NORDIC HAMSTRING STRENGTH OF HIGHLY TRAINED YOUTH FOOTBALL PLAYERS AND ITS RELATION TO SPRINT PERFORMANCE

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ABSTRACT

Markovic, G, Sarabon, N, Boban, F, Zoric, I, Jelcic, M, Sos, K, and Scappaticci, M. Nordic hamstring strength of highly trained youth football players and its relation to sprint performance. *J Strength Cond Res* XX(X): 000–000, 2018—We aimed to characterize Nordic hamstring (NH) strength and bilateral NH strength asymmetry in highly trained youth footballers and to investigate the relationship between NH strength and sprint performance. Twenty-two adult and 133 highly trained youth footballers in the age groups U12–U18 participated in this study. Eccentric hamstring strength was assessed using the NH device. Youth footballers ($n = 119$) also performed 20-m sprint test. Age-related changes in absolute and relative NH strength, and bilateral NH strength asymmetry were analyzed using 1-way analysis of variance. The linear relationship between relative NH strength and sprint performance was established using a Pearson correlation analysis. Significant age-related increases ($F = 3.6$–18.9; all $p < 0.01$) in NH strength were reported for all units except $\text{N}\cdot\text{kg}^{-1}$ ($F = 1.9$; $p = 0.08$). The largest differences in absolute NH strength were seen between U15 and U16 groups. Bilateral NH strength asymmetry varied from 8 to 16% ($F = 1.8$; $p = 0.09$) across all age groups. A large correlation between NH strength and sprint performance was observed ($r = -0.52$; $p < 0.01$). Our results indicate that NH strength increases nonlinearly with players' age, with the highest values observed in U16 group. Furthermore, bilateral NH strength asymmetry varied nonsignificantly between 8 and 16%. Finally, 27% of variance of sprint performance of youth footballers could be explained by relative NH strength. The reported NH strength data could be used as normative standards during testing and training of youth football players. Present results also suggest that coaches should pay close attention to eccentric hamstring function in youth footballers.

KEY WORDS muscle injuries, growth and maturation, association football, sprinting

INTRODUCTION

With over 265 million active participants, association football is the most popular sport in the world (11). Although playing football could have positive health benefits (20), it also poses a relatively high risk of injuries (11). The most prevalent form of injury in football is hamstring strain injury (HSI), which accounts for 12–16% of all injuries (11,24). The HSI also has a relatively high recurrence rate (i.e., 14–63%) (8). Finally, a recent longitudinal study has shown that HSIs have increased by 4% in men's football in the past 13 years (12). Clearly, HSI represents a significant health, performance, and economic burden in football (13).

Among numerous risk factors associated with HSIs (25), hamstring weakness and bilateral strength asymmetries measured in the eccentric mode have received considerable scientific interest (26,31,32). Recently, Opar et al. (24) have developed a field test for measuring eccentric hamstring strength and strength asymmetries during the Nordic hamstring (NH) exercise. This testing methodology proved to be valid in predicting the risk of HSIs in sports involving high-speed running (26,32), although controversy remains regarding the role of bilateral strength asymmetry as a risk factor (32). In addition, the regular use of NH exercise within a season proved to substantially reduce the incidence of HSIs in football players (28).

Despite its potential usefulness in reducing the risk of HSI in football and other sprint-based sports, there is a general lack of data regarding the age-related changes and reference

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Table 1. Physical characteristics and sprint performance for all groups of players (mean values ± *SD*).

Group	*N*	Body mass (kg)	Height (cm)	Body mass index (kg·m^{-2})	20-m sprint test (s)
U12	15	40.0 ± 6.7*	151.7 ± 7.5*	17.2 ± 1.2*	3.49 ± 0.14§§
U13	18	50.9 ± 8.7†	163.9 ± 8.7†	18.8 ± 1.6‡	3.35 ± 0.13‖‖
U14	20	56.0 ± 7.6‡	168.5 ± 8.1‡	19.7 ± 1.3‡	3.31 ± 0.10¶¶
U15	21	60.8 ± 9.2§	173.9 ± 7.9§	20.1 ± 1.9‡	3.21 ± 0.14##
U16	25	67.2 ± 6.0‖	176.6 ± 5.8‖	21.6 ± 1.6††	3.08 ± 0.10***
U17	16	69.5 ± 4.9¶	177.7 ± 5.8¶	22.1 ± 1.6#	2.99 ± 0.09†††
U18	8	70.1 ± 3.6#	175.2 ± 7.2#	22.9 ± 2.0#	2.99 ± 0.09†††
1st team	22	79.1 ± 7.9**	183.1 ± 6.1**	23.5 ± 1.4‡‡	n/a

