sports).

REFERENCES

1. Ahmad CS, Clark AM, Heilmann N, Schoeb JS, Gardner TR, Levine WN. Effect of gender and maturity on quadriceps-to-hamstring strength ratio and anterior cruciate ligament laxity. Am J Sports Med 34(3):370-374, 2006. https://doi.org/10.1177/0363546505280426

2. Andrade MS, Junqueira MS, De Lira CAB, Vancini RL, Seffrin A, Nikolaidis PT, Rosemann T, Knechtle B. Age-related differences in torque in angle-specific and peak torque hamstring to quadriceps ratios in female soccer players from 11 to 18 years old: Alpha cross-sectional study. Res Sports Med 29(1):77-89, 2021. https://doi.org/10.1080/15438627.2020.1742713

3. Barber-Westin SD, Galloway M, Noyes FR, Corbett G, Walsh C. Assessment of lower limb neuromuscular control in prepubescent athletes. Am J Sports Med 33(12):1853-1860, 2005. https://doi.org/10.1177/0363546505278257

4. Bell DR, Post EG, Trigsted SM, Hetzel S, McGuine TA, Brooks MA. Prevalence of sport specialization in high school athletics: A 1-year observational study. Am J Sports Med 44(6):1469-1474, 2016. https://doi.org/10.1177/0363546516629943

5. Buchanan PA, Vardaxis VG. Sex-related and age-related differences in knee strength of basketball players ages 11-17 years. J Athl Train 38(3):231-237, 2003.

6. Buchanan PA, Vardaxis VG. Lower-extremity strength profiles and gender-based classification of basketball players ages 9-22 years. J Strength cond Res 23(2):406-419, 2009. https://doi.org/10.1519/JSC.0b013e3181942140

7. Chicorelli AM, Micheli LJ, Kelly M, Zurakowski D, MacDougall R. Return to sport after anterior cruciate ligament reconstruction in the skeletally immature athlete. Clin J Sport Med 26(4):266-271, 2016. https://doi.org/10.1097/JSM.0000000000000275

8. Cohen J. The effect size. Statistical power analysis for the behavioral sciences. Abingdon: Routledge, 77-83. 1998.

9. Davidson SP, McLean SG. Effects of maturation on combined female muscle strength and acl structural factors. J Sci Med Sport 19(7):553-558, 2016. https://doi.org/10.1016/j.jsams.2015.07.016

10. De Ste Croix M, Deighan M, Armstrong N. Assessment and interpretation of isokinetic muscle strength during growth and maturation. Sports Med 33(10):727-743, 2003. https://doi.org/10.2165/00007256-200333100-00002

11. DiStefano LJ, Martinez JC, Crowley E, Matteau E, Kerner MS, Boling MC, Nguyen AD, Trojian TH. Maturation and sex differences in neuromuscular characteristics of youth athletes. J Strength Cond Res 29(9):2465-2473, 2015. https://doi.org/10.1519/JSC.0000000000001052

12. Downes MJ, Brennan ML, Williams HC, Dean RS. Development of a critical appraisal tool to assess the quality of cross-sectional studies (axis). BMJ Open 6(12):e011458, 2016. https://doi.org/10.1136/bmjopen-2016-011458

13. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ 315(7109):629-634, 1997. https://doi.org/10.1136/bmj.315.7109.629

14. Ford KR, Myer GD, Schmitt LC, Uhl TL, Hewett TE. Preferential quadriceps activation in female athletes with incremental increases in landing intensity. J Appl Biomech 27(3):215-222, 2011. https://doi.org/10.1123/jab.27.3.215

15. Hadzić V, Erculj F, Bracic M, Dervisević E. Bilateral concentric and eccentric isokinetic strength evaluation of quadriceps and hamstrings in basketball players. Coll Antropol 37(3):859-865, 2013.

16. Hansen L, Bangsbo J, Twisk J, Klausen K. Development of muscle strength in relation to training level and testosterone in young male soccer players. J Appl Physiol (1985) 87(3):1141-1147, 1999. https://doi.org/10.1152/jappl.1999.87.3.1141

17. Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. J Bone Joint Surg Am 86(8):1601-1608, 2004. https://doi.org/10.2106/00004623-200408000-00001

18. Higgins JPT TJ, Chandler J, Cumpston M, Li T, Page MJ, Welch VA. Cochrane handbook for systematic reviews of interventions version 6.3 (updated february 2022). 2022.

