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Resistance Training in Health and Sports Performance

Gender and Age Related Differences in Leg Stiffness and Reactive Strength in Adolescent Team Sports Players

by
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The aim of the present study was to identify potential gender differences in leg stiffness and reactive strength during hopping tasks in 13 to16-year old team sports players. Reactive strength index (RSI) and leg stiffness were obtained in two consecutive seasons from 51 girls (U14: n = 31, U16: n = 20) and 65 boys (U14: n = 32, U16: n = 33). A significant main effect on absolute (U14: p = 0.022, η^2 = 0.084; U16: p < 0.001, η^2 = 0.224) and relative leg stiffness (U14 p<0.001; η^2 = 0.195; U16; p = 0.008, η^2 = 0.128) for gender was found in both groups with values higher in boys than in girls. For absolute and relative stiffness gender differences in the U14 group were significant in the 1st year only (p=0.027 and p=0.001), and for the U16s in the 2nd year only (p < 0.001 and p = 0.022). For RSI, a significant main effect for gender was observed in the U16 group only (p < 0.001 η^2 = 0.429) with values significantly higher in boys than in girls in both years of measurement (p = 0.001; p < 0.001). Results of this study support previous limited findings, mostly related to non-athletes, suggesting lower stretch-shortening cycle capability in adolescence female compared to male, however our data only partly supports the theory that quality of neuromuscular functions increases with age until post puberty.

Key words: *youth, neuromuscular, stretch-shortening cycle, reactive strength index.*

Introduction

Throughout sport-specific movements, athletes routinely use stretch-shortening cycle (SSC) actions. The SSC is characterized as a successive combination of fast eccentric (stretching) and concentric (shortening) action with a rapid transition between them (Nicol et al., 2006). High efficiency of the SSC is needed for success in many sports especially in high intensity movements that require high levels of the rate of force development, such as maximal velocity running and jumping (De Ste Croix et al., 2017). However, efficiency of the SSC is also important from the point of view of joint stability and injury prevention.

Injury incidence data has shown that females have a higher injury rate than males (Waldén et al., 2011) and that in the case of the same sports, females have a three to eight times greater incidence of non-contact ACL injury (Agel et al., 2005; Myklebust et al., 1998). Epidemiological data also suggest that females appear to have a greater relative risk of a non-contact ACL injury compared to males when hours of athlete exposure are taken into account (Rumpf and Cronin, 2012). ACL and muscle injuries in many competitive team sports predominantly occur as non-contact injuries during movements often associated with high

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external knee joint loads (Alentorn-Geli et al., 2009; Krosshaug et al., 2007; Waldén et al., 2011; Kabešová et al., 2019; Kalinowski et al., 2020). It has been proved that low knee joint stability to withstand the demands of the fastest situations in the game like sprinting, rapid changes of direction, acceleration and deceleration, cutting, and jumping are contributing factor to ACL injury (Hughes and Watkins, 2006; Mandelbaum et al., 2005). It has been also suggested that ACL injury occurs due to failure of the dynamic rather than the passive stabilising structures (Hughes and Watkins, 2006) and that muscle and neuromuscular control of the knee joint play a key role in reducing the tension on the ACL and reducing the risk of injury (Oliver et al., 2014; Smith et al., 2012).

From the neuromuscular perspective, knee joint stability and protection against injury during movements with SSC relies on adequate feedback and feed-forward systems to improve muscular stiffness during functional tasks (Riemann and Lephart, 2002). Active muscular stiffness contributes to leg stiffness, which is commonly used as a measure to characterize SSC function during functional tasks. Leg stiffness points to an ability to generate strength and resist to deformation resulting from movement including a direct transition from eccentric to concentric muscle contraction (Padua et al., 2006). Greater level of leg stiffness increases the ability of the dynamic mechanisms to generate rebound movements during the stretch shortening cycle (Granata et al., 2002a; Padua et al., 2005) and leads to a lesser probability of excessive load of the knee passive structures such as the ACL (Hughes and Watkins, 2006).

Limited number of studies have explored gender differences in stiffness (both passive and active) in youth, and especially during growth and maturation. Limited previous data suggest differences between boys and girls in stiffness with higher levels in boys compared to age-matched girls (Blackburn et al., 2004; Granata et al., 2002a; Granata et al., 2002b; Kitamura et al., 2017). In a recent study on 11-20 year old youth with no experience with competitive sport (Laffaye et al., 2016) the authors reported significant gender difference in the case of both absolute and relative (values normalised for body weight) leg stiffness in the 17-18 years age group only with higher values in boys. Hewett et al. (2004) found a significant decrease in neuromuscular control of the muscles spanning the knee in girls from puberty onset extending into late puberty, which was not observed in the boys studied. It is also recognised that stiffness in boys is lower compared with adults and the quality of neuromuscular functions increases with age in children until post puberty (around 15–16 years of age) (Di Giminiani and Visca, 2017; Laffaye et al., 2016; Lloyd et al., 2011, 2012; Oliver and Smith, 2010). However only a few studies have been focused on girls and with conflicting results (De Ste Croix, 2012). Moreover, owing to the limited published literature for paediatric leg stiffness measures, whether the same trend exists for relative stiffness is unclear (De Ste Croix et al., 2019; Strniště et al., 2019).

Another way of assessing SSC efficiency is to calculate the reactive strength index (RSI). RSI has been developed as a tool to monitor stress on the muscle-tendon complex during plyometric exercise and is described as the ability of transition from eccentric to concentric muscle action (Flanagan and Comyns, 2008; Young, 1995). It was suggested that RSI is a potential risk factor in ACL injury (Toumi et al., 2006) and that low values of RSI seem to be a reliable measure of poor SSC function for athletes (Lloyd et al., 2009). This assumption was confirmed in a recent 10-year longitudinal study exploring injury risk factors, which indicated that low RSI was one of eight significant predictors of ACL injury (Raschner et al., 2012). In another study (Müller et al., 2017), authors suggested that youth athletes with a higher RSI should be considered as individuals at a lower injury risk or as more robust athletes (which may be demonstrated from fewer days of absence from training) as shown in youth alpine ski racers. However, others have also indicated that RSI increases with the level of performance, suggesting a potential training affect above the natural development due to growth and maturation (Flanagan and Comyns, 2008).

Longitudinal studies exploring gender differences in SSC capability are not available and our current understanding is based on cross-sectional data, which is limiting. In the study by Laffaye et al. (2016) boys demonstrated significantly higher RSI than girls from 15-16 years onward, with significant difference at 17-18 and 19-20 years. The authors suggested that15-16 years is a threshold of maturity and gender differentiation in SSC efficiency. However, there are also recent studies on adolescent male players, although primarily focused on fatigue-related responses to soccer game and simulated basketball game respectively (De Ste Croix et al., 2019; Lehnert et al., 2018), where no age effects have been found. Studies dealing with the effect of age on RSI point to a gradual improvement in reactive strength during adolescence due to the development of motor control (Lloyd et al., 2011, 2012).

Collectively, greater knowledge around gender differences in stiffness and reactive strength during hopping tasks in important periods of adolescence is useful for better understanding of the differences in SSC efficiency to develop appropriate performance enhancing and injury management strategies, especially during periods of growth and maturation with higher incidence of ACL injuries. To the best of our knowledge, there are no longitudinal studies focusing on the influence of gender on SSC capability in youth athletes, which has been suggested to be associated with lower level of knee joint stability and increased risk of injury. The goal of the present study was to identify potential gender differences in leg stiffness and reactive strength during hopping tasks in 13 to16-year olds team sports players.

Methods

Participants

For the purpose of this study, 149 youth male and female players aged 13 years (competition age groups U14; girls n = 39 boys n = 44) and 15 years (competition age groups U16; girls n = 21, boys n = 45) of various team sports (basketball, soccer, handball, and floorball) who played in the highest national league in his/her sport were recruited. On average, the players trained for five days a week and normally played one competitive match per week during the competitive season. The criteria for inclusion into this study was absence of serious thigh and knee injuries in the last six months before the first measurement and participation in the evaluations. Finally, the data were obtained from 51 girls (U14: n = 31, U16: n = 20) and 65 boys (U14: n = 32, U16: n = 33) (Table 1). The reasons for exclusions were interruption of the participation in the training sessions due to injury longer than 4 weeks during the observed two competitive seasons, absence at a test session, change of club, and termination of the contract. All players were fully informed about the aim of the study and the testing procedures that would be employed. Written informed consent in accordance with the Declaration of Helsinki 2013 regarding the use of human subjects to the testing procedures and the use of the data for further research was obtained from the players' parents and the players.

Biological maturity of the players was predicted by calculation of age from peak height velocity (PHV) using the sex appropriate equation of Mirwald et al. (2002). Leg length, tibia length, standing and sitting height measures were obtained using a stadiometer A-226 Anthropometer (Trystom, Olomouc, Czech Republic). Body mass was measured using Tanita UM-075 weighing scales (Tanita, Tokyo, Japan).