*Significantly different ($p < 0.01$) from U13, U14, U15, U16, U17, U18, and the first team.
†Significantly different ($p < 0.01$) from U12, U15, U16, U17, U18, and the first team.
‡Significantly different ($p < 0.01$) from U12, U16, U17, U18, and the first team.
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#Significantly different ($p < 0.01$) from U12, U13, U14, and U15.
**Significantly different ($p < 0.01$) from U12, U13, U14, U15, U16, and U17.
††Significantly different ($p < 0.01$) from U12, U13, U14, U15, and the first team.
‡‡Significantly different ($p < 0.01$) from U12, U13, U14, U15, and U16.
§§Significantly different ($p < 0.01$) from U13, U14, U15, U16, U17, and U18.
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†††Significantly different ($p < 0.01$) from U12, U13, U14, U15, and U16.

standards for NH strength and bilateral asymmetry in youth football players. To this point, only one study (2) reported NH strength (but not bilateral strength asymmetry) of young football players of a relatively narrow age range (U17, U20, and U21). Here, we aimed to characterize NH strength and bilateral NH strength asymmetry in highly trained U12–U18 football players. Given that the eccentric hamstring strength could also be of importance for football-specific movement performance such as sprint acceleration (21), we also examined and quantified the relationship between NH strength and sprint performance in youth footballers.

METHODS

Experimental Approach to the Problem

In this cross-sectional study, we applied a between-subject design to examine the group differences in NH strength and bilateral NH strength asymmetry among highly trained youth football players. We also applied correlational analysis to establish the linear relationship between NH strength and sprint performance of youth football players. Given that the results of NH strength seem to be largely body-mass dependent (2), we have reported both the absolute and body-mass normalized data using various normalization procedures.

Subjects

Altogether, 133 young (age range: 11–17 years) and 22 adult (age range: 19–30 years) highly trained football players (no goalkeepers) participated in this study. The first team played in the Union of European Football Associations (UEFA) Champions League in the last 3 seasons. Players' demographic characteristics are described in Table 1. Players with a previous or current lower-extremity injury that had not yet been fully rehabilitated were excluded from the study. Each player (and their parent/legal guardian for players <18 years) was informed about the purpose, benefits, and risks of the study before signing written informed consent, approved by the University of Zagreb, Faculty of Kinesiology Ethics Committee. The study was conducted in accordance with the Declaration of Helsinki (17).

Procedures

Testing was performed 1 week after the end of the national competitive season. Body mass and body height were measured to the nearest 0.1 kg and 0.5 cm using a calibrated medical scale and stadiometer (SECA 284; Seca, Hamburg, Germany). Body mass index (BMI) was calculated using a standard formula. Shank length, determined using previously described procedure (31), was used to convert the force measurements to torque.

The assessment of eccentric knee flexor strength was performed using a valid and reliable NH device (2,24,32). In brief, participants knelt on a padded board, with the ankles secured immediately superior to the lateral malleolus by individual ankle braces, which were attached to custom-made uniaxial load cells (FL34-100 kg; Forsentek Co., Shenzhen, China). After a standardized warm-up (running 5 minutes at a comfortable pace, 60 seconds of dynamic

TABLE 2. Absolute and relative eccentric Nordic hamstring (NH) strength and bilateral strength asymmetry for all groups of players (mean values ± *SD*).

		Eccentric force		Eccentric torque		Relative eccentric force		Relative eccentric torque		
Group	*N*	Dominant (N)	Nondominant (N)	Dominant (N·m)	Nondominant (N·m)	Dominant ($N\cdot kg^{-1}$)	Nondominant ($N\cdot kg^{-1}$)	Dominant ($N\cdot m\cdot kg^{-1}$)	Nondominant ($N\cdot m\cdot kg^{-1}$)	Bilateral asymmetry (%)
U12	15	154 ± 38*	166 ± 32¶	57.1 ± 15.1*	61.8 ± 13.9*	3.90 ± 1.00	4.21 ± 0.83	1.44 ± 0.35¶¶	1.55 ± 0.30	16.3 ± 13.3
U13	18	185 ± 51†	180 ± 47¶	73.6 ± 21.6¶	71.6 ± 20.6¶	3.66 ± 0.96	3.57 ± 0.85	1.45 ± 0.38##	1.41 ± 0.34#	15.5 ± 8.5
U14	20	240 ± 54‡	226 ± 47#	99.2 ± 25.0‡	93.3 ± 21.1‡	4.32 ± 0.95	4.08 ± 0.94	1.77 ± 0.38†††	1.67 ± 0.37	10.2 ± 8.9
U15	21	233 ± 61‡	222 ± 76#	92.0 ± 27.6‡	87.6 ± 33.5¶	3.84 ± 0.87	3.65 ± 1.12	1.50 ± 0.36	1.43 ± 0.45#	11.5 ± 13.2
U16	25	300 ± 64§	286 ± 60§	127.5 ± 27.6§	121.1 ± 25.8§	4.46 ± 0.87	4.24 ± 0.78	1.89 ± 0.36***	1.79 ± 0.32‖‖‖	8.9 ± 6.8
U17	16	269 ± 57‖	274 ± 72**	113.5 ± 23.8‖	115.9 ± 32.3††	3.88 ± 0.92	3.94 ± 1.04	1.64 ± 0.36	1.67 ± 0.45	10.0 ± 12.4
U18	8	287 ± 50‖	263 ± 42‖	113.6 ± 16.0‡	100.4 ± 13.2‡‡	4.11 ± 0.73	3.62 ± 0.60	1.64 ± 0.26	1.44 ± 0.21	11.4 ± 3.6
1st team	22	326 ± 68§	336 ± 58§	139.2 ± 36.5§	142.5 ± 28.9§§	4.17 ± 0.93	4.30 ± 0.86	1.77 ± 0.43†††	1.81 ± 0.36‖‖‖	8.1 ± 8.0

*Significantly different ($p < 0.05$) from U14, U15, U16, U17, U18, and the first team.
†Significantly different ($p < 0.05$) from U16, U17, U18, and the first team.
‡Significantly different ($p < 0.05$) from U12, U16, and the first team.
§Significantly different ($p < 0.05$) from U12, U13, U14, and U15.
‖Significantly different ($p < 0.05$) from U12 and U13.
¶Significantly different ($p < 0.05$) from U16, U17, and the first team.
#Significantly different ($p < 0.05$) from U16 and the first team.
**Significantly different ($p < 0.05$) from U12, U13, and the first team.
††Significantly different ($p < 0.05$) from U12, U13, U15, and the first team.
‡‡Significantly different ($p < 0.05$) from U12 and the first team.
§§Significantly different ($p < 0.05$) from U12, U13, U14, U15, U17, and U18.
‖‖‖Significantly different ($p < 0.05$) from U13 and U15.
¶¶Significantly different ($p < 0.05$) from U14, U16, and the first team.
##Significantly different ($p < 0.05$) from U16.
***Significantly different ($p < 0.05$) from U12, U13, and U15.
†††Significantly different ($p < 0.05$) from U12.

