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Strength and jumping performance in youth athletes: do sport specialization and age categories affect strength asymmetry?

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ABSTRACT

The aim of the study was to determine the influence of sports specialization and age on isokinetic strength, vertical jump performance and strength asymmetry in elite youth athletes.

Methods: A total of 181 young male athletes were recruited and categorized according to sport specialization (soccer or athletics) and age categories (U15, U17 or U19). Isokinetic strength was measured as peak muscle torque (PT), normalized to body mass, for the knee extensors (PT_{KE}) and knee flexors (PT_{KF}) during concentric muscle contraction at three angular velocities (60°s$^{-1.}$ 180°s$^{-1.}$ 300°s^{-1}). Vertical jump performance was measured during a countermovement jump with arms fixed (CMJ) and a squat jump (SJ).

Results: Significantly higher values of bilateral asymmetry (BA) of PT_{KF} for angular velocity 60°s^{-1} and 180°s^{-1} were found in the athletics group compared to the soccer group in the U17 category (14.40% to 16.02% vs 9.07% to 10.45%). Significantly higher values of BA for angular velocity 300°s^{-1} for both PT_{KE} and PT_{KF} were found in the U15 compared to U19 category. Significantly higher values of H:Q ratio at all angular velocity except for the non-dominant leg in the highest angular velocity in soccer compared to the athletes in the U17 category were found. Soccer players exhibited significantly higher values of PT_{KF} compared to those in athletics and jump height in the U17 category.

Conclusion: Soccer players displayed increased isokinetic strength and more balanced BA compared to the athletics group. Physiotherapists and strength coaches should focus on younger age groups, especially U15, due to the higher incidence of BA and lower relative strength regardless of specialization.

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Introduction

Professionalization of youth soccer has resulted in increased physical requirements representative of high training loads, thus increasing risk of injury (Arnold et al., 2017). The most common injuries in both adult and youth soccer are found in the lower limbs, specifically the hamstrings, knee and ankle joints (Ekstrand et al., 2016; Read et al., 2018). It has also been found that higher strength asymmetries in lower limbs may have a negative influence on specific soccer skills performance (Maly et al., 2018). Preseason assessment of strength and identification of asymmetries can serve as valuable tools for identifying athletes at increased risk of injury. Common assessment tools include isokinetic testing or lower limb explosive strength (Menzel et al., 2013). It has been reported in a systematic review (Asimakidis et al., 2024) that isokinetic knee (extensors and flexors) strength testing and countermovement jump with arms fixed (CMJ) were the most administered strength and power test in elite soccer players. Strength asymmetries do not appear to have an unequivocal effect on measures of athletic performance, but bilateral asymmetry (BA) values greater than 10% were associated with a higher risk of lower extremity injury (Liporaci et al., 2019). Furthermore, it has been revealed that soccer players displaying BA were 4.66 times more likely to experience hamstring strain injuries (Croisier et al., 2008). In addition, isokinetic testing and the evaluation of strength and asymmetries are widely recognized as crucial tools for monitoring rehabilitation progress and facilitating a safe return to sport (Güzel et al., 2022; Kehribar et al., 2022). Previously injured male professional soccer players showed significantly greater asymmetry during CMJ when compared to non-injured players (L. M. Hart et al., 2019). Both isokinetic strength assessment and power assessment by CMJ are crucial for a thorough evaluation of asymmetries since their findings may differ, directly influencing training interventions (Menzel et al., 2013).

Côté et al. (2007) reported that elite players achieved more hours in specific soccer training during childhood and adolescence compared to those who did not achieve professional status. In contrast, dynamics of the sport, especially with more intensive use of the preferred limb compared to the non-preferred, may impose athletes to reproduce functional and morphological asymmetries (N. H. Hart et al., 2016; Kalata et al., 2020). This has led to growing critique of early sport specialization, despite its contribution to skills development (Baker et al., 2009). Despite the substantial literature how soccer specialization may affect asymmetry, the conclusions are controversial (DeLang et al., 2019). It should be noted that imbalances have also been found in sports with a predominantly cyclical character, such as sprinting (Exell et al., 2012) or long-distance running (Ueberschär et al., 2019). Ueberschär et al. (2019) argue that during running, these disparities can be associated with asymmetric loading of the tibia for compensation of individual anatomical characteristics of the athlete.

N. H. Hart et al. (2016) presented that more experienced Australian football players showed significantly greater asymmetry between limbs in parameters such as tibial bone mass and cross-sectional area than inexperienced players (<3 years). Such findings would suggest that asymmetries are an adaptive consequence that is exacerbated by long-term sport participation. However, some authors demonstrated that higher incidence of lower limb bilateral asymmetry may also occur in younger categories, U13-U15 (Kalata et al., 2021) and U14-U16 (Atkins et al., 2016) and decreased in the later stages of adolescence for U17 (Kalata et al., 2021). Trecroci et al. (2020) also support the claim that asymmetry decreases in older soccer players (≥16 years) during change-of-direction tests. In younger players, maturation leads to potential changes in motor control and the so-called "motor awkwardness," which often impairs coordination abilities (Rommers et al., 2019).