Measures

Leg stiffness was calculated from contact time data obtained during a sub-maximal bilateral hopping protocol. Coefficient of variation for female youth soccer players has been reported to be 8.2% (De Ste Croix et al., 2017). Players performed three sets of a 20 sub-maximal bilateral hopping protocol. For each trial, participants were instructed to perform consecutive hops on a mobile 2-axis force plate PS-2142 (Pasco, Roseville, CA, USA) at a frequency of 2.5 Hz to reflect the typical behaviour of a spring model (Lloyd et al., 2009). Hopping frequency was maintained via an audio signal from a quartz Wittner metronome (WITTNER, Isny, Germany). Participants were instructed to: a) keep hands on the hips at all times to avoid upper body interference; b) jump and land on the same spot; c) land with legs fully extended and to look forward at a fixed position to aid balance. For data analysis the first 4 hops were discounted and the next 10 consecutive hops closest to the hopping frequency were used for analysis. Absolute leg stiffness ($kN \cdot m^{-1}$) was calculated using the equation proposed by Dalleau et al. (2004). Relative leg stiffness was determined by dividing absolute leg stiffness by body mass and limb length to provide a dimensionless value. This method has been shown to be valid and reliable in youth athletes (De Ste Croix et al., 2017;

Lloyd et al., 2009).

RSI was determined during a 5 maximum hop test which was performed on a mobile contact mat (FITRO Jumper, Fitronic, Bratislava, Slovakia) and the RSI variable was calculated using the equation of Flanagan and Comyns (2008). The participants were instructed to maximize jump height and minimize ground contact time (Dalleau et al., 2004). The first hop served as a counter movement jump (impetus) and was consequently excluded from analysis, with the 4 remaining hops averaged for analysis of RSI. The players performed three trials of five consecutive jumps wearing trainers with a 2 min rest interval between trials. The greatest average value of RSI from the three trials was used for subsequent analysis. This method has been shown to be valid and reliable in youth athletes (Lloyd et al., 2009).

Design and Procedures

To avoid changes that might occur during the pre-season and after the rest period (in the off-season), measurements were 2–3 matches into the 2016/2017 and 2017/2018 competitive seasons and were performed at least 3 days after the competitive match. The day before testing, the players were not exposed to any high intensity exercises. All outcome variables were determined using a randomized "circuit" style approach to minimize testing time. Each outcome variable station was run by an experienced researcher. The following measures were used for the purposes of this study: RSI, absolute leg stiffness (ALS), relative leg stiffness (RLS).

Statistical analysis

The statistical analysis was performed using the data analysis software Statistica (Version 12; StatSoft, Inc., Tulsa, OK, USA). Firstly, the distribution of raw data sets was checked for homogeneity and skewness using the Kolmogorov-Smirnov test. Descriptive statistics including means and standard deviations were calculated for each measure. A two-way ANOVA was performed to determine significant group and time effects for raw outcome variables (stiffness/RSI x gender x age category). The Mann-Whitney U test was used to compare each age group change based on year. The Scheffe post hoc test was performed to identify any significant effects or interactions. The effect size was assessed by the Eta squared coefficient (η^2). Calculated effect sizes were classified as small ($\eta^2 \leq 0.05$), medium ($0.06 \leq \eta^2 \leq 0.13$), and large ($\eta^2 \geq 0.14$). The level of significance was set at $p \leq 0.05$ for all tests.

Results

Descriptive data for girls and boys from competitive age groups U14 and U16 can be found in Table 2.

Absolute leg stiffness

A significant main effect on absolute leg stiffness for gender was found in the case of both the group U14 ($p = 0.022$, $\eta^2 = 0.084$) and U16 ($p < 0.001$, $\eta^2 = 0.224$) with higher values in boys in both the groups and in both years of evaluations. In the U14 the gender differences were significant in the 1st year of measurement only (p = 0.027), while in U16 the significant differences were found only in the 2nd year of measurement ($p < 0.001$). An age × gender interaction was significant only in the U14 group ($p = 0.030$, $\eta^2 = 0.076$). The absolute leg stiffness decrease between the 1st and 2nd measurement was significantly higher in the U14 boys in comparison to U14 girls ($p = 0.013$, Z = -2.48), who maintained their values (Figure 1).

Relative leg stiffness

A significant main effect on relative leg stiffness was found for gender in the case of both the U14 (p < 0.001; $\eta^2 = 0.195$) and U16 groups (p = 0.008, $\eta^2 = 0.128$) with higher values in boys than in girls in both the groups and both annual evaluations. In the U14 the differences were significant in the 1st year of measurement only (p = 0.001), while in U16 the differences were significant in the 2nd year of evaluations only (p = 0.022). An age × gender interaction was nonsignificant in both age categories. The relative leg stiffness decrease between first and second measurement was significantly higher in U14 boys ($p = 0.036$, Z = -2.09), U16 boys ($p = 0.047$, Z = -1.99) and U16 girls ($p < 0.01$, Z = -3.63) group in comparison to U14 girls, who maintained their values (Figure 1).

Reactive strength index

In the RSI, a nonsignificant effect on RSI was found for gender in the case of group U14 ($p = 0.446$, $\eta^2 = 0.013$), while, a significant main effect on RSI for gender ($p < 0.001$ $\eta^2 = 0.429$) was observed in U16 group. Values were significantly higher in boys than in girls ($p = 0.001$; $p < 0.001$) in both measured years in U16. An age × gender interaction was non-significant in both age categories. In U14 differences were non-significant in both years (p = 0.997, p = 0.635) with nearly identical values in the 1st year and non-significant but higher in boys than in girls in the 2nd year of measurement. During two years, RSI increased non-significantly (p = 0.280) in U14 boys, while no trend was recorded in girls (p=1.000). In the case of U16, RSI increased non-significantly in boys (p = 0.459) and decreased non-significantly in girls (p = 0.939).

Table 1.

Anthropometric characteristics of players according to gender, competition age group and year of measurement.

Parameter	Gender	U14		U16	
		M1	M2	M1	M2
Number	Girls	31	31	20	20
	Boys	32	32	33	33
Stature (cm)	Girls	162.4 ± 7.4	164.0 ± 13.6	166.1 ± 5.8	167.3 ± 6.3
	Boys	166.0 ± 9.3	172.8 ± 9.5	179.2 ± 7.2	182.0 ± 5.9
Body mass (kg)	Girls	54.4 ± 10.3	59.0 ± 9.2	59.1 ± 7.9	61.5 ± 8.0
	Boys	52.6 ± 9.8	60.9 ± 9.7	66.7 ± 9.3	72.8 ± 9.3
Maturity offset (y)	Girls	–0.5 ± 0.8	0.3 ± 0.7	0.9 ± 0.5	1.7 ± 0.6
	Boys	–0.1 ± 0.7	0.6 ± 0.7	1.7 ± 0.7	2.7 ± 0.7

Note. M1 = first measurement; M2 = second measurement; U14 = competition age groups U14; U16 = competition age groups U16.

Table 2

Mean (±SD) values for hopping tests characteristics.

Parameter	Gender	U14		U16	
		M1	M2	M1	M2
Absolute leg stiffness ($kN·m^{-1}$)	Girls	21.4 ± 4.5	22.4 ± 4.0	24.6 ± 5.0	21.9 ± 3.5
	Boys	25.4 ± 5.8	23.8 ± 5.8	28.1 ± 5.7	27.9 ± 4.8
Relative leg stiffness	Girls	30.5 ± 4.6	30.8 ± 4.8	34.1 ± 6.8	28.6 ± 3.9
	Boys	36.3 ± 6.2	33.8 ± 6.2	36.9 ± 7.6	34.1 ± 5.0
Reactive strength index	Girls	1.36 ± 0.23	1.45 ± 0.28	1.34 ± 0.24	1.28 ± 0.21
	Boys	1.31 ± 0.28	1.95 ± 2.13	1.74 ± 0.33	1.82 ± 0.33

Note. M1 = first measurement; M2 = second measurement; U14 = competition age groups U14; U16 = competition age groups U16.

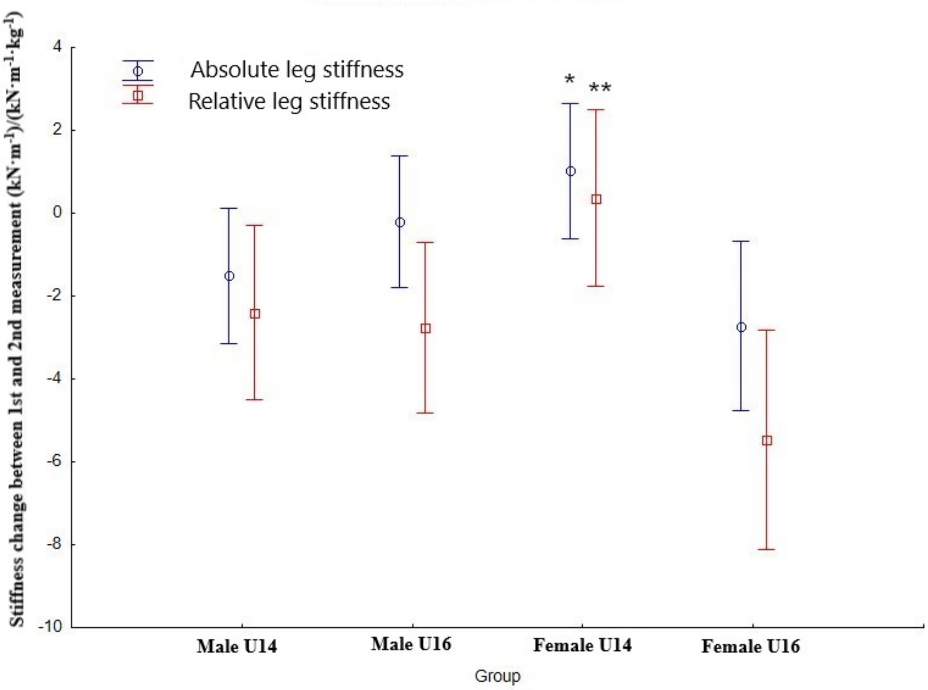

Figure 1

Comparison of groups changes in absolute and relative leg stiffness and RSI based on age category.

*Note. *difference to male U14, **difference to other groups.*

Discussion

To the best of our knowledge, the current study is the first longitudinal study exploring gender differences in SSC capability determined by leg stiffness and RSI in trained youth during periods of growth and maturation. The main finding of this study is that female players at the age of 13-16 years exhibited significantly lower absolute leg stiffness, relative leg stiffness, and RSI than males. In the case of RSI, a significant difference was found only in the U16 group in both observed years (age 15-16 y). Our data are consistent with previous limited literature suggesting lower SSC capability in adolescent females compared to males. On the contrary, the results only partly support the theory that quality of neuromuscular function increases with age in children until post puberty. Specifically, positive, however non-significant, trends were observed only in RSI in boys.

Leg stiffness – gender differences

In the current study, a significant main effect on absolute leg stiffness and relative leg stiffness was found for gender in competition age groups U14 and U16, with higher values in boys in both considered years (U14: absolute leg stiffness +6.3% and +18.7%, respectively; relative leg stiffness +19.0% and +9.7%, respectively; U16: absolute leg stiffness +14.2% and +27.4%, respectively; relative leg stiffness +8.2% and +19.2%, respectively). In U14, the effect size was medium for absolute leg stiffness and large for relative leg stiffness. In U16, the effect size was large for absolute leg stiffness and medium for relative leg stiffness. The findings of our study support results of most previous studies which reported differences between male and female leg stiffness, with girls showing less active muscle stiffness than boys during open-chain and closed-chain functional tasks (Blackburn et al., 2004; Granata et al., 2002a; Granata et al., 2002b; Padua et al., 2005). However, in a cross-sectional study by Laffaye et al. (2016) on 11-20 years boys and girls with no experience with competitive sport only a trend for gender difference was observed in absolute leg stiffness with higher values in boys and no trend for relative leg stiffness. Significant gender difference in the case of both absolute leg stiffness and relative leg stiffness (values normalised for body weight) were observed in the 17-18 years age group with higher values in boys. Thus, further body of evidence is needed to clarify gender differences in leg stiffness during preadolescence and adolescence.

Leg stiffness – changes with age

The data of the present study do not indicate an age related increase of stiffness associated with positive changes in neural regulation of the SSC in observed groups. In the case of U14, both absolute leg stiffness and relative leg stiffness were maintained in the 2nd year of evaluations (girls: absolute leg stiffness –4.7%; relative leg stiffness +1.0%; boys: absolute leg stiffness –6.3 % a relative leg stiffness –6.9%). In U16 in the case of absolute leg stiffness, no trend was observed in boys while there was a non-significant decrease in girls (–11%). Relative leg stiffness decreased in both boys and girls, however only in girls, it was significant (girls –16.1%; boys –7.6%).

The finding of the present study contradicts most of the other studies, in particular in boys, which shows an increase of stiffness with age in pre- and post-pubescence (although non-linear) (Di Giminiani and Visca, 2017; Laffaye et al., 2016; Lloyd et al., 2011, 2012; Oliver and Smith, 2010). In the case of absolute leg stiffness our data are also not in line with the expectation that increases in body mass as a result of puberty will lead to increases in absolute leg stiffness in order to maintain true spring-mass model behaviour during ground contact (Granata et al., 2002a). However, in a recent study Laffaye et al. (2016) reported a progressive increase in absolute leg stiffness with age in 11-20-year-old boys and girls (except of 17-18-year-old in later case), but not in relative leg stiffness. Our finding of a significant decrease in relative leg stiffness between 15-16 years in girls partly coincides with the results of the study by De Ste Croix (2012), in which the authors reported no significant age difference in relative leg stiffness in 12-17-year-old girls, but, although not statistically significant, lower stiffness was noticeable in 16-17-year-old compared to younger age groups. Similarly, Lloyd et al. (2011) observed plateauing of relative leg stiffness in 13-16 year old subjects in a study of 7-17-year-old boys.

In the current study, an age × gender interaction was significant only in the case of absolute leg stiffness in the U14 group. The data surprisingly show that in this group absolute leg stiffness decreases with increasing age in males and increases in females, so the difference between genders with increasing age decreases. However, it is appropriate to mention that changes in two measured years were small in both genders (boys –6.3%; girls +4.7%). This result is not in line with the suggestion of Laffaye et al. (2016) that from the point of view of evolution of leg stiffness, it seems that the main increase occurs after 14 years (with higher values in boys), and that it is expected that the age-related increase in muscular mass impacts on absolute leg stiffness values and may differ between boys and girls during puberty.

Reactive strength index – gender differences

The data from the present study indicate differences between girls and boys in reactive strength. The gender disparity, although non-significant, appeared in the age group U14 in the 2nd evaluation period (+ 15%), however a significant main effect on RSI for gender was observed only in the U16 group in both annual evaluations. The values in boys were significantly higher than in girls (+13.0% and +14.2%). This finding is in agreement with the knowledge that during puberty differences between males and females are magnified as a result of distinct hormonal changes (Beunen and Malina, 1988). Our data coincide with the finding of Laffaye et al. (2016), who found a significant main effect on RSI for gender in 11-19 years old non-athletes, although significant gender differences for RSI were observed from the age of 17 years, with lower values in girls compared to boys. We assume that observation of the significant gender differences at an earlier age (15 years) in the present study could be explained by the systematic exploitation of the higher adaptation potential of boys than girls associated with hormonal changes during the regular training process.

Our finding of gender differences in the U16 group in both years of measurement in the case of RSI may have a consequence for injury risk and performance. This is based on suggestions that the growing disparity in strength accounts for the larger proportion of ACL injuries in 14-18 years old athletes (Griffin et al., 2006), and that the period between 16 and 18 years is the riskiest period of life (Shea et al., 2004). However, it is necessary to consider that in the current study, an age × gender interaction was not significant, indicating that dynamics of change in reactive strength within two years of observation was not different in girls and boys.

Reactive strength index – changes with age

In the observed team sport players, RSI increased, although non-significantly, only in boys in both the U14 (14.6%) and U16 age groups (10.5 %). These data confirm a gradual improvement in reactive strength during adolescence due to the development of motor control, and is in line with improvements in efficiency of the SSC, in particular in post-pubertal boys reported in previous studies (Laffaye et al., 2016; Lloyd et al., 2011, 2012; Radnor et al., 2018). These studies also indicate that the increase of SSC performance with age in jumping tasks in youth is non-linear (Laffaye et al., 2016; Lloyd et al., 2011). This progress is in particular due to changes in the neuromuscular system, which include increases in muscle size, pennation angle, fascicle length, tendon stiffness, motor unit recruitment and pre-activation (Radnor et al., 2018).

Findings of the present study are also in agreement with the statement by Laffaye et al. (2016), that 15-16 years of age may be a threshold of maturity for lower limb behaviour in untrained adolescents. Furthermore, there is evidence that RSI increases during adolescence while contact time duration in boys does not change after the age of 13-14 years (Laffaye et al., 2016), which implies that jumping performance increases with age for the same contact time. Although in our study, we did not analyse the changes in contact time and flight time separately, based on the increase in RSI, we may assume improvement in the ability to increase force in a shorter amount of time as well in observed male players. This has an implication for the increase in jump height as other injury risk indicator as well as sport performance indicator in many sports.

One of the limits of the present study is that the gender differences only in post-PHV trained players during two consecutive years were explored. It is also necessary to consider that gender differences in the observed groups of active youth may have been affected by differences in training loads, in particular the specificities of sport training and competition loads of individual team sports (basketball, soccer, handball, and floorball).

Conclusions

In the present study, 13-16 years old trained female players exhibited significantly lower leg stiffness compared to trained males of the same age. In the case of RSI significant differences were found only at the age of 15-16 years. Results of this study support previous limited cross-sectional findings, mostly related to non-athletes, suggesting lower SSC capability in adolescence females compared to males. On the contrary, our findings only partly support the theory that quality of neuromuscular functions increases with age in children until post puberty. The results of the study may be useful for the understanding of gender and age-related aspects of SSC efficiency during adolescence and may help understand and identify risk factors of ACL injury.

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References

Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: A 13-year review. *Am J Sports Med*, 2005; 33: 524-530.

Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lázaro-Haro C, Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*, 2009; 17: 705-729.

Beunen G, Malina RM. Growth and physical performance relative to the timing of the adolescent spurt. *Exerc Sport Sci Rev*, 1988; 16: 503-540.

Blackburn JT, Riemann BL, Padua DA, Guskiewicz KM. Sex comparison of extensibility, passive, and active stiffness of the knee flexors. *Clin Biomech*, 2004; 19: 36-43.

Dalleau G, Belli A, Viale F, Lacour JR, Bourdin M. A simple method for field measurements of leg stiffness in hopping. *Int J Sports Med*, 2004; 25: 170-176.

De Ste Croix M, Lehnert M, Maixnerova E, Zaatar A, Svoboda Z, Botek M, Varekova R, Stastny P. Does maturation influence neuromuscular performance and muscle damage after competitive match-play in youth male soccer players? *Eur J Sport Sci*, 2019; 19: 1130-1139.

De Ste Croix MBA. *The effect of football specific fatigue on dynamic knee stability in female youth players* (UEFA Research Grant Programme Final Report). 2012.

De Ste Croix MBA, Hughes JD, Lloyd RS, Oliver JL, Read PJ. Leg stiffness in female soccer players: Intersession reliability and the fatiguing effects of soccer-specific exercise. *J Strength Cond Res*, 2017; 31: 3052-3058.

Di Giminiani R, Visca C. Explosive strength and endurance adaptations in young elite soccer players during two soccer seasons. *PLOS ONE*, 2017; 12: e0171734.

Flanagan EP, Comyns TM. The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Str Cond J*, 2008; 30: 32-38.

Granata KP, Padua DA, Wilson SE. Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *J Electromyogr Kinesiol*, 2002a; 12: 127-135.

Granata KP, Wilson SE, Padua DA. Gender differences in active musculoskeletal stiffness. Part I. Quantification in controlled measurements of knee joint dynamics. *J Electromyogr Kinesiol*, 2002b; 12: 119-126.

Griffin LY, Albohm MJ, Arendt EA, Bahr R, Beynnon BD, DeMaio M, Dick RW, Engebretsen L, Garrett Jr WE, Hannafin JA, Hewett TE, Huston LJ, Ireland ML, Johnson RJ, Lephart S, Mandelbaum BR, Mann BJ, Marks PH, Marshall SW, Myklebust G, Noyes FR, Powers C, Shields Jr C, Shultz SJ, Silvers H, Slauterbeck J, Taylor DC, Teitz CC, Wojtys EM, Yu B. Understanding and preventing noncontact anterior cruciate ligament injuries: A review of the Hunt Valley II Meeting, January 2005. *Am J Sports Med*, 2006; 34: 1512-1532.

Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am*, 2004; 86: 1601-1608.

Hughes G, Watkins J. A risk-factor model for anterior cruciate ligament injury. *Sports Med*, 2006; 36: 411-428.

Kabešová H, Vaněčková J, Tarantová N, Heidler J, Černá L. The effects of the application of dynamic and PNF stretching on the explosive strength abilities of the lower limbs in warm-up in hockey and football athletes *TRENDS in Sport Sciences,* 2019; 1(26): 33-39

Kalinowski P, Sysiak W, Jerszyński D, Gronek P. Resistance training in football. *TRENDS in Sport Sciences*, 2020; 27(1): 25-28

Kitamura K, Pereira LA, Kobal R, et al. Loaded and unloaded jump performance of top-level volleyball players from different age categories. *Biol Sport*, 2017; 34(3): 273-278

Krosshaug T, Nakamae A, Boden BP, Engebretsen L, Smith G, Slauterbeck JR, Hewett TE, Bahr R. Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *Am J Sports Med*, 2007; 35: 359-367.

Laffaye G, Choukou MA, Benguigui N, Padulo J. Age- and gender-related development of stretch shortening cycle during a sub-maximal hopping task. *Biol Sport*, 2016; 33: 29-35.

Lehnert M, Hůlka K, De Ste Croix M, Horutová K. Acute effect of basketball-specific exercise on lower limb injury risk mechanisms in male basketball players U16 and U18. *Res Invest Sports Med*, 2018; 2: 000539.

Lloyd RS, Oliver JL, Hughes MG, Williams CA. Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. *J Sports Sci*, 2009; 27: 1565-1573.

Lloyd RS, Oliver JL, Hughes MG, Williams CA. The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys. *J Strength Cond Res*, 2011; 25: 1889-1897.

Lloyd RS, Oliver JL, Hughes MG, Williams CA. Age-related differences in the neural regulation of stretch-shortening cycle activities in male youths during maximal and sub-maximal hopping. *J Electromyogr Kinesiol*, 2012; 22: 37-43.

Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, Garrett Jr W. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med*, 2005; 33: 1003-1010.

Mirwald RL, Baxter-Jones ADG, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc*, 2002; 34: 689-694.

Müller L, Hildebrandt C, Müller E, Fink C, Raschner C. Long-Term athletic development in youth alpine ski racing: The effect of physical fitness, ski racing technique, anthropometrics and biological maturity status on injuries. *Front Physiol*, 2017; 8.

Myklebust G, Mæhlum S, Holm I, Bahr R. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scand J Med Sci Sports*, 1998; 8: 149-153.

Nicol C, Avela J, Komi PV. The stretch-shortening cycle: A model to study naturally occurring neuromuscular fatigue. *Sports Med*, 2006; 36: 977-999.

Oliver JL, De Ste Croix MBA, Lloyd RS, Williams CA. Altered neuromuscular control of leg stiffness following soccer-specific exercise. *Eur J Appl Physiol*, 2014; 114: 2241-2249.

Oliver JL, Smith PM. Neural control of leg stiffness during hopping in boys and men. *J Electromyogr Kinesiol*, 2010; 20: 973-979.

Padua DA, Arnold BL, Perrin DH, Gansneder BM, Carcia CR, Granata KP. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. *J Athl Train*, 2006; 41: 294-304.

Padua DA, Garcia CR, Arnold BL, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Motor Behav*, 2005; 37: 111-125.

Radnor JM, Oliver JL, Waugh CM, Myer GD, Moore IS, Lloyd RS. The influence of growth and maturation on stretch-shortening cycle function in youth. *Sports Med*, 2018; 48: 57-71.

Raschner C, Platzer HP, Patterson C, Werner I, Huber R, Hildebrandt C. The relationship between ACL injuries and physical fitness in young competitive ski racers: A 10-year longitudinal study. *Br J Sports Med*, 2012; 46: 1065-1071.

Riemann BL, Lephart SM. The sensorimotor system, part I: The physiologic basis of functional joint stability. *J Athl Train*, 2002; 37: 71-79.

Rumpf MC, Cronin J. Injury incidence, body site, and severity in soccer players aged 6–18 years: Implications for injury prevention. *Str Cond J*, 2012; 34: 20-31.

Shea KG, Pfeiffer R, Jo HW, Curtin M, Apel PJ. Anterior cruciate ligament injury in pediatric and adolescent soccer players: An analysis of insurance data. *J Pediatr Orthop*, 2004; 24: 623-628.

Smith HC, Vacek P, Johnson RJ, Slauterbeck JR, Hashemi J, Shultz S, Beynnon BD. Risk factors for anterior cruciate ligament injury: A review of the literature - part 1: Neuromuscular and anatomic risk. *Sports Health*, 2012; 4: 69-78.

Strniště M, Hůlka K, Lehnert M, Maixnerová E, Vařeková R, Lazecká Š. Neuromuscular control of the knee joint during basketball season in male youth players. *Acta Gymnica*, 2019; 49: 125-131.

Toumi H, Poumarat G, Best TM, Martin A, Fairclough J, Benjamin M. Fatigue and muscle-tendon stiffness after stretch-shortening cycle and isometric exercise. *Appl Physiol Nutr Metab*, 2006; 31: 565-572.

Waldén M, Hägglund M, Werner J, Ekstrand J. The epidemiology of anterior cruciate ligament injury in football (soccer): A review of the literature from a gender-related perspective. *Knee Surg Sports Traumatol Arthrosc*, 2011; 19: 3-10.

Young W. Laboratory strength assessment of athletes. *N Stud Athletic*, 1995; 10: 88-96.

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