19. Holm I, Vøllestad N. Significant effect of gender on hamstring-to-quadriceps strength ratio and static balance in prepubescent children from 7 to 12 years of age. Am J Sports Med 36(10):2007-2013, 2008. https://doi.org/10.1177/0363546508317963

20. Holmes JR, Alderink GJ. Isokinetic strength characteristics of the quadriceps femoris and hamstring muscles in high school students. Phys Ther 64(6):914-918, 1984. https://doi.org/10.1093/ptj/64.6.914

21. Kalata M, Hank M, Bujnovsky D, Michalek J, Varjan M, Kunzmann E, Zahalka F, Maly T. Bilateral strength asymmetry in elite youth soccer players: Differences between age categories. Symmetry-Basel 13(11)2021. https://doi.org/10.3390/sym13111982

22. Kanehisa H, Ikegawa S, Tsunoda N, Fukunaga T. Strength and cross-sectional area of knee extensor muscles in children. Eur J Appl Physiol Occup Physiol 68(5):402-405, 1994. https://doi.org/10.1007/BF00843736

23. Kellis S, Kellis E, Manou V, Gerodimos V. Prediction of knee extensor and flexor isokinetic strength in young male soccer players. J Orthop Sports Phys Ther 30(11):693-701, 2000. https://doi.org/10.2519/jospt.2000.30.11.693

24. Koopman-Verhoeff ME, Gredvig-Ardito C, Barker DH, Saletin JM, Carskadon MA. Classifying pubertal development using child and parent report: Comparing the pubertal development scales to tanner staging. J Adolesc Health 66(5):597-602, 2020. https://doi.org/10.1016/j.jadohealth.2019.11.308

25. Nagai T, Bates N, McPherson A, Hale R, Hewett T, Schilaty ND. Effects of sex and age on quadriceps and hamstring strength and flexibility in high school basketball athletes. Int J Sports Phys Ther 16(5):1302-1312, 2021. https://doi.org/10.26603/001c.27986

26. Nagai T, Bates N, McPherson A, Hale R, Hewett T, Schilaty ND. Effects of sex and age on quadriceps and hamstring strength and flexibility in high school basketball athletes. Int J Sports Phys Ther 16(5)2021. https://doi.org/10.26603/001c.27986

27. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1):1-8, 2019.

28. Noyes FR, Barber-Westin SD. Isokinetic profile and differences in tibial rotation strength between male and female athletes 11 to 17 years of age. Isokinetics Exerc Sci 13(4):251-259, 2005. https://doi.org/10.3233/IES-2005-0211

29. Otsuki R, Del Bel MJ, Benoit DL. Sex differences in muscle activation patterns associated with anterior cruciate ligament injury during landing and cutting tasks: A systematic review. J Electromyogr Kinesiol 60:102583, 2021. https://doi.org/10.1016/j.jelekin.2021.102583

30. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA, Thomas J, Tricco AC, Welch VA, Whiting P, Moher D. The prisma 2020 statement: An updated guideline for reporting systematic reviews. BMJ 372:n71, 2021. https://doi.org/10.1136/bmj.n71

31. Peek K, Ford KR, Myer GD, Hewett TE, Pappas E. Effect of sex and maturation on knee extensor and flexor strength in adolescent athletes. Am J Sports Med 50(12):3280-3285, 2022. https://doi.org/10.1177/03635465221118081

32. Peterson JR, Krabak BJ. Anterior cruciate ligament injury: Mechanisms of injury and strategies for injury prevention. Phys Med Rehabil Clin N Am 25(4):813-828, 2014. https://doi.org/10.1016/j.pmr.2014.06.010

33. Pletcher ER, Dekker TJ, Lephart SM, Sell TC. Sex and age comparisons in neuromuscular and biomechanical characteristics of the knee in young athletes. Int J Sports Phys Ther 16(2):438-449, 2021. https://doi.org/10.26603/001c.21358

34. Quatman-Yates CC, Myer GD, Ford KR, Hewett TE. A longitudinal evaluation of maturational effects on lower extremity strength in female adolescent athletes. Pediatr Phys Ther 25(3):271-276, 2013. https://doi.org/10.1097/PEP.0b013e31828e1e9d

35. Rosene JM, Fogarty TD, Mahaffey BL. Isokinetic hamstrings: Quadriceps ratios in intercollegiate athletes. Journal of Athletic Training 36(4):378-383, 2001.

36. Schedler S, Kiss R, Muehlbauer T. Age and sex differences in human balance performance from 6-18 years of age: A systematic review and meta-analysis. PLoS One 14(4):e0214434, 2019. https://doi.org/10.1371/journal.pone.0214434

37. Senefeld JW, Lambelet Coleman D, Johnson PW, Carter RE, Clayburn AJ, Joyner MJ. Divergence in timing and magnitude of testosterone levels between male and female youths. JAMA 324(1):99-101, 2020. https://doi.org/10.1001/jama.2020.5655

38. Sunnegårdh J, Bratteby LE, Nordesjö LO, Nordgren B. Isometric and isokinetic muscle strength, anthropometry and physical activity in 8 and 13 year old swedish children. Eur J Appl Physiol Occup Physiol 58(3):291-297, 1988. https://doi.org/10.1007/BF00417265

39. Wojtys EM, Huston LJ. Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. Am J Sports Med 22(1):89-104, 1994. https://doi.org/10.1177/036354659402200116