Although considerable attention is paid in the literature to modifiable injury risk factors and screening strategies for young soccer players (Heering et al., 2023), it is not clear how much regular specific soccer participation can affect strength asymmetry and performance. Therefore, the aim of this study was to compare young soccer players with track and field athletes aged 13 to 19 years. It was hypothesized that significantly higher values for BA would be found in the soccer players compared to the athletics group and that isokinetic strength and jumping performance would be higher in older participants for both sports.

Methods

Study design

In this study, a cross-sectional design was used. Research was conducted at the beginning of pre-season (2021/2022). The measurements were performed under constant conditions during the morning hours (9.00–11.00 a.m.). The study was approved by the Institution's ethics committee of the Faculty of Physical Education and Sport, Charles University, in Prague, Czech Republic and conformed to the Declaration of Helsinki regarding the use of human participants. All players were fully informed about the aim of the study and the testing procedures that would be employed. Written informed consent to the testing procedures and data use for further research was obtained from the players' parents and assent from the children and adolescents. The participants were familiarized with the experimental protocol and did not perform any strenuous physical activity at least for 48 h prior to testing.

Participants

A total of 181 young male athletes with different sport specialization (soccer and athletics) were recruited (Table 1). According to the criteria of McKay et al. (2021), athletes were classified into the highly trained/elite tier. The first group included 68

Table 1. Descriptive characteristics (mean ± standard deviation) of the participant from different sport specialization and age category.

Sport	Athletics n = 68			Soccer n = 113		
Category	U15	U17	U19	U15	U17	U19
Number	25	23	20	37	54	22
Age (y)	14.07±0.67	15.94±0.58	17.70±0.78	13.66±0.56	15.83±0.73	17.29±0.83
Stature (m)	1.70±0.07	1.78±0.06	1.80±0.06	1.64±0.09	1.77±0.05	1.80±0.06
Body mass (kg)	54.88±8.28	65.38±7.46	67.84±9.47	49.73±8.65	66.44±7.66	72.35±6.30
Training age (y)	5–6	7–8	9–10	5–6	7–8	9–10

males from athletics (mean ± SD: age, 16.02 ± 1.90 years; stature, 1.76 ± 0.07 m; body mass, 62.67 ± 9.9 kg). Middle and long distance in track and field (U17 and U19) and general athletics preparation, for example track and field (U15; races in several disciplines e.g., running, jumping, throwing, events) athletes, were selected. The second group consisted of 113 youth soccer players (mean ± SD: age, 15.37 ± 1.54 years; stature, 1.73 ± 0.09 m; body mass, 61.91 ± 11.9 kg). Inclusion criteria included the following: minimum of 5 years of specialization; three key components were required for the participants to be involved in sport specialization: year-round training at least 8 months, choosing a main sport, and quitting other sports (Jayanthi et al., 2013); 90% of training and competition availability for the last 3 months prior to measurement and be officially registered and compete at minimally national level. Exclusion criteria included: high resistance or strenuous training performance within the last 48 h that may affect the maximal physical performance and strength asymmetry manifestation; recent history of lower limb or trunk injury within the last 6 months to minimize the potential for injury-related strength asymmetries and any knee surgery in their entire playing career.

Stature and body mass

Stature was measured using a digital stadiometer (Seca 242. Seca, Hamburg, Germany) with an accuracy of 0.1 cm, and body mass was measured using a digital scale (Seca 769, Seca, Hamburg, Germany) with an accuracy of 0.1 kg. Athletes were weighed just in underwear and barefoot.

Isokinetic dynamometry

Before measurement, all participants underwent a standardized warm-up focused mainly on the quadriceps and hamstring muscle groups (5 min indoor cycling at 120 w/100 revolutions per minute and two sets with 10 repetitions of front squats, front lunges, and glute bridges). Isokinetic dynamometer (Cybex NORM®, Humac, CA, USA) was used for measurement of peak muscle torque (PT) normalized to players' body mass of the knee extensors (PT_{KE}) and knee flexors (PT_{KF}) during concentric muscle contraction, at three angular velocities ($60^{\circ}s^{-1}$ $180^{\circ}s^{-1}$ $300^{\circ}s^{-1}$). Impellizzeri et al. (2008) reported a high reliability of peak muscle torque knee extensors (ICC = 0.98, 95% CI = 0.95–0.99) and flexors (ICC = 0.95, 95% CI = 0.88–0.98) and strength asymmetry (3.2–8.7%). The participant was in the sitting position, with trunk and tested leg fixed by belts and contralateral leg fixed by a leg adapter. The dynamometer was adjusted according to the instructions and individual somatic characteristics of the participants. The range of motion was 90° (full knee extension was marked and set as anatomical zero "0°"), and results were refined by gravity correction. The isokinetic trial protocol was set for five sub-maximal concentric test repetitions at the speed of $60°s^{-1}$. The diagnostics protocol was set for two concentric test repetitions with maximal effort at the velocity of $60°s^{-1}$, $180°s^{-1}$ and $300°s^{-1}$. For further processing, the best result (highest PT) of the two trials was obtained. Visual feedback and verbal encourage were provided during the testing. Limb dominance was determined as the foot the participant preferred to use to kick the ball from penalty set piece (Maly et al., 2021).

The bilateral strength asymmetry ratio (BA) between limbs was calculated according to the following formula (*Eq.1) by Impellizzeri et al. (2007).

$$\text{Bilateral ratio} = \frac{\textit{Higher limb score} - \textit{Lower limb score}}{\textit{Higher limb score}} \times 100\% \qquad (1)$$

Unilateral strength ratio (hamstring to quadriceps: H:Q) was expressed as the percentage proportion of peak torque of agonist and antagonist muscle on the same limb according following formula (*Eq.2) by Maly et al. (2015).

$$\text{H : Q ratio} = \frac{\textit{Peak torque of hamstring}}{\textit{Peak torque of quadriceps}} \times 100\% \qquad (2)$$

Vertical jump

Before measurement, all participants completed a warm-up (dynamic half squats 2 sets x 10 repetitions). All participants performed two types of vertical jumps: countermovement jump with arms fixed on hips (CMJ) and squat jump (SJ). Jump height (JH) and inversion dynamic kinetic parameters of each lower limb were measured using two force platforms Kistler B8611A at a sampling rate of 1000 hz (KISTLER Instrumente AG, Switzerland). Hori et al. (2009) reported the following coefficient of reliability for the Kistler force plate: peak force: ICC = 0.92, peak velocity: ICC = 0.98, and peak power: ICC = 0.98. JH was calculating based on applying the impulse-momentum theorem to the force-time curve (Linthorne, 2001). The peak vertical ground reaction forces (VGRF) and relative force impulse (FI) in newton normalized to body mass exerted under each foot separately were examined during the concentric take-off phase. Participants completed two warm-ups followed by three testing trials for each type of vertical jump. The trial with the highest achieved value of JH was selected for further result processing. For data processing, software BioWare 4.0.0 and MatlabR2013 were used. Outcome variables were assessed: JH, VGRF, FI and bilateral force deficit (BFD). BFD of the maximum force exerted by the legs was assessed according following formula (*Eq.3) by Maly et al. (2015):

$$\text{Bilateral force deficit} = \frac{\textit{Dominant limb score} - \textit{Nondominat limb score}}{\textit{Dominant limb score}} \times 100\% \qquad (3)$$

Statistical and data analysis

Descriptive statistics (means and standard deviations) were calculated for all dependent variables. A Shapiro–Wilk test was used to evaluate the normality of the data distribution. A non-equal group (based on double group size ratio for soccer players as inclusion criterion) sample size with $n_1 = 48$ (athletic population) and $n_2 = 96$ (soccer population) was estimated *a priori* based on power analysis calculated by SPSS with an aim to provide the necessary estimated power ($\alpha = 0.05$ and $\beta = 0.80$) and to observe a moderate effect size (ES = 0.50). Differences in the observed variables among the groups were assessed using a multivariate analysis of variance (MANOVA). Multiple comparisons of means (Bonferroni's post-hoc test) were used to compare differences in particular parameters among the groups. The independent samples t-test was used to compare the means between specialization within the same chronological age. Cohen's d for the effect size (d=(mean 1) – (mean 2)/pooled SD) was used to quantify pairwise effect size between dominant (DL) and non-dominant (NDL) legs and between extensors and flexors. Cohen's d was interpreted as $d > 0.2$, small; $d > 0.5$ moderate; $d > 0.8$ large (Cohen, 1992). Pearson's χ^2 test was used to compare the prevalence of BA (>10%) among age groups, and the effect size was assessed using the phi coefficient. The phi coefficient values of 0.1, 0.3 and 0.5 are considered small, medium and large effects, respectively (Coolican, 2017). For all analyses, the statistical significance level was set at alpha $p < 0.05$. Statistical analysis was performed using IBM SPSS® v21.

Results

Differences in strength and power asymmetry between the athletic and soccer group in different age groups

The results of BA revealed a significant effect of sport specialization ($F = 2.219$, $p < 0.05$, $\eta p^2 = 0.073$) and age category ($F = 2.471$, $p < 0.05$, $\eta p^2 = 0.080$). The interaction between the two main factors was non-significant ($F = 0.631$, $p > 0.05$, $\eta p^2 = 0.022$). The results of BFD revealed non-significant effect of sport specialization ($F = 0.572$, $p > 0.05$, $\eta p^2 = 0.007$) and age category ($F = 0.682$, $p > 0.05$, $\eta p^2 = 0.008$). The interaction between the two factors was significant ($F = 2.411$, $p < 0.05$, $\eta p^2 = 0.027$). Significantly higher values of BA in angular velocity 300°s^{-1} for both PT_{KE} and PT_{KF} in the U15 compared to U19 category were found. Significantly higher values BA of PT_{KF} for angular velocity 60°s^{-1} and 180°s^{-1} with medium effect size ($d = 0.61$ and 0.65, respectively) were found in the athletics group compared to soccer for the U17 category. The significant higher proportion of players with BA > 10% of PT_{KE} and PT_{KF} for angular velocity 180°s^{-1} and 300°s^{-1} in U15 (43.5% and 66.1% of all players) compared to U17 (32.5% and 58.4% of all players) and U19 categories (19.0% and 38.1%), with a small effect size observed (phi = 0.194 and 0.195, respectively). Significantly higher values BA of PT_{KF} compared to the BA of PT_{KE} with small to medium effect size were found (Table 2).

Differences in unilateral asymmetry between the athletic and soccer group in different age groups

The results of H:Q ratio revealed a significant effect of sport specialization ($F = 2.885$, $p < 0.05$, $\eta p^2 = 0.092$) and age category ($F = 2.670$, $p < 0.01$, $\eta p^2 = 0.086$). The interaction between the two main factors was non-significant ($F = 1.383$, $p > 0.05$, $\eta p^2 = 0.047$). A significantly ($p < 0.05$) higher value of H:Q ratio between DL compared to the NDL with small effect size for angular velocity 60°s^{-1} and 180°s^{-1} were found. Significantly lower values of H:Q ratio at all angular velocities in the U15 compared to the U17 and U19 categories were found. Significantly higher values of H:Q ratio at all angular velocity except for NL in the highest (300°s^{-1}) angular velocity in soccer compared to the U17 athletes were found (Table 3).

Differences in isokinetic strength performance

The U15 category had a significantly lower age, stature and body mass compared to the older U17 and U19 categories ($p < 0.001$). Players U17 had also significantly lower body mass compared to U19 ($p < 0.05$). The results of PT_{KE} and PT_{KF} revealed a significant effect of sport specialization (PT_{KE} : $F = 2.928$, $p < 0.05$, $\eta p^2 = 0.094$; PT_{KF} : $F = 3.389$ $p < 0.01$, ηp^2

Table 2. Differences (%) of bilateral asymmetry of isokinetic and power strength between athletic and soccer group and different age category.

	U15 Mean ± SD			U17 Mean ± SD			U19 Mean ± SD			P			Post Hoc	Extensors vs flexors		
Parameters	A (25)	S(37)	BA (%)	A(23)	S(54)	BA (%)	A(20)	S(22)	BA (%)	Sport	AC	IE	AC	p	ES value	ES effect
Q:Q $_{60}$	10.87±10.98	8.09±6.18	32.3	10.00±6.97	7.81±7.46	27.3	5.62±5.72	5.41±4.51	23.8	.136	.019	.634	†*	.000	0.358	Small
H:H $_{60}$	13.65±9.43	10.78±8.88	51.6	14.40±10.78*	9.07±7.69	42.9	11.06±5.96	8.45±5.40	38.1	.006	.312	.625	N			
Q:Q $_{180}$	12.18±11.37	10.25±8.21	43.5$^{\#}$	9.32±8.29	7.66±7.58	32.5	5.02±4.26	5.66±4.86	19.0	.432	.001	.768	† **	.000	0.591	Medium
H:H $_{180}$	21.75±19.04	19.20 ± 17.48	64.5	16.02±10.27*	10.45±7.68	53.2	15.65±10.82	10.06±8.21	54.8	.025	.002	.350	‡*			
Q:Q $_{300}$	7.85±7.50	12.39 ± 9.75*	43.5	9.28±12.58	9.04±6.40	33.8	6.31±5.33	6.10±4.93	26.2	.289	.052	.134	†*	.000	0.646	Medium
H:H $_{300}$	21.68±16.96	18.77 ± 15.90	66.1$^{\#}$	18.46±14.80	15.29±13.04	58.4	12.70±8.91	9.89±8.66	40.5	.173	.006	.802	†*			
BFD-CMJ	9.84±10.09	4,79±3.34**	12.9	6.50 ± 4.76	7.90 ± 7.99	18.2	6.95 ± 5.20	7.30 ± 6.21	26.2	.308	.990	.023	N	.000	0.461	Small
BFD-SJ	5.21 ± 7.76	4.90 ± 3.97	4.8	3.10 ± 3.16	4.56 ± 3.57	5.2	5.15 ± 2.98	4.10 ± 2.47	4.8	.959	.273	.290	N			

Notes: A-athletics, S-soccer, BA-bilateral asymmetry > 10%, SD-standard deviation, AC-age category, IE-interaction effect, ES-effect size, p-probability of significant differences in compared means, N-none, Q:Q-bilateral asymmetry ratio of knee extensors, H:H-bilateral asymmetry ratio of knee flexors, BFD-bilateral deficit, CMJ-countermovement jump without arms, SJ-squat jump, *- significant difference on level $p < 0.05$, **- significant difference on level $p < 0.01$, ***- significant difference on level $p < 0.001$, †-significant higher values in U15 than U19, ‡- significant higher values in U15 than U17 and U19, #– significant age category on bilateral asymmetry more than 10%.

Table 3. Differences (%) of unilateral asymmetry (H:Q ratio) between athletic and soccer group and different age category.

	U15 Mean ± SD		U17 Mean ± SD		U19 Mean ± SD		P			Post Hoc	Dominant vs Nondominant		
Parameters	A (25)	S(37)	A(23)	S(54)	A(20)	S(22)	Sport	AC	IE	AC	p	ES value	ES effect
H:Q DL $_{60}$	53.32±9.03	53.55±6.79	53.68±8.89	59.43±9.25*	57.48±6.72	61.61±7.74	.011	.001	.172	‡**	.016	0.253	Small
H:Q NDL $_{60}$	53.75±10.35*	49.16±6.83	52.20±9.74	56.45±7.66*	56.25±8.95	60.07±7.52	.380	.000	.007	‡**			
H:Q DL $_{180}$	52.77±15.63	54.57±12.35	53.31±7.01	61.32±12.00***	60.27±7.18	64.39±8.29	.010	.000	.308	‡**	.027	0.234	Small
H:Q NDL $_{180}$	51.65±14.92	49.94±11.98	52.40±10.64	59.44±9.66**	54.37±10.21	61.61±8.15*	.017	.003	.050	‡**			
H:Q DL $_{300}$	49.48±12.33	52.86±11.56	53.06±6.81	60.13±13.34*	57.08±7.14	66.26±10.39**	.000	.000	.415	‡**	.092	0.178	Trivial
H:Q NDL $_{300}$	51.00±11.54	49.14±12.73	52.30±10.86	57.57±13.07	53.36±10.64	63.12±9.19**	.020	.003	.046	‡**			

Notes: A-athletics, S-soccer, SD-standard deviation, AC-age category, IE-interaction effect, ES-effect size, p-probability of significant differences in compared means, H:Q-hamstring to quadriceps ratio, DL-dominant lower limb, NDL-non-dominant lower limb *- significant difference on level $p < 0.05$, **- significant difference on level $p < 0.01$, ***- significant difference on level $p < 0.001$, ‡- significant lower values in U15 than U17 and U19.

= 0.107) and age category (PT_{KE} : F = 5.804, $p < 0.001$, $\eta p^2 = 0.170$; PT_{KF} : F = 7.218, $p < 0.001$, $\eta p^2 = 0.203$). The interaction between the two factors was non-significant for both (PT_{KE} : F = 1.080, $p > 0.05$, $\eta p^2 = 0.036$; PT_{KF} : F = 1.372, $p > 0.05$, $\eta p^2 = 0.046$). Significantly lower values of PT_{KE} and PT_{KF} for all angular velocities in the U15 compared to U17 and U19 categories were found ($p < 0.001$). Significantly higher PT_{KE180} for the DL and NDL was found in U19 compared to the U17 category ($p < 0.05$). Significantly higher values for PT_{KE180} in the NDL (U17 and U19) in soccer compared to athletics were found ($p < 0.05$) (Table 4.). Significantly higher values of PT_{KF} at all angular velocities in soccer compared to athletics for the U19 category were found ($p < 0.01$). Significantly higher values of all dependent variables, except $PT_{KF300,}$ in soccer compared to athletics in the U17 category were found (60°s^{-1} and 180°s^{-1}, $p < 0.01$ and $p < 0.05$, respectively).

Differences in power performance in the different age groups

The comparison of vertical jump performance revealed a significant effect of both sport specialization (F = 4.963 $p < 0.001$, $\eta p^2 = 0.191$) and age category (F = 6.306, $p < 0.001$, $\eta p^2 = 0.231$). The interaction between the two factors was non-significant (F = 1.441. $p > 0.05$, $\eta p^2 = 0.064$). Significantly lower values for JH of both tests CMJ and SJ in the U15 compared to the U17 and U19 categories were found ($p < 0.001$). A significantly higher JH in soccer compared to athletics in the U17 category was also found ($p < 0.05$) (Table 5.). Table 5. Differences of power performance between the athletic and soccer group in different age groups.

Discussion

The main finding was significantly higher values of BA of PT_{KF} for lower angular velocities (60°s^{-1}, 180°s^{-1}) in the athletics group compared to soccer in the U17 category (14.40% to 16.02% vs 9.07% to 10.45%). These unexpected findings indicate that lateral-specific soccer movements, such as kicking or passing, may not have a negative impact on the prevalence of BA when compensatory mechanisms (non-dominant leg work) are involved in the training process. By contrast, individual characteristics (scoliosis or a congenital/acquired articular malalignment) can play a greater role, which act as a compensatory strategy to balance lateral asymmetry even during obviously cyclical movements such as running (Ueberschär et al., 2019). No significant differences between DL and NDL in PT_{KE} and PT_{KF} were found, which is consistent with previous studies (Kalata et al., 2021; Maly et al., 2016). This balance may be justified by a training approach in elite youth sports that focuses on both legs and not only on the dominant limb. Unlike athletics, soccer players regularly undergo pre-season testing with the aim to detect potential asymmetries, and subsequent tailored training interventions made by clinical practitioners, may have influenced lower bilateral asymmetries. The results showed significantly higher BA of PT_{KF} compared to BA of PT_{KE} with small to medium effect size found, which is in line with previous research (Kalata, 2023). In contrast, Maly et al. (2024) found no differences in elite adult soccer players. A significantly higher level of BFD in CMJ was found compared to SJ, which is consistent with previous research on the topic (Kalata, 2023; Miratsky et al., 2021). One explanation could be that the absence of an eccentric phase in SJ reduces intermuscular coordination requirements (Kalata, 2023). Results showed significantly higher BA for both PT_{KE} and PT_{KF} in the U15 compared to U19 category at the highest angular velocity. Higher velocities may be more sensitive in identifying asymmetry between limbs due to greater similarity to sport situations, such as jumping (Lehnert et al., 2013) or kicking

Table 4. Differences of isokinetic strength of knee extensors and flexors (N.m.kg^{-1}) between athletic and soccer group in different age category.

	U15 Mean ± SD		U17 Mean ± SD		U19 Mean ± SD		P			Post Hoc	Dominant vs Nondominant		
Parameters	A (25)	S(37)	A(23)	S(54)	A(20)	S(22)	Sport	AC	IE	AC	P	ES value	ES effect
$PT_{KE}DL_{60}$	2.62±0.44	2.58±0.27	2.85±0.58	2.88±0.35	2.97±0.37	3.08±0.30	.614	.000	.605	‡***	.895	.014	Trivial
$PT_{KE}NDL_{60}$	2.56±0.47	2.64±0.32	2.71±0.63	2.90±0.34	2.93±0.45	3.12±0.29	.020	.000	.677	‡***			
$PT_{KE}DL_{180}$	1.74±0.30	1.72±0.25	1.97±0.41	2.07±0.23	2.10±0.26	2.26±0.23*	.074	.000	.220	‡***†*	.896	.014	Trivial
$PT_{KE}NDL_{180}$	1.78±0.32	1.75±0.27	1.89±0.47	2.07±0.30*	2.07±0.27	2.30±0.21**	.012	.000	.089	‡***†*			
$PT_{KE}DL_{300}$	1.40±0.21	1.39±0.23	1.61±0.23	1.63±0.24	1.69±0.19	1.72±0.19	.708	.000	.900	‡***	.711	.039	Trivial
$PT_{KE}NDL_{300}$	1.40±0.25	1.36±0.25	1.55±0.37	1.62±0.27	1.66±0.24	1.77±0.17	.323	.000	.313	‡***			
$PT_{KF}DL_{60}$	1.39±0.25	1.38±0.23	1.51±0.32	1.69±0.25*	1.71±0.31	1.88±0.20*	.006	.000	.102	‡***†**	.053	.204	Small
$PT_{KF}NDL_{60}$	1.34±0.21	1.29±0.23	1.42±0.41	1.63±0.23*	1.64±0.35	1.87±0.25*	.004	.000	.015	‡***†**			
$PT_{KF}DL_{180}$	0.92±0.29	0.95±0.27	1.05±0.27	1.26±0.24**	1.26±0.19	1.45±0.19**	.000	.000	.117	‡***†**	.085	.182	Trivial
$PT_{KF}NDL_{180}$	0.89±0.21	0.88±0.26	1.00±0.28	1.22±0.22**	1.13±0.27	1.41±0.18***	.000	.000	.004	‡***†*			
$PT_{KF}DL_{300}$	0.69±0.20	0.74±0.23	0.85±0.17	0.98±0.24*	0.97±0.17	1.13±0.18**	.000	.000	.379	‡***†*	.089	.179	Trivial
$PT_{KF}NDL_{300}$	0.70±0.15	0.67±0.21	0.81±0.25	0.93±0.23	0.88±0.15	1.11±0.15***	.002	.000	.009	‡***†*			

Notes: A-athletics, S-soccer, SD-standard deviation, AC-age category, IE-interaction effect, ES-effect size, p-probability of significant differences in compared means, PT_{KE}-maximal peak torque of knee extensors, PT_{KF}-maximal peak torque of knee flexors, DL-dominant lower limb, NDL-non-dominant lower limb, *- significant difference on level $p < 0.05$, **- significant difference on level $p < 0.01$, ***- significant difference on level $p < 0.001$, ‡-significant lower values in category U15 than U17 and U19, †- significant higher values in U19 than U17.

Table 5. Differences of power performance between athletic and soccer group in different age groups.

	U15 Mean ± SD		U17 Mean ± SD		U19 Mean ± SD		p			Post Hoc
Parameters	A(25)	S(37)	A(23)	S(54)	A(20)	S(22)	Sport	AC	IE	AC
Jump height CMJ (cm)	31.02±4.87	29.93±4.45	34.99±6.23	37.28±3.90	37.23±5.36	38.32±4.12	.304	.000	.131	‡***
VGRF DLCMJ (Nkg^{-1})	11.96±1.68	12.56±1.68	12.71±1.76	12.27±1.36	12.36±1.41	13.01±1.45	.270	.399	.102	N
VGRF NDLCMJ (Nkg^{-1})	11.87±1.73	12.21±1.72	12.20±1.78	12.01±01.25	12.26±1.50	12.49±1.20	.600	.532	.609	N
Force Impulse CMJ ($Nskg^{-1}$)	2.82±0.47	2.99±0.38	2.91±0.37	2.92±0.37	2.77±0.45	3.02±0.39	.029	.972	.309	N
Jump heightSJ (cm)	28.84±4.67	28.24±4.67	31.48±5.92	34.80±4.13*	33.51±6.43	35.88±4.03	.028	.000	.071	‡***
VGRF DLSJ (Nkg^{-1})	10.13±0.79	11.30±1.50***	10.19±0.77	10.85±0.85**	10.61±0.84	11.14±0.72*	.000	.191	.207	N
VGRF NDLSJ (Nkg^{-1})	10.19±1.04	11.14±1.52**	10.11±0.89	10.80±0.86**	10.39±0.85	11.01±0.72*	.000	.387	.698	N
Force ImpulseSJ ($Nskg^{-1}$)	2.33±0.19	2.49±0.34*	2.48±0.28	2.61±0.18*	2.48±0.32	2.66±0.16*	.000	.002	.845	‡**

Notes: A-athletics, S-soccer, SD-standard deviation, AC-age category, IE-interaction effect, p-probability of significant differences in compared means, N-none, CMJ-countermovement jump, SJ-squat jump, VGRF-vertical ground reaction force, DL-dominant lower limb, NDL-non-dominant lower limb, *- significant difference on level $p < 0.05$, **- significant difference on level $p < 0.01$, ***- significant difference on level $p < 0.001$, ‡-significant lower values in category U15 than U17 and U19.

(Nunome et al., 2002). These sport-specific movements could potentially lead to higher variability in strength expression. This fact is also confirmed by the prevalence of BA > 10% for both KE and KF, which increased with angular velocity (Table 2.). However, significantly higher proportion of players with BA > 10% of PT_{KE} and PT_{KF} for angular velocity 180°s^{-1} and 300°s^{-1} in the U15 compared to the U17 and U19 categories, with a small effect size being observed. One of the reasons could be attributed to potential changes in motor control that may arise during the growth spurt, which represent this age category (Atkins et al., 2016). Kalata et al. (2021) showed that longer training experience improves the neuromuscular environment; thus, athletes become more resilient, and BA appears to stabilize. For this reason, the U15 group should be targeted for specific intervention, especially as a detected BA > 10% could be associated with a higher risk of injury (Liporaci et al., 2019). Therefore, elite players may still require an intervention to limit potential performance deficits and reduce injury risk (Menzel et al., 2013).

The type of sport specialization showed a significant effect on H:Q ratio except for NL in the slowest (60°s^{-1}) angular velocity. In general, we observed a higher H:Q ratio in the group of soccer players in older categories (U17 and U19), although a significantly higher H:Q ratio was found at all angular velocities only for the U17 category except for NL in the highest (300°s^{-1}) angular velocity. We hypothesized that higher H:Q in older soccer players would be induced by natural structure of soccer specific movement with high demanding activities for knee flexors as deceleration, change of direction speed, high intensity and sprint running, and follow-up phase after kicking/shooting. In contrast, in the U15 category, we observed similar values of H:Q ratio between the athletics and soccer groups. These findings could be explained by the specification only for running disciplines in the U17 and U19 categories compared to the category U15, which is more general preparation, e.g. running, jumping and throwing events. For this reason, runners in older groups (U17 and U19) may lack high-intensity stimuli as high force magnitude during acceleration, deceleration, change of direction speed, jumping, tackling, kicking and other sport specific tasks, which are inherent to soccer. This study also showed a significant effect of age category on the level of the unilateral strength ratio (H:Q) for the DL and NDL (Table 3.). Significantly lower values H:Q ratio at all angular velocities were found in U15 compared to U17 and U19. This observation could be explained by possible adaptive changes in intermuscular coordination in older categories due to higher attention to proper gym work (particularly for knee flexors), higher speed exposure in training and competitive events, longer training experience, higher magnitudes of deceleration when change of direction is needed (Kalata, 2023). The importance of measuring H/Q ratio at multiple angular velocities is supported by Güzel et al. (2022), whose findings demonstrated significant improvement in knee extensor strength and less pronounced gains in flexor strength 6 months post-ACL surgery. This imbalance led to a reduction in the H/Q ratio at 60°s^{-1} (not for 180°s^{-1} and 240°s^{-1}), potentially complicating a safe return to sports.

Our results showed significantly higher values of isokinetic strength at all angular velocities for both extensors and flexors in the older categories U17 and U19 compared to U15, which is in line with previous research (Kalata et al., 2021). These observations show that concentric muscle strength (normalized to body weight) increases in young athletes over time and specific sport specialization (from development (U15) over performance (U17) to professional phase U19). Furthermore, our findings revealed that in most isokinetic results for flexors and extensors, the U19 age group achieved significantly higher values compared to the U17 age group. This increase may be related to the gradual transition to adult sports, where elite young athletes usually train full-time between the ages of 17 and 18 y. Dotan et al. (2012) confirmed that the increase in muscle strength observed in childhood and adolescence is due to the growing ability to make full use of motor units with a higher threshold (type II) in the range typical of adults. Conversely, Maly et al. (2021) did not show any significant differences between the U17 and U19 categories in both flexors and extensors in high performance level players. One possible explanation is that our athletes were selected from only one soccer and athletics academy and therefore adhered to a long-term sports development. In contrast, Maly et al. (2021) presented results across youth soccer national teams, where players were selected as "best of the best" for their individual age category, which may explain the non-significant difference between them. In the current study, only in the older categories (U17 and U19) was isokinetic strength significantly higher in soccer compared to athletics. This finding shows that increasing training age and long-term development of specific soccer skills, such as kicking and rapid change of direction, can explain a difference in the muscular strength of the extensors and flexor knees favouring soccer players.

Significantly higher JH in both types CMJ and SJ in older categories U17 and U19 compared to U15 were found, but there was no significant difference between U17 and U19. These findings are in accordance with the study by Loturco et al. (2020), which examined the age-specific development of vertical JH in soccer players from different age-categories (U15, U17, U20 and Senior). One of the explanations why JH did not improve between U17 and U19 could be that aerobic load increases and may result in reduced capacity to produce force quickly (Loturco et al., 2020). Other explanations could be that there will be natural limit to the amount of jump improvement through maturation or without specific jump training interventions, jump capacity is likely to plateau (Jeffreys & Moody, 2016). In contrast to the JH, there were no differences in VGRF for both legs between age categories. Our results are in accordance with the study by Focke et al. (2013), where peak force normalized to body mass during CMJ was stable across different age categories (4 to 17 years). Therefore, VGRF itself does not explain jumping performance in players in phase of growing and maturation, while JH increased in the older categories (U17 and U19). For this reason, other possibilities should be considered, for example the stretch-shortening cycle, which would explain the increase in the JH in the later stages (U17 and U19) of young players, and muscle tendon stiffness. The ability to utilize the stretch-shortening cycle quickly is typically assessed during vertical jumping tasks by calculating the reactive strength index (RSI). The RSI provides valuable insight into neuromuscular and stretch-shortening cycle function by accounting for the duration over which force has been produced to achieve a given JH (Flanagan & M, 2008). De Ste Croix et al. (2021) present the results of the improvement of RSI during a 3-year mixed-longitudinal study in youth soccer and basketball players for both categories (U14 to U16 and U16 to U18), which may be partly due to the development of motor control. Mechanisms that could explain the increase in RSI with age and maturation observed in the current study include increases in motor unit recruitment and preactivation, increased tendon stiffness and decreased co-contraction (Radnor et al., 2018).

One limitation of this study was the absence of eccentric muscle contraction during isokinetic testing as an indicator of functional deficits (Impellizzeri et al., 2007) or the similarity of frequent actions in sport performance, e.g. braking and changing direction. Furthermore, differentiation of playing positions in soccer and higher homogeneity in the athletic group (one specialization focus) could be considered. In addition, biological age, which may play a role in the prevalence of asymmetry, was not considered for the U15 category. Furthermore, due to fluctuations of asymmetry over time, long-term monitoring of asymmetry is appropriate, especially in youth. Future studies should also consider tracking injury data that could clarify the impact of strength and asymmetry on athlete health.

Practical applications

These results can serve as a new benchmark for the expected level of strength, vertical jump and asymmetry with respect to age and the choice of sports specialization in young athletes. Clinical practitioners, such as physical therapists, strength and conditioning coaches, should focus on younger age groups due to the higher incidence of BA and lower relative strength that could predispose players to potential injuries, or decreasing of performance. Athletic specialization, especially middle and long-distance running, should pay attention to the reduced H:Q ratio due to the increased risk of injury. Regularly monitoring of strength and asymmetry due to detected weaker lower limb and targeted intervention may help athletes to reduce risk of injury, and further proper development and performance enhancement.

Conclusion

Practitioners should be focused on younger athletes when training higher speed, because this study revealed significantly higher bilateral asymmetries at $300°s^{-1}$ for both PT_{KE} and PT_{KF} in the U15 compared to the U19 category. Compared to athletics specialization, soccer players achieved a higher H:Q ratio. As soccer players achieve less bilateral asymmetries compared to athletics, unilateral movements like kicking and passing may not have a negative impact on the prevalence of bilateral asymmetry. This could be due to compensatory mechanisms (non-dominant leg work) involved in the training process in highly trained players. Older age categories (U17 and U19) achieved significantly performance in both power and isokinetic testing compared to younger athletes (U15).

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Author contributions

Conceptualization, M.K., T.M. and C.A.W.; methodology, M.K. and T.M. and C.A.W.; software, M.K.; validation, T.M., C.A.W., M.D.C. and F.Z.; formal analysis, M.K. and F.F.V.; investigation, M.D.C, F.F.V., M. L. and F.Z.; resources, M.K.; data curation, M.K. and T.M.; writing – original draft preparation, M.K., T. M., C.A.W., M.D.C., F.F.V., M.L. and F.Z.; writing – review and editing, C.A.W, M.K. and T.M.; visualization, M.K., T.M. and C.A.W.; supervision, T.M., M.D.C, C.A.W., M.L. and F.Z.; funding acquisition: T.M; All authors have read and agreed to the published version of the manuscript.

Data availability statement

The dataset used and analysing code that support the findings of this study are available from the corresponding author, upon reasonable request.

Informed consent statement

Informed consent was obtained from all participants involved in the study.

Institutional review board statement

The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of Ethical Committee of the Faculty of Physical Education and Sport, Charles University, in Prague, Czech Republic.

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