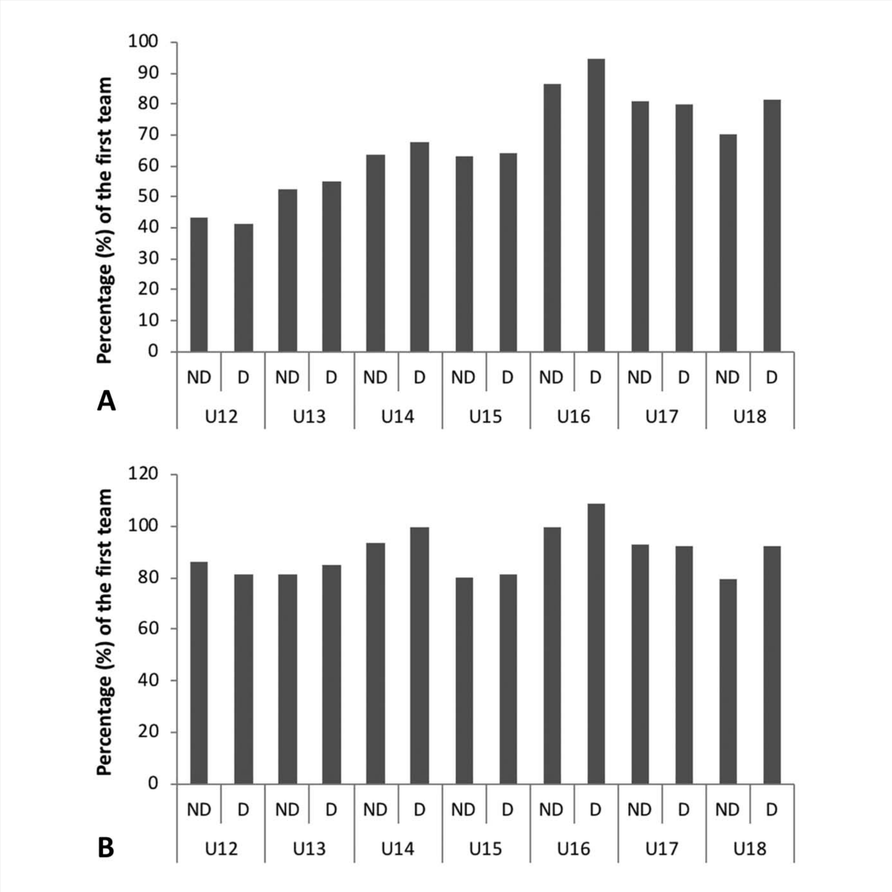

Figure 1. Absolute (A–in N·m) and relative (B–in N·m·kg^{-1}) Nordic hamstring strength of the dominant (D) and nondominant leg (ND) of all age groups, expressed as percentage of Nordic hamstring strength of the first team.

stretching, 2 minutes of skipping and footwork drills, 10 body-weight squats, 10 sit-ups, 10 forward lunges, 5 short sprint accelerations, and 1 set of 3 submaximal NHs), players performed 1 set of 3 maximal repetitions of the bilateral NH exercise. Instruction to the players was to gradually lean forward at the slowest possible speed while maximally resisting this movement with both lower limbs while keeping the trunk and hips in a neutral position throughout, and the hands held across the chest (32). They were verbally encouraged to ensure maximal effort.

After NH strength testing, youth footballers performed additional sprint-specific warm-up for 10 minutes on the outdoor artificial turf, followed by a maximal sprint 20-m test. Briefly, players were instructed to start freely from a standing stance behind the first pair of infrared photocells (TC Timing System; Brower Timing Systems; Draper, Utah), and to accelerate as fast as possible to the second pair of photocells positioned at a 20-m distance. Each player repeated the sprint test twice with approximately 1-minute rest between repetitions. Because of a short break between the end of the previous competitive season and the start of a new preseason (only 15 days), players of the first team did not participate in sprint testing. Also, 14 of 133 youth footballers (i.e., 3 players from U12, 3 players from U13, 3 players from U14, 3 players from U15, and 2 players from U17) did not participate in sprint testing because they had to play the official match for national teams in the following days.

Data analysis

Force signals were sampled at 1,000 Hz and were transferred to a personal computer using a 2-channel amplifier (InsAmp, Isotel, Logatec, Slovenia) and analogue-to-digital card (NIUSB-6009; National Instruments, Austin, TX, USA). Force signals were preprocessed with moving average filter using 10-ms window. The peak force value during the NH exercises for the left and right limb was analyzed using custom-developed software (ARS-Dynamometry, S2P, Ljubljana, Slovenia; developed in Labview 8.1; National Instruments). Eccentric knee flexor strength, reported in absolute (N and N·m) and relative (N·kg^{-1} and N·m·kg^{-1}) terms, was determined as the peak force from the 3 repetitions for dominant and nondominant limb. Bilateral strength asymmetry was expressed in % using the following formula (32):

$$\text{Bilateral strength asymmetry} = \left|1 - \frac{\text{dominant leg strength}}{\text{non-dominant leg strength}} \times 100.\right|$$

Statistical Analyses

All data are reported as mean ± *SD*. Reliability of NH strength testing proved to be high in a previous study (24). In our pilot study on a subsample of selected footballers (age: 14–17 years; $n = 30$), we have performed a second NH strength test 4 days after the first test and found high test-retest reliability of NH strength testing (intraclass correlation coefficient = 0.89). Normality of distribution of data was confirmed using a Shapiro-Wilk test. Age-related changes in NH strength and bilateral strength asymmetry were analyzed using 1-way analysis of variance and Tukey post hoc tests. Correlation analysis was used to determine the

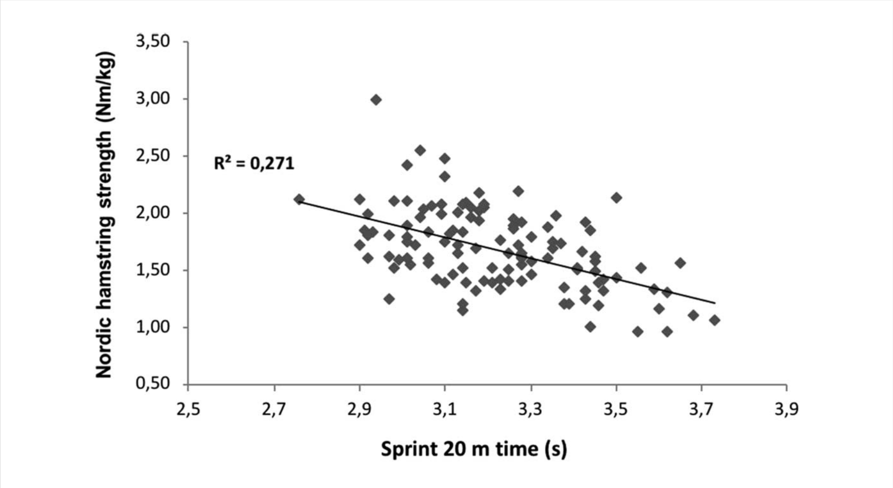

Figure 2. Linear relationship between relative Nordic hamstring strength and 20-m sprint time among youth football players ($n = 119$).

relationship between a player's sprint performance time and normalized NH strength (in $\text{N}\cdot\text{m}\cdot\text{kg}^{-1}$; averaged between legs). Pearson correlation coefficient was used to quantify the relationship. Thresholds of 0.1, 0.3, 0.5, 0.7, and 0.9 for small, moderate, large, very large, and extremely large correlation coefficients suggested by Hopkins et al. (18) were used. The level of significance was set at $p \leq 0.05$. All statistical analyses were performed with Statistica for Windows software, version 10.0 (StatSoft, Inc., Tulsa, OK, USA).

RESULTS

Physical characteristics, absolute and normalized NH strength data, and bilateral strength asymmetry data for all age groups are shown in Tables 1 and 2. We observed significant between-group differences ($F = 31.9$–48.3; all $p < 0.01$; $\eta^2 = 0.61$–0.72; observed power = 1.00) for body mass, height, and BMI (Table 1). Group differences in sprint performance times were also significant ($p < 0.01$; $\eta^2 = 0.47$; observed power = 1.00) (Table 1). Furthermore, significant between-group differences ($F = 3.6$–18.9; all $p < 0.01$; $\eta^2 = 0.16$–0.52; observed power = 0.96–1.00) were observed for NH strength reported as force, torque, and relative torque, but not as relative force ($F = 1.9$; $p = 0.08$; $\eta^2 = 0.09$; observed power = 0.73–0.75), respectively (Table 2). We found no significant between-group differences for bilateral NH strength asymmetry ($F = 1.8$; $p = 0.09$; $\eta^2 = 0.15$; observed power = 0.95).

Figure 1 depicts absolute (in $\text{N}\cdot\text{m}$) and relative (in $\text{N}\cdot\text{m}\cdot\text{kg}^{-1}$) NH strength of all age groups expressed as % of NH strength of the first team.

We observed a large inverse relationship between normalized NH strength and 20-m sprint time ($r = -0.52$; 95% confidence interval [CI]: -0.36 to -0.63; Figure 2). Controlling for players' age did not affect the strength of association between 2 variables ($r = -0.50$; 95% CI: -0.35 to -0.62).

DISCUSSION

Our study is the first to describe NH strength and bilateral NH strength asymmetry in highly trained male football players during the period of growth and maturation, as well as quantify the relationship between NH strength and sprint performance. Previous studies have yielded only limited descriptions of NH strength in youth football players (2). Moreover, contrary to other physical performance measures, age-related changes in lower-body strength of male football players have been rarely studied (14,15,30). Therefore, opportunities to compare our results with existing literature data are limited. Some comparisons, nevertheless, have been observed. In particular, our U17 players displayed approximately 10% lower NH strength than elite French U17 football players (2). Furthermore, NH strength of our first team players is comparable with those observed in elite Australian football and football (soccer) players (26,27,32). Somewhat higher NH strength values have been recently observed in top European football players (2). Overall, we may conclude that NH strength values of the tested sample of U17 and adult football players correspond well to the values reported for elite football players of similar age.

In this study, we have observed a specific pattern of age-related increase in players' absolute NH strength. Between the U12 and U14 categories, there was a gradual increase in absolute NH strength from 40% to about 65% of NH strength of the first team, followed by an abrupt increase in absolute NH strength in U16 category (Figure 1A). Indeed, absolute NH strength of U16 players reached approximately 90% of NH strength of the first team. The observed large gain in absolute NH strength in U16 group may be related to the pubertal growth spurt and the accompanying increase of serum androgen hormones, which has been shown to have a significant effect on strength in football players (16). Data from previous research support this hypothesis. One study (14) also reported a similar pattern of age-related changes in isokinetic eccentric hamstring torque in 11- to 17-year-old football players. Furthermore, Deprez et al. (9) studied the longitudinal development of explosive leg power from childhood to adulthood in football players and observed the highest gain in vertical and horizontal jump performance in U16 age group.

Another factor that may affect the relationship between age and muscle strength is body size. Indeed, Buchheit et al. (2) recently reported high correlation coefficients between body mass and NH strength in young and adult athletes. We, therefore, also reported body mass–normalized NH strength of the tested football players. Based on the theory of geometric similarity, muscle force is proportional to body mass$^{2/3}$, while muscle torque is proportional to body mass. Thus, methodologically appropriate expression of NH strength should be $N\cdot m\cdot kg^{-1}$. When muscle strength was appropriately normalized for body size (i.e., expressed in $N\cdot m\cdot kg^{-1}$), age-related changes in NH strength of youth football players displayed a different pattern (Figure 1B). First, note that U12 and U13 categories already displayed $\geq$80% relative NH strength of the first team. Thereafter, we observed 2 large gains in relative NH strength of youth football players; in U14 category (94–100% relative NH strength of the first team) and in U16 category (100–108% relative NH strength of the first team). Overall, these findings indicate that body size is largely responsible for the observed age-related increase in absolute NH strength in youth football players. Our results also question the usefulness of absolute NH strength threshold value to identify players with increased risk of HSIs (2).

Interestingly, we have observed a declining trend in relative NH strength from U16–U18 category. Similar finding was also observed in 1 study (14) for relative eccentric hamstring peak torque measured on an isokinetic device. Notably, the authors also reported that the concentric quadriceps strength increased considerably faster than the eccentric hamstring strength (particularly in the U18 category), resulting in unfavorable reduction of functional hamstring-to-quadriceps strength ratio in late adolescence (14). Collectively, these results may have repercussions for performance and injury risk in U18 football players because low eccentric hamstring strength has been associated with decreased sprint performance (21) and increased risk of HSIs (25,26,31). Further studies are needed to explain this finding and its relevance for sports performance and hamstring injury prevention.

Despite conflicting findings in literature, a number of studies have identified that bilateral hamstring strength asymmetry leads to an increased risk of sustaining an HSI in high-speed running sports (for review, Opar et al. (25)). The suggested cut-off points for bilateral hamstring strength asymmetry above which the risk of HSI increases in athletes ranged between 8 and 15%, respectively (25). In this study, the observed bilateral NH strength asymmetry was comparable with those cut-off points (i.e., 8–16%) and did not vary significantly among the tested age groups. Only U12 and U13 categories had mean bilateral NH strength asymmetries >15%. Similar bilateral NH strength asymmetry has been reported in other studies that involved elite football players (32), elite Australian football players (27), and cricket players of different qualitative rank (3). To the best of our knowledge, only one study (15) reported age-related variation in eccentric hamstring strength in highly trained young football players. Contrary to our findings, they observed only minor asymmetries (about 1–3%) in eccentric hamstring strength between the dominant and nondominant leg (15). The observed discrepancy in findings could be related to bilateral vs. unilateral nature of testing in those 2 studies; we have used the bilateral strength test (i.e., a NH testing device), while Forbes et al. (15) used the unilateral strength test (i.e., an isokinetic machine). This opens the question as to which type of eccentric strength testing (bilateral vs. unilateral) is optimal for quantifying bilateral strength asymmetry for HSI risk assessment in sports involving high-speed running.

Our results generally show that the eccentric hamstring function during NH strength testing is lower (i.e., lower relative NH strength and higher bilateral asymmetry) in U12 and U13 age groups compared with other age groups and the first team. We have also observed a reduction in relative NH strength in U17 and U18 age groups compared with U16 group. Interestingly, recent prospective cohort study performed on Premier League youth football academy players aged 9–18 years showed that the highest number of injuries, including HSIs, occurs in U12 and U13 age groups (29). The authors also reported a decrease in the number of HSIs for U15 and U16 age groups, followed by another increase in U18 age group (29). Cloke et al. (4) prospectively studied the pattern of thigh muscle injuries over a 5-year period in U9–U16 English Premiership football academy squads. The authors reported an increase in the thigh muscle injury incidence from U9 to U15 age groups, followed by a decrease in the injury incidence from U15 to U16 age groups. To which extent, findings from these studies are related to the findings of this study remains to be explored in future prospective studies that will track both NH strength and injury rates in youth football.

Another important finding of our study is a large inverse relationship between relative NH strength and sprint performance. In particular, 27% of 20-m sprint time variance of youth footballers could be explained by their relative NH strength. Previous similar studies provided conflicting findings in this regard. For example, one study (1) reported moderate inverse relationships between both concentric and eccentric isokinetic hamstring muscle strength and sprint performance of college-aged male athletes. Similar findings for concentric isokinetic hamstring strength were also observed in a group of elite male performers (10), athletes involved in sprint-type sports (22), and football players (23). Recently, it was reported that athletes who produced the greatest amount of horizontal force during sprint acceleration were both able to highly activate their hamstring muscles just before ground contact and present high eccentric hamstring peak torque capability (21).

By contrast, low correlation coefficients between isokinetic concentric hamstring strength and sprinting performance were observed in American football players (19), professional Rugby league players (7), English Premier League football players (6), and French football players (5). The latest group of authors reported similar findings also for eccentric hamstring strength (5). The observed discrepancy in findings could be related to several factors, including differences in sprint distances (range: 5–40 m), use of normalization methods for hamstring strength expression (N·m or $N\cdot m\cdot kg^{-1}$), and variation in sprint acceleration skill among differing adult subject cohorts. Notably, all cited studies included adult athletes and used seated isokinetic test for assessment of hamstring muscle strength. Hence, our finding is difficult to compare with the published literature and requires further research for verification. Also, given the importance of horizontal ground reaction force production for sprint acceleration performance (21), future studies involving youth footballers should assess the relationship between hip extensor strength and sprint acceleration.

In this study, which included highly trained U12–U18 football players, we have observed that both the absolute and relative NH strength increases with players' age; however, this increase was not linear and was the highest in U16 age group. Bilateral NH strength asymmetry varied nonsignificantly (8–16%) between age groups, with the highest values observed in U12 and U13 age groups. Finally, we found that 27% of variance of sprint performance of youth footballers could be explained by relative NH strength. Further longitudinal studies are needed to test the validity of our findings.

PRACTICAL APPLICATIONS

The results of this study may have the following practical applications:

1. The reported NH strength data for each age group could be used as normative standards during testing, training and profiling of youth male football players.
2. Football coaches and strength and conditioning coaches should pay close attention to eccentric hamstring function in U12–U15, and U18 players, as these age groups have the lowest eccentric hamstring strength and the highest bilateral strength asymmetry.
3. High eccentric strength seems to be positively related to sprint performance; therefore, eccentric hamstring strength training may be of benefit to youth as well as adult football players.

REFERENCES

1. Anderson, MA, Gieck, JH, Perrin, DH, Weltman, A, Rutt, RA, and Denegar, CR. The relationships among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and three components of athletic performance. *J Orthop Sports Phys Ther* 14: 114–120, 1991.
2. Buchheit, M, Cholley, Y, Nagel, M, and Poulos, N. The effect of body mass on eccentric knee-flexor strength assessed with an instrumented Nordic hamstring device (Nordbord) in football players. *Int J Sports Physiol Perform* 11: 721–726, 2016.
3. Chalker, WJ, Shield, AJ, Opar, DA, and Keogh, JW. Comparisons of eccentric knee flexor strength and asymmetries across elite, sub-elite and school level cricket players. *PeerJ* 4: e1594, 2016.
4. Cloke, D, Moore, O, Shah, T, Rushton, S, Shirley, MD, and Deehan, DJ. Thigh muscle injuries in youth soccer: Predictors of recovery. *Am J Sports Med* 40: 433–439, 2012.
5. Cometti, G, Maffiuletti, NA, Pousson, M, Chatard, JC, and Maffulli, N. Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *Int J Sports Med* 22: 45–51, 2001.
6. Cotte, T and Chatard, J-C. Isokinetic strength and sprint times in English Premier League football players. *Biol Sport* 28: 89–94, 2011.
7. Cronin, JB and Hansen, KT. Strength and power predictors of sports speed. *J Strength Cond Res* 19: 349–357, 2005.
8. de Visser, HM, Reijman, M, Heijboer, MP, and Bos, PK. Risk factors of recurrent hamstring injuries: A systematic review. *Br J Sports Med* 46: 124–130, 2012.
9. Deprez, D, Valente-Dos-Santos, J, Coelho, ESMJ, Lenoir, M, Philippaerts, R, and Vaeyens, R. Longitudinal development of explosive leg power from childhood to adulthood in soccer players. *Int J Sports Med* 36: 672–679, 2015.
10. Dowson, MN, Nevill, ME, Lakomy, HK, Nevill, AM, and Hazeldine, RJ. Modelling the relationship between isokinetic muscle strength and sprint running performance. *J Sports Sci* 16: 257–265, 1998.
11. Ekstrand, J, Hagglund, M, and Walden, M. Injury incidence and injury patterns in professional football: The UEFA injury study. *Br J Sports Med* 45: 553–558, 2011.
12. Ekstrand, J, Walden, M, and Hagglund, M. Hamstring injuries have increased by 4% annually in men's professional football, since 2001: A 13-year longitudinal analysis of the UEFA Elite Club injury study. *Br J Sports Med* 50: 731–737, 2016.
13. Ekstrand, J. Preventing injuries in professional football: Thinking bigger and working together. *Br J Sports Med* 50: 709–710, 2016.
14. Forbes, H, Bullers, A, Lovell, A, McNaughton, LR, Polman, RC, and Siegler, JC. Relative torque profiles of elite male youth footballers: Effects of age and pubertal development. *Int J Sports Med* 30: 592–597, 2009.
15. Forbes, H, Sutcliffe, S, Lovell, A, McNaughton, LR, and Siegler, JC. Isokinetic thigh muscle ratios in youth football: Effect of age and dominance. *Int J Sports Med* 30: 602–606, 2009.
16. Hansen, L, Bangsbo, J, Twisk, J, and Klausen, K. Development of muscle strength in relation to training level and testosterone in young male soccer players. *J Appl Physiol* 87: 1141–1147, 1999.
17. Harriss, DJ and Atkinson, G. Ethical standards in sport and exercise science research: 2016 update. *Int J Sports Med* 36: 1121–1124, 2015.
18. Hopkins, WG, Marshall, SW, Batterham, AM, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3–12, 2009.
19. Kin-Isler, A, Ariburun, B, Ozkana, A, Aytarb, A, and Tandogana, R. The relationship between anaerobic performance, muscle strength and sprint ability in American football players. *Isokin Exerc Sci* 16: 87–92, 2008.
20. Krustrup, P, Aagaard, P, Nybo, L, Petersen, J, Mohr, M, and Bangsbo, J. Recreational football as a health promoting activity: A topical review. *Scand J Med Sci Sports* 20: 1–13, 2010.
21. Morin, JB, Gimenez, P, Edouard, P, Arnal, P, Jimenez-Reyes, P, and Samozino, P. Sprint acceleration mechanics: The major role of hamstrings in horizontal force production. *Front Physiol* 6: 404, 2015.
22. Nesser, TW, Berg, K, and Prentice, E. Physiological determinants of 40-meter sprint performance in young male athletes. *J Strength Cond Res* 10: 263–267, 1996.
23. Newman, MA, Tarpenning, KM, and Marino, FE. Relationships between isokinetic knee strength, single-sprint performance, and repeated-sprint ability in football players. *J Strength Cond Res* 18: 867–872, 2004.

24. Opar, DA, Piatkowski, T, Williams, MD, and Shield, AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: A reliability and retrospective injury study. *J Orthop Sports Phys Ther* 43: 636–640, 2013.
25. Opar, DA, Williams, MD, and Shield, AJ. Hamstring strain injuries: Factors that lead to injury and re-injury. *Sports Med* 42: 209–226, 2012.
26. Opar, DA, Williams, MD, Timmins, RG, Hickey, J, Duhig, SJ, and Shield, AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Med Sci Sports Exerc* 47: 857–865, 2015.
27. Opar, DA, Williams, MD, Timmins, RG, Hickey, J, Duhig, SJ, and Shield, AJ. The effect of previous hamstring strain injuries on the change in eccentric hamstring strength during preseason training in elite Australian footballers. *Am J Sports Med* 43: 377–384, 2015.
28. Petersen, J, Thorborg, K, Nielsen, MB, Budtz-Jorgensen, E, and Holmich, P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: A cluster-randomized controlled trial. *Am J Sports Med* 39: 2296–2303, 2011.
29. Renshaw, A and Goodwin, PC. Injury incidence in a Premier League youth soccer academy using the consensus statement: A prospective cohort study. *BMJ Open Sport Exerc Med* 2: e000132, 2016.
30. Rochcongar, P, Morvan, R, Jan, J, Dassonville, J, and Beillot, J. Isokinetic investigation of knee extensors and knee flexors in young French soccer players. *Int J Sports Med* 9: 448–450, 1988.
31. Sugiura, Y, Saito, T, Sakuraba, K, Sakuma, K, and Suzuki, E. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *J Orthop Sports Phys Ther* 38: 457–464, 2008.
32. Timmins, RG, Bourne, MN, Shield, AJ, Williams, MD, Lorenzen, C, and Opar, DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. *Br J Sports Med* 50: 1524–1535, 2016.