M. biceps femoris architecture and sprint ability in youth soccer players: a cross- sectional analysis

Received: June 27, 2020

Supplementary materials:

osf.io/vy2pw/

For correspondence:

paul.ritsche@unibas.ch

Paul Ritsche¹, Thomas Bernhard^{1,2}, Ralf Roth¹, Eric Lichtenstein¹, Martin Keller¹, Sabrina Zingg², Martino V. Franchi³, Oliver Faude¹

¹ Department of Sport, Exercise and Health, University of Basel, Basel, Switzerland

² FC Basel 1893, Basel, Switzerland

³ Institute of Physiology, Department of Biomedical Sciences, University of Padua, Italy

Ritsche, P., Bernhard, T., Roth, R., Lichtenstein, E., Keller, M., Zingg, S., Franchi M., V. & Faude, O. (2020, June 30). M. biceps femoris architecture and sprint ability in youth soccer players: a cross-sectional analysis. <https://doi.org/10.31236/osf.io/gnxhd>

ABSTRACT

Background. It has been proposed that muscle architecture can be associated with sprint performance and the risk of sustaining a muscle injury. During puberty, sprint performance as well as muscle injury risk increases in young soccer players. In this study, we investigated the changes in m. biceps femoris long head (BFlh) cross-sectional area (ACSA), fascicle length (FL) and pennation angle (PA) and sprint performance as well as their relationship in under 13 to 15 youth soccer players.

Methods. In total, we measured 85 youth soccer players in under 13 (n=29, age=12.5 y (SD=0.1), height=155.3 cm (6.2), weight=43.9 kg (7.6)), under 14 (n=25, age=13.5 y (0.3), height=160.6 y

(7.7), weight=47.0 kg (6.8)) and under 15 (n=31, age=14.4 y (0.3) , height=170.0 cm (7.7), weight=58.1 kg (8.8)) teams of three high level soccer clubs. We used ultrasound to measure BFIh ACSA, FL and PA. We performed sprint tests to assess 10m and 30m sprint time, maximal velocity (v_{max}) and maximal acceleration (a_{max}). We calculated Pearson's r and 95% compatibility intervals to assess the relationship between sprint ability, maturity ratio, chronological age and architectural parameters. In addition, we calculated the best set of predictors for sprint ability using multiple regression models.

Results. All muscle architectural parameters increased from the under 13 to the under 15 age group (BFIh ACSA: 37%, BFIh FL: 11%, BFIh PA: 8%). All sprint performance parameters improved from the under 13 to under 15 age categories (30m time: 7%, 10m time: 4%, v_{max} : 9%, a_{max} : 7%). BFIh ACSA was correlated with 30m sprint time ($r = -0.61$ (95% CI = -0.73, -0.45)) and v_{max} ($r = 0.61$ (0.45, 0.72)). The correlation for maturity ratio with assessed parameters were larger compared to the correlation for chronological age. A combination of BFIh ACSA, FL, chronological age and height best predicted sprint parameters.

Discussion. Parallel to improvements in sprint performance, muscle architectural parameters increase from the under 13 to under 15 age groups. BFIh ACSA seems to be related to sprint performance in youth soccer players. BFIh ACSA and chronological age are the main predictors of most sprint parameters.

INTRODUCTION

Within the past decades, the percentage of sprints and sprint duration in a match increased by 35% in adult soccer (Barnes et al., 2014). Sprinting accounts for 1 to 4% of the total distance covered (Barnes et al., 2014) and it represents the most frequent action preceding goal situations (Faude et al., 2012). These data may also have affected youth soccer training, since sprint ability increased over the last few years in players aged 12 to 17 (Gonaus et al., 2019). In general, physical performance increases during puberty in youth soccer players with improved 5m, 10m and 20m sprint performance (Gonaus et al., 2019, Perroni et al., 2018, Read et al., 2017). The hamstring muscles have a key role in contributing to forward propulsion (Morin et al., 2015). During the swing phase of the gait cycle, the hamstrings decelerate the leg in order to move the foot underneath the centre of mass of the body and subsequently aid in hip extension during the foot-strike (Schache et al., 2012). A larger horizontal ground reaction force was found in individuals who were able to highly activate their hamstring muscles just before ground contact and produced a high eccentric knee flexion peak torque (Morin et al., 2015). Even though the hamstrings are crucial during sprinting, the high strain at fast running speeds is one of the main causes for injury to the long head of the m. biceps femoris (Chumanov et al., 2012, Ekstrand et al., 2011). As shown by Fiorentino & Blemker (2014) during high speed running, wider muscle and smaller proximal aponeurosis widths increase strain on proximal muscle tissue and therefore increase injury susceptibility.

The incidence of thigh muscle injuries in youth soccer players aged under 13 is low with an incidence of 0.1 per 1000 exposure hours (Rössler et al., 2016). However, the occurrence of muscle injuries increases with age (Rössler et al., 2016, Faude et al., 2013). Maturation seems to influence injury risk in youth soccer. More severe lower limb injuries occurred in under 14 and under 16 years age groups, coinciding with the ages where biological maturation typically takes place (Hall et al., 2020). Valle et al. (2018) also showed that the incidence of hamstring injuries in youth soccer players was highest at the age of 13 and 15, with 0.2 injuries per 1000 exposure hours. Most injuries occurred in the m. biceps femoris and the m. semimembranosus (Valle et al., 2018). In professional soccer, hamstring injuries are among those injuries with the highest injury burden and have an incidence of 1.2 per 1000 exposure hours (Ekstrand et al., 2011). Since hamstring injuries are common in soccer players, several studies tried to shed light on the mechanisms that potentially explain these injuries. A prospective cohort study for example found that players with longer BFlh muscle fascicles and higher eccentric knee flexor strength show less hamstring injuries (Timmins et al., 2016). The idea of an interplay between fascicle length and injury incidence was also supported by a recent review (Kellis, 2018). Based on these observations, several studies investigated in adults if muscle architecture could be altered in response to a training regimen and if this also affects the occurrence of muscle injuries (Mendiguchia et al., 2020, Pollard et al., 2019, Bourne et al., 2018, Krommes et al., 2017). BFlh architecture may also impact sprint performance. A higher knee flexor cross-sectional area and volume is associated with increased eccentric knee flexor peak torque and therefore acceleration (Evangelidis et al., 2016, Morin et al., 2015, Masuda et al., 2003). At similar shortening velocity, muscles with longer fascicles produce more force (Lieber & Friden, 2000) and operate more effectively at longer muscle lengths (Guex et al., 2016). Data on the relationship between hamstring muscle architecture and sprint performance in children is lacking so far.

Different methods can be used to assess muscle architecture with ultrasound. Extended field of view (EFOV) ultrasound may be superior to static ultrasound in assessing BFlh muscle architecture in order to avoid extrapolation error (Franchi et al., 2018, 2020). Ultrasonography is a valid and reliable method for assessing anatomical cross-sectional area (ACSA) and fascicle length (FL) in the BFlh (Franchi et al., 2020, Kositsky et al., 2020, Kellis et al., 2009). The accuracy of determining the pennation angle (PA), however, seems to be dependent on the applied ultrasound methodology (Franchi et al., 2020, Pimenta et al., 2018).

Monitoring muscle architecture and performance in youth soccer players could help to optimize player development and reduce the risk of hamstring injuries. This is important especially during puberty, since there is an increase in performance accompanied with an increase in injuries (Gonaus et al., 2019, Valle et al., 2018, Faude et al., 2013). To our knowledge, this is the first study to investigate the BFlh architecture and sprint ability in youth soccer players at the age of 12 to 15 years. We aimed to investigate distinctions in BFlh ACSA, FL and PA and sprint ability in circa-pubertal soccer players of different age groups as well as the relationship of these parameters.

METHODS

General Design and Participants

In this cross-sectional investigation, we conducted ultrasound measurements and sprint testing during the regular soccer season on two different days (one to 18 days between tests). In total, 95 players of the under 13, under 14 and under 15 age categories were voluntarily recruited. Four high level Swiss soccer clubs were contacted, three agreed to take part. Playing levels were similar in all clubs for the under 13 to the under 15 age groups, ranging from regional to national level. Training frequency was three to six times per week and was higher in the older age groups. Training volume was four to seven hours for under 13 and under 14 teams and six to ten hours per week for the under 15 teams. To be included in the investigation, players had to be between 12 and 15 years of age and being without injury to the lower limbs for at least six months. The study protocol was approved by the local ethics committee (Ethics Committee of North-Western and Central Switzerland, approval number: 2019-01826) and complied with the Declaration of Helsinki. Since most participants were under the age of 14, parents as well as all participants signed an informed written consent prior to the start of the study after receiving all relevant study information.

Procedures

On test day 1, anthropometric data was collected prior to sprint testing and, on test day 2, ultrasound measurements were performed. We recorded height and sitting height to the nearest 0.1 cm using a stadiometer (seca 217, seca Deutschland, Hamburg, Germany). Weight was determined to the nearest 0.1 kg using an electronic scale (Breuer GS10, Breuer GmbH, Ulm, Germany). Leg length was determined by subtracting sitting height from height. We then calculated maturity ratio using the regression equation suggested by Fransen et al. (2018) to estimate maturational status of the players. This formula includes chronological age, stature, body mass and leg length. The maturity ratio characterizes the ratio of chronological age and age at peak height velocity (Fransen et al., 2018). We assessed BFLh architecture in both legs using B-Mode ultrasonography (ACUSON Juniper, SIEMENS Healthineers, Erlangen, Germany) with a 5.6 cm, linear-array probe (6.2-13.3 MHz, 12L3, Acuson 12L3). Players were positioned ventral, in a supine position with their hip and knees fully extended and feet completely on the bench. In order to reduce the influence of fluid shift, players rested for five minutes before measurement (Lopez et al., 2017). They were asked to stay relaxed during the assessment. Proximal and distal muscle tendon junctions and region of interest (50% of BFLh length $\pm$ 5cm) were determined and marked on the skin. A splint was mounted alongside the region of interest, granting linear extended field of view (EFOV) ultrasound measurements to assess FL and PA (Franchi et al., 2020, 2018). Transducer orientation was adapted whilst scanning to ensure visibility of BFLh fascicles and aponeurosis (Franchi et al., 2020, 2018, Bolsterlee et al., 2016). For ACSA, transverse EFOV pictures at 50% of BFLh length were taken (Kositsky et al., 2020). During measurements, transmission gel was used to ensure acoustic contact and minimize pressure of the probe on the skin (Martino V. Franchi et al., 2020). We took at least two

EFOV pictures in the longitudinal as well as the transversal plane. Three values for FL and PA and one value for ACSA was measured in every image. ACSA, FL and PA were determined in the region of interest using a specialized software integrated in the ultrasound device (ACUSON Juniper, SIEMENS Healthineers, Erlangen, Germany). ACSA was assessed by tracking along the aponeurosis surrounding the BFLh. BFLh FL was assessed by tracking a fascicle originating from the intermediate and inserting into the superficial aponeurosis of the BFLh, PA was measured as the angle in which a fascicle originates from the intermediate aponeurosis (Franchi et al., 2020). A comparison of this method with assessment of BFLh ACSA, FL and PA according to standard procedure (Franchi et al., 2020) using ImageJ software (ImageJ 1.48v, National Institutes of Health, Bethesda, USA) revealed coefficients of variance of lower than 1% when assessing the same fascicles and pennation angles with both methods (for detailed information see Tab. S1 of online supplementary material). Ultrasound measurements were conducted by an experienced investigator. Our own laboratory data shows good inter-session reliability using this procedure (for detailed information see Tab. S2 of online supplementary material). Kositsky et al. (2020) also showed good to excellent inter-session reliability for measuring ACSA in the BFLh at 50% of thigh length (intraclass correlation coefficient (ICC) = 0.98 (0.93, 0.99), SEM (%) = 0.30 cm² (3.0%)). We assessed sprint data using a local positioning system with a frequency of 30 Hz (Inmotiotec GmbH, Regau, Austria). Sprint testing was conducted separately with every team and club. Subsequently to a warm-up program, players performed two linear 40m sprints separated by three minutes of active rest from a standing position (Faude et al., 2010). Players started 30cm behind the starting line which was the extrapolated horizontal line of the penalty box. The testing was performed outside on an artificial turf soccer field and players wore their habitual soccer boots. We measured 10m and 30m sprint split time and maximal velocity ($v_{\max}$), whereas maximal acceleration ($a_{\max}$) was calculated by the Imo-Client software (ImoClient, v 5.1.0.324, Inmotiotec GmbH, Regau, Austria). Frencken et al. (2010) reported high accuracy for this LPM device to assess speed and sprint parameters (SEM = 0.5 km/h (0.4, 0.7), CV = 3.2 % (2.5, 4.3)) compared to distance and speed measurements using measurement tape and timing gates. However, this LPM system was shown to overestimate maximal acceleration by $0.48 \pm 1.27 \text{ m/s}^2$ compared to measurements using a VICON system (Stevens et al., 2014).

Statistics

All statistical analyses were performed in R software (v. 3.6.1., R Core Team, 2019) using the base (R Core Team, 2019), MASS (Venables & Ripley, 2002), psychometric (Fletcher, 2010) and faraway (Faraway, 2016) packages. Normality was assessed for all parameters using Shapiro-Wilk tests. We calculated mean values and standard deviations (SD) for all parameters and age groups as well as mean differences with 95% compatibility intervals (CI) between age groups. We used the means of the BFLh ACSA, FL and PA values of the right and left leg for the analyses. We further calculated Pearson's correlations with 95% CI to assess the relation between all parameters for the whole cohort and within age groups. Additionally, we calculated correlations between all parameters and maturity ratio and chronological age. Correlations were classified according to Hopkins et al. (2009). Thresholds of 0.1, 0.3, 0.5, 0.7 and 0.9 indicating small, moderate, large, very large and extremely large correlations. We used multiple regression models to estimate the best set of predictors for sprint parameters. Models were chosen using the stepAIC command

(Venables & Ripley, 2002). This allowed for a stepwise model selection by Aikake's information criterion (AIC). The model with lowest AIC was deemed best fitting. Collinearities were considered by calculating the variance inflation factor ensuring none of the predictors were highly correlated.

RESULTS

Ten players had to be excluded from the analysis due to sickness or injury at one of the test days. The data of 85 players was finally included in the analysis. Means and standard deviations (SD) of all parameters as well as mean differences with 95% CI between all age groups are reported in Tab. 1. We observed a decrease in 30m time from the under 13 to the under 15 age group by 7%. Similar results were found for 10m time, which decreased by 4%. Both, $v_{\max}$ and $a_{\max}$ increased by 9% and 7%, respectively, from the under 13 to the under 15 age group. However, 30m time and $v_{\max}$ improved more pronounced between the under 13 and under 14 age group, whereas 10m time and $a_{\max}$ improved to a greater extent between the under 14 and under 15 age group. BFIh ACSA increased by 36% from the under 13 to the under 15 age group. BFIh FL and BFIh PA increased by 11% and 8%, respectively, from the under 13 to the under 15 age group. The increase in BFIh PA was higher between the under 13 and under 14 age group, whereas BFIh ACSA and BFIh FL increased more between the under 14 and under 15 age group. Pearson's r with 95% CI for sprint performance and architectural parameters are presented in Tab. 2 (for age group specific correlations see Tab. S3 of online supplementary material). We found a large negative correlation between the 30m sprint time and BFIh ACSA with a moderate to very large effect also being compatible with the data (Fig. 2). A moderate negative correlation of 10m sprint time and BFIh ACSA was found and a small to large effect is compatible with the data as well. We observed a moderate positive correlation for maximal velocity ($v_{\max}$) and BFIh PA with a small to large effect being also compatible. We found a large positive correlation between $v_{\max}$ and BFIh ACSA, with a compatible moderate to large effect (Fig. 2). $a_{\max}$ showed a moderate positive correlation to BFIh ACSA, with compatible small to large effects. Additional figures of correlations can be found in Fig. S1 and Fig. S2 of the online supplementary material. We found large to very large correlations between maturity ratio and 30m sprint time, $v_{\max}$, BFIh ACSA and BFIh FL with moderate to very large effects also being compatible with the data. We found large correlations between chronological age and 30m sprint time and BFIh ACSA, with small to very large effects being compatible as well. Pearson's r is displayed in Fig. 3. Additional correlations can be found in Fig. S2 of the online supplementary material. A combination of BFIh ACSA and chronological age resulted in the best prediction of 30m time, 10m time and $a_{\max}$ (Tab. 3). $v_{\max}$ was best predicted by a combination of FL, ACSA and height (Tab.3).

DISCUSSION

In this study, we investigated the relationship of BFlh architecture and sprint abilities in youth soccer players aged between 12 and 14 years. We found an improved sprint performance with increasing age as well as an increase in BFlh ACSA, PA and FL. Largest correlations were found between BFlh ACSA and 30m sprint time as well as $v_{\max}$. Our findings further indicate that BFlh ACSA and chronological age are the main predictors of most sprint parameters, explaining nearly 50% of the variance in 30m time. BFlh fascicle length, ACSA and height together explained nearly 50% of the variance in maximal sprinting velocity.

Key results

The results of our study demonstrate a decrease in 30m and 10m time as well as an increase in $v_{\max}$ and $a_{\max}$ with increasing age. Other investigations have shown an increase in physical performance with increasing age as well (Gonaus et al., 2019, Perroni et al., 2018, Read et al., 2017, Amonette et al., 2014). 30m sprint performance and $v_{\max}$ increased to a higher extent prior to age at peak height velocity (APHV), whereas 10m sprint performance and $a_{\max}$ seem to increase more pronounced after APHV. Knee flexor volume might contribute to sprint acceleration (Evangelidis et al., 2016, Morin et al., 2015). In this regard, the greater increase in BFlh ACSA and BFlh FL after APHV might explain the enhanced development of 10m time and $a_{\max}$ following APHV. However, our findings are somewhat contradictory to those of Murtagh et al. (2018a) where 10m and 20m sprint time of youth soccer players both decreased more pronounced prior to APHV.

In general, muscle architecture parameters such as ACSA, FL and PA increase during maturation (Radnor et al., 2018, O'Brien et al., 2010). Radnor and colleagues (2020) demonstrated that muscle thickness (+30%), FL (+16%) and PA (+13%) in the m. vastus lateralis increased from pre to post APHV in active school-aged boys. On the contrary, O'Brien et al. (2010) found an increase in all m. quadriceps femoris muscles only in FL and volume in adults compared to children. In our investigation, BFlh ASCA, FL and PA increased from the under 13 to the under 15 age group, although not continuously. We found high variance of BFlh ACSA, FL and PA within age groups. A reason for that might be differences in maturational status, which would be in line with the findings of Franchi et al. (2019).

Measured BFlh FL was lower in this investigation for all age groups compared to elite adolescent soccer players aged 17 years (Lacome et al., 2020) and elite adult soccer players (Timmins et al., 2016). PA was higher in all groups compared to adults (Franchi et al., 2020; Pimenta et al., 2018) and ACSA was smaller in all age groups compared to adults (Kositsky et al., 2020). The adaptation and growing processes of muscles are different during maturation (Radnor et al., 2018). In accordance with our data, Binzoni et al. (2001) showed that, for example, m. gastrocnemius medialis PA

increases until becoming stable after APHV. As BFIh ACSA and FL increased more profound after APHV, maturational status might account for the observed architectural differences and disappear with increasing chronological age. On the other hand, higher BFIh PA and shorter FL values observed in this investigation might as well be considered soccer specific. Tendon stiffness increases with biological maturation (Radnor et al., 2018). If a tendon is more compliant, the amount of fascicle shortening during contraction would therefore be increased (Reeves et al., 2004). A higher BFIh PA would increase the amount of contractile material in parallel and allow fascicles to shorten less compared to whole muscle shortening during contraction (Maden-Wilkinson et al., 2020; Franchi et al., 2014). This might increase force production of the muscle (Maden-Wilkinson et al., 2020). However, since this is a cross-sectional study, we cannot clearly distinguish whether the differences in BFIh architecture and performance between the age groups are specific to soccer training or associated with maturation.

Masuda et al. (2003) showed that whole hamstring ACSA in adults at 50% thigh length is positively correlated to maximal isokinetic knee flexion and hip extension strength. Additionally, Evangelidis et al. (2016) showed that muscle volume is related to eccentric peak torque in the knee flexors. Since eccentric peak torque is related to acceleration during sprinting (Morin et al., 2015), an increased BFIh ACSA could contribute to an enhanced sprint ability in youth soccer players. BFIh ACSA increases with age, which could explain the enhanced sprint ability in the older age groups. Mendiguchia et al. (2020) showed a small increase in BFIh FL and a trivial increase in PA in adult soccer players after six weeks of sprint training. However, this investigation evaluated BFIh FL through manual extrapolation and from images presenting a small field of view (4.7 cm) which may result in imprecise estimations (Franchi et al., 2020). In adult sprinters, longer m. vastus lateralis and m. gastrocnemius medialis and lateralis fascicles were associated with superior 100m sprint performance (Kumagai et al., 2000). We observed, that longer BFIh FL were associated with improved sprint ability. If a muscle shortens with the same velocity, longer fibers might produce more force (Lieber & Friden, 2000). Longer FL additionally enables the muscle to operate more effectively at longer muscle lengths and with lower strain during eccentric contractions over a given range of motion (Mendiguchia et al., 2020, Guex et al., 2016). In contrast to the results of Kumagai et al (2000) who reported lower m. vastus lateralis pennation angles in adults with better sprint performance, we observed, that a larger BFIh PA were positively related to sprint performance. This might be the case, because a larger PA increases the force generating capacity of the muscle (Maden-Wilkinson et al., 2020, Radnor et al., 2018). A higher physiological cross-sectional area in muscles with increased PA and lower shortening of the muscle fibres compared to the shortening of the whole muscle are possible reasons (Maden-Wilkinson et al., 2020, Wakeling et al., 2011).

Longer BFIh FL as well as higher eccentric knee flexor strength decreases the risk of a hamstring injury (Bourne et al., 2018, Timmins et al., 2016). Starting at the under 14 age group, matches are

played on adult size pitches and training volume is increased, resulting in higher conditional demands for the players (Goto et al., 2019). Biological maturation typically coincides with increments in training volume and pitch size, potentially increasing injury risk (Hall et al., 2020).

Our results show larger correlations between maturity ratio and architectural as well as sprint parameters compared to chronological age. One reason could be, that the chronological age does not include any physiological characteristics. As indicated by the larger correlations, maturational status is potentially more influential on muscle architecture. The growth of the femur bone provides a stimulus for muscle growth (Xu et al., 2009). Additionally, m. vastus lateralis thickness increase was shown to coincide with the gain of body mass during maturation resulting in a greater mechanical load (Radnor et al., 2020). Maturational status influences physical performance and, in combination with weight, accounts for up to 50% of the differences sprint among youth soccer players aged 13 to 15 (Malina et al., 2007, 2004). In 10m to 20m sprints, heavier and taller players aged 13 to 16 years performed better, whereas this was not the case for players aged 10 to 12 years (Mathisen & Pettersen, 2015). Itoh & Hirose (2019) showed, that early maturing children performed better over a 50m sprint but not over a 10m sprint. This was explained by the higher correlation of 50m sprint time with physical characteristics such as height, body mass and thigh circumference. Still, power to weight ratio might be lower in early maturing players, explaining similar 10m sprint results compared to late maturing players.

Sprint ability was best predicted by a combination of BFLh ACSA, chronological age, height and FL. Maturity ratio is calculated using chronological age and several physiological characteristics (Fransen et al., 2018), therefore the single components might better predict sprint ability, e.g. height (Itoh & Hirose, 2019). As maturity ratio was collinear to other predictors as well, it was not included in any model. Knee flexor ACSA is related to eccentric peak torque and therewith acceleration (Evangelidis et al., 2016, Morin et al., 2015), which could explain the inclusion of BFLh ACSA in all models. Chronological age was included in most models, likely because of its moderate to large correlation to sprint ability parameters and low collinearity to the other predictors.

Limitations

The following limitations of this investigation need to be mentioned. BFLh architecture was only assessed at one location across the thigh. Since architecture differs alongside the muscle, results might be different for other regions (Kositsky et al., 2020; Franchi et al., 2020; Kellis, 2018). Different muscle regions have different tasks (Earp et al., 2015), therefore the understanding of this relationship could have been improved if additional muscle regions had been investigated. We only assessed one of the four hamstring muscles. Because of different architectural properties (Kellis et al., 2012), we cannot conclude on the relationship of sprint ability and architecture of the other hamstring muscles. Ultrasound pictures were taken at rest. This might limit the transferability to dynamic tasks (Hodson-Tole & Lai, 2019). We used 2D-ultrasound to measure architecture.

Because of this we cannot account for 3D fascicle curvature and 3D orientation of PA (Franchi et al., 2018). In addition to that, there is uncertainty about the ideal method to assess PA, as measurements of PA in EFOV pictures yield different results compared to static pictures of the same region (Franchi et al., 2020). Since this is a cross-sectional study, we cannot conclude on causality of the assessed correlations. A longitudinal investigation could provide insight into adaptations to sprint and athletic training in youth soccer players relative to maturation. Additionally, including a wider age range into the investigation might have served to better understand the development of the players.

CONCLUSION

The study has shown that BFlh architecture is related to 30m and 10m sprint time, $v_{\max}$ and $a_{\max}$ in youth soccer players. Differences among the age groups could be training induced or a consequence of maturation. Even though we found correlations for all architectural parameters, BFlh ACSA was best related to the assessed sprint parameters. Chronological age and BFlh ACSA are better predictors of sprint ability than maturity ratio. Adaptations to sprint training of youth soccer players and the investigation of other key muscles for sprinting should be considered in future research.

PRACTICAL APPLICATIONS

Sprint ability in soccer is of great importance. The percentage of sprint running increased in soccer over the last few years and it is the most frequent action preceding goal situations. On the other hand, the risk for a hamstring strain injury is increased during sprinting. Our results demonstrate, that BFlh architecture, especially BFlh ACSA, is related to sprint ability in youth soccer players. Therefore, strength training targeting hamstring hypertrophy could improve sprint ability by increasing BFlh ACSA. Additionally, an increase in strength, preferably eccentric hamstring strength, could reduce the risk for hamstring strain injury while similarly enhancing sprint ability.

CONTRIBUTIONS

OF, RR and TB designed the study. PR, MK and MF assisted in designing the study. PR, TB and SZ were responsible for the assessments. PR analysed the data and wrote the first manuscript draft with assistance of OF. All authors read and revised the manuscript draft and approved the final manuscript.

ACKNOWLEDGEMENTS

We would like to thank the players as well as trainers of the FC Basel, FC Concordia Basel and BSC Old Boys Basel for taking part in this investigation.

FUNDING INFORMATION

No sources of funding.

SUPPLEMENTARY MATERIAL ACCESSIBILITY

Supplementary tables and figures can be found here: osf.io/vy2pw/

REFERENCES

- Amonette, W. E., Brown, D., Dupler, T. L., Xu, J., Tufano, J. J., & De Witt, J. K. (2014). Physical Determinants of Interval Sprint Times in Youth Soccer Players. *Journal of Human Kinetics*, 40(1), 113–120. <https://doi.org/10.2478/hukin-2014-0013>
- Barnes, C., Archer, D. T., Hogg, B., Bush, M., & Bradley, P. S. (2014). The Evolution of Physical and Technical Performance Parameters in the English Premier League. *International Journal of Sports Medicine*, 35(13), 1095–1100. <https://doi.org/10.1055/s-0034-1375695>
- Binzoni, T., Bianchi, S., Hanquinet, S., Kaelin, A., Sayegh, Y., Dumont, M., & Jéquier, S. (2001). Human gastrocnemius medialis pennation angle as a function of age: From newborn to the elderly. *Journal of Physiological Anthropology and Applied Human Science*, 20(5), 293–298.
- Bolsterlee, B., Gandevia, S. C., & Herbert, R. D. (2016). Effect of Transducer Orientation on Errors in Ultrasound Image-Based Measurements of Human Medial Gastrocnemius Muscle Fascicle Length and Pennation. *PloS One*, 11(6), e0157273. <https://doi.org/10.1371/journal.pone.0157273>
- Bourne, M. N., Timmins, R. G., Opar, D. A., Pizzari, T., Ruddy, J. D., Sims, C., Williams, M. D., & Shield, A. J. (2018). An Evidence-Based Framework for Strengthening Exercises to Prevent Hamstring Injury. *Sports Medicine*, 48(2), 251–267. <https://doi.org/10.1007/s40279-017-0796-x>
- Earp, J. E., Newton, R. U., Cormie, P., & Blazevich, A. J. (2015). Inhomogeneous Quadriceps Femoris Hypertrophy in Response to Strength and Power Training: *Medicine & Science in Sports & Exercise*, 47(11), 2389–2397. <https://doi.org/10.1249/MSS.0000000000000669>
- Ekstrand, J., Hagglund, M., & Walden, M. (2011). Injury incidence and injury patterns in professional football: The UEFA injury study. *British Journal of Sports Medicine*, 45(7), 553–558. <https://doi.org/10.1136/bjsm.2009.060582>
- Evangelidis, P. E., Massey, G. J., Pain, M. T. G., & Folland, J. P. (2016). Strength and size relationships of the quadriceps and hamstrings with special reference to reciprocal muscle balance. *European Journal of Applied Physiology*, 116(3), 593–600. <https://doi.org/10.1007/s00421-015-3321-7>

Faraway, J. (2016). Faraway: Functions and Datasets for Books by Julian Faraway. R package version 1.0.7. <https://CRAN.R-project.org/package=faraway>.

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sports Sciences*, 30(7), 625–631. <https://doi.org/10.1080/02640414.2012.665940>

Faude, O., Rößler, R., & Junge, A. (2013). Football Injuries in Children and Adolescent Players: Are There Clues for Prevention? *Sports Medicine*, 43(9), 819–837. <https://doi.org/10.1007/s40279-013-0061-x>

Faude, O., Schlumberger, A., Fritsche, T., Treff, G., & Meyer, T. (2010). Performance Diagnosis in Football – Methodological Standards. *Deutsche Zeitschrift für Sportmedizin*, 61(6), 129–132.

Fiorentino, N. M., & Blemker, S. S. (2014). Musculotendon variability influences tissue strains experienced by the biceps femoris long head muscle during high-speed running. *Journal of Biomechanics*, 47(13), 3325–3333. <https://doi.org/10.1016/j.jbiomech.2014.08.010>

Fletcher, T. (2010). Psychometric: Applied Psychometric Theory. R package version 2.2. <https://CRAN.R-project.org/package=psychometric>.

Franchi, M. V., Atherton, P. J., Reeves, N. D., Flück, M., Williams, J., Mitchell, W. K., Selby, A., Beltran Valls, R. M., & Narici, M. V. (2014). Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiologica (Oxford, England)*, 210(3), 642–654. <https://doi.org/10.1111/apha.12225>

Franchi, M., V., Ellenberger, L., Javet, M., Bruhin, B., Romann, M., Frey, W. O., & Spörri, J. (2019). Maximal Eccentric Hamstrings Strength in Competitive Alpine Skiers: Cross-Sectional Observations From Youth to Elite Level. *Frontiers in Physiology*, 10, 88. <https://doi.org/10.3389/fphys.2019.00088>

Franchi, M., V., Fitze, D. P., Raiteri, B. J., Hahn, D., & Spörri, J. (2020). Ultrasound-derived Biceps Femoris Long Head Fascicle Length: Extrapolation Pitfalls. *Medicine & Science in Sports & Exercise*, 52(1), 233–243. <https://doi.org/10.1249/MSS.00000000000002123>

Franchi, M., V., Raiteri, B. J., Longo, S., Sinha, S., Narici, M. V., & Csapo, R. (2018). Muscle Architecture Assessment: Strengths, Shortcomings and New Frontiers of in Vivo Imaging Techniques. *Ultrasound in Medicine & Biology*, 44(12), 2492–2504. <https://doi.org/10.1016/j.ultrasmed-bio.2018.07.010>

- Fransen, J., Bush, S., Woodcock, S., Novak, A., Deprez, D., Baxter-Jones, A. D., Vaeyens, R., & Lenoir, M. (2018). Improving the prediction of maturity from anthropometric variables using a maturity ratio. *Pediatr Exerc Sci*., 30(2), 296–307. <https://doi.org/10.1123/pes.2017-0009>.
- Frencken, W. G. P., Lemmink, K. A. P. M., & Delleman, N. J. (2010). Soccer-specific accuracy and validity of the local position measurement (LPM) system. *Journal of Science and Medicine in Sport*, 13(6), 641–645. <https://doi.org/10.1016/j.jsams.2010.04.003>
- Gonaus, C., Birklbauer, J., Lindinger, S. J., Stöggl, T. L., & Müller, E. (2019). Changes Over a Decade in Anthropometry and Fitness of Elite Austrian Youth Soccer Players. *Frontiers in Physiology*, 10, 333. <https://doi.org/10.3389/fphys.2019.00333>
- Goto, H., Morris, J. G., & Nevill, M. E. (2019). Influence of Biological Maturity on the Match Performance of 8- to 16-Year-Old, Elite, Male, Youth Soccer Players: *Journal of Strength and Conditioning Research*, 33(11), 3078–3084. <https://doi.org/10.1519/JSC.0000000000002510>
- Guex, K., Degache, F., Morisod, C., Saily, M., & Millet, G. P. (2016). Hamstring architectural and functional adaptations following long vs. Short muscle length eccentric training. *Frontiers in Physiology*, 7(AUG). Scopus. <https://doi.org/10.3389/fphys.2016.00340>
- Gunnar Mathisen, & Pettersen, S. A. (2015). Anthropometric factors related to sprint and agility performance in young male soccer players. *Open Access Journal of Sports Medicine*, 337. <https://doi.org/10.2147/OAJSM.S91689>
- Hall, E., Jon Larruskain, Susana M Gil, Jose A Lekue, Philipp Baumert, Edgardo Rienzi, Sacha Moreno, Marcio Tannure, Conall F Murtagh, Jack D Ade, Paul Squires, Patrick Orme, Liam Anderson, Craig M Whitworth-Turner, James P Morton, Barry Drust, Alun G Williams, & Robert M Erskine. (2020). An injury audit in high-level male youth soccer players from English, Spanish, Uruguayan and Brazilian academies. *Physical Therapy in Sports*. <https://doi.org/10.1016/j.ptsp.2020.04.033>
- Hodson-Tole E.F., & Lai A.K.M. (2019). Ultrasound-derived changes in thickness of human ankle plantar flexor muscles during walking and running are not homogeneous along the muscle mid-belly region. *Scientific Reports*, 9(1), 15090. Medline. <https://doi.org/10.1038/s41598-019-51510-4>
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science: *Medicine & Science in Sports & Exercise*, 41(1), 3–13. <https://doi.org/10.1249/MSS.0b013e31818cb278>

Ishøi, L., Hölmich, P., Aagaard, P., Thorborg, K., Bandholm, T., & Serner, A. (2018). Effects of the Nordic Hamstring exercise on sprint capacity in male football players: A randomized controlled trial. *Journal of Sports Sciences*, 36(14), 1663–1672.

<https://doi.org/10.1080/02640414.2017.1409609>

Itoh, R., & Hirose, N. (2019). Relationship Among Biological Maturation, Physical Characteristics, and Motor Abilities in Youth Elite Soccer Players: *Journal of Strength and Conditioning Research*, 1. <https://doi.org/10.1519/JSC.0000000000003346>

Kellis, E. (2018). Intra- and Inter-Muscular Variations in Hamstring Architecture and Mechanics and Their Implications for Injury: A Narrative Review. *Sports Medicine*, 48(10), 2271–2283.

<https://doi.org/10.1007/s40279-018-0975-4>

Kellis, E., Galanis, N., Kapetanios, G., & Natsis, K. (2012). Architectural differences between the hamstring muscles. *Journal of Electromyography and Kinesiology*, 22(4), 520–526.

<https://doi.org/10.1016/j.jelekin.2012.03.012>

Kellis, E., Galanis, N., Natsis, K., & Kapetanios, G. (2009). Validity of architectural properties of the hamstring muscles: Correlation of ultrasound findings with cadaveric dissection. *Journal of Biomechanics*, 42(15), 2549–2554. <https://doi.org/10.1016/j.jbiomech.2009.07.011>

Kositsky, A., Goncalves, B. A. M., Stenroth, L., Barrett, R. S., Diamond, L. E., & Saxby, D. J. (2020). Reliability and Validity of Ultrasonography for Measurement of Hamstring Muscle and Tendon Cross-Sectional Area. *Ultrasound in Medicine and Biology*, 46(1), 55–63.

<https://doi.org/10.1016/j.ultrasmedbio.2019.09.013>

Krommes, K., Petersen, J., Nielsen, M. B., Aagaard, P., Hölmich, P., & Thorborg, K. (2017). Sprint and jump performance in elite male soccer players following a 10-week Nordic Hamstring exercise Protocol: A randomised pilot study. *BMC Research Notes*, 10(1), 669.

<https://doi.org/10.1186/s13104-017-2986-x>

Kumagai, K., Abe, T., Brechue, W. F., Ryushi, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, 88(3), 811–816. <https://doi.org/10.1152/jappl.2000.88.3.811>

Lacome, M., Avrillon, S., Cholley, Y., Simpson, B. M., Guilhem, G., & Buchheit, M. (2020). Hamstring Eccentric Strengthening Program: Does Training Volume Matter? *International Journal of Sports Physiology & Performance*, 15(1), 81–90. <https://doi.org/10.1123/ijsp.2018-0947>

Lieber, R. L., & Friden, J. (2000). Functional and clinical significance of skeletal muscle architecture. *MUSCLE & NERVE*, 23, 1647–1666.

- Lopez, P., Wilhelm, E. N., Rech, A., Minozzo, F., Radaelli, R., & Pinto, R. S. (2017). Echo intensity independently predicts functionality in sedentary older men. *Muscle & Nerve*, 55(1), 9–15. <https://doi.org/10.1002/mus.25168>
- Maden-Wilkinson, T. M., Balshaw, T. G., Massey, G. J., & Folland, J. P. (2020). What makes long-term resistance-trained individuals so strong? A comparison of skeletal muscle morphology, architecture, and joint mechanics. *Journal of Applied Physiology*, 128(4), 1000–1011. <https://doi.org/10.1152/jappphysiol.00224.2019>
- Malina, R. M., Ribeiro, B., Aroso, J., Cumming, S. P., Unnithan, V., & Kirkendall, D. (2007). Characteristics of youth soccer players aged 13-15 years classified by skill level. *British Journal of Sports Medicine*, 41(5), 290–295. <https://doi.org/10.1136/bjsm.2006.031294>
- Malina, Robert M., Eisenmann, J. C., Cumming, S. P., Ribeiro, B., & Aroso, J. (2004). Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13 to 15 years. *European Journal of Applied Physiology*, 91(5–6), 555–562. <https://doi.org/10.1007/s00421-003-0995-z>
- Masuda, K., Kikuhara, N., Takahashi, H., & Yamanaka, K. (2003). The relationship between muscle cross-sectional area and strength in various isokinetic movements among soccer players. *Journal of Sports Sciences*, 21(10), 851–858. <https://doi.org/10.1080/0264041031000102042>
- Mendiguchia, J., Martinez-Ruiz, E., Morin, J. B., Samozino, P., Edouard, P., Alcaraz, P. E., Esparza-Ros, F., & Mendez-Villanueva, A. (2015). Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players: Hamstring training and performance. *Scandinavian Journal of Medicine & Science in Sports*, 25(6), e621–e629. <https://doi.org/10.1111/sms.12388>
- Mendiguchia, Jurdan, Conceição, F., Edouard, P., Fonseca, M., Pereira, R., Lopes, H., Morin, J.-B., & Jiménez-Reyes, P. (2020). Sprint versus isolated eccentric training: Comparative effects on hamstring architecture and performance in soccer players. *PLOS ONE*, 15(2), e0228283. <https://doi.org/10.1371/journal.pone.0228283>
- Morin, J.-B., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli, M., & Mendiguchia, J. (2015). Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production. *Frontiers in Physiology*, 6. <https://doi.org/10.3389/fphys.2015.00404>
- Murtagh, C. F., Brownlee, T. E., O'Boyle, A., Morgans, R., Drust, B., & Erskine, R. M. (2018). Importance of Speed and Power in Elite Youth Soccer Depends on Maturation Status: *Journal of Strength and Conditioning Research*, 32(2), 297–303. <https://doi.org/10.1519/JSC.0000000000002367>

O'Brien, T. D., Reeves, N. D., Baltzopoulos, V., Jones, D. A., & Maganaris, C. N. (2010). Muscle-tendon structure and dimensions in adults and children. *Journal of Anatomy*, 216(5), 631–642. <https://doi.org/10.1111/j.1469-7580.2010.01218.x>

Perroni, F., Pintus, A., Frandino, M., Guidetti, L., & Baldari, C. (2018). Relationship Among Repeated Sprint Ability, Chronological Age, and Puberty in Young Soccer Players: *Journal of Strength and Conditioning Research*, 32(2), 364–371. <https://doi.org/10.1519/JSC.0000000000001799>

Pimenta, R., Blazeovich, A. J., & Freitas, S. R. (2018). Biceps Femoris Long-Head Architecture Assessed Using Different Sonographic Techniques. *Medicine and Science in Sports and Exercise*, 50(12), 2584–2594. <https://doi.org/10.1249/MSS.0000000000001731>

R Core Team (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>. (o. J.).

Radnor, J. M., Oliver, J. L., Waugh, C. M., Myer, G. D., & Lloyd, R. S. (2020). The Influence of Maturity Status on Muscle Architecture in School-Aged Boys. *Pediatric Exercise Science*, 32(2), 89–96. <https://doi.org/10.1123/pes.2019-0201>

Radnor, J. M., Oliver, J. L., Waugh, C. M., Myer, G. D., Moore, I. S., & Lloyd, R. S. (2018). The Influence of Growth and Maturation on Stretch-Shortening Cycle Function in Youth. *Sports Medicine*, 48(1), 57–71. <https://doi.org/10.1007/s40279-017-0785-0>

Read, P., Oliver, J., De Ste Croix, M., Myer, G., & Lloyd, R. (2017). Hopping and Landing Performance in Male Youth Soccer Players: Effects of Age and Maturation. *International Journal of Sports Medicine*, 38(12), 902–908. <https://doi.org/10.1055/s-0043-114009>

Reeves, N. D., Narici, M. V., & Maganaris, C. N. (2004). In vivo human muscle structure and function: Adaptations to resistance training in old age. *Experimental Physiology*, 89(6), 675–689. <https://doi.org/10.1113/expphysiol.2004.027797>

Rössler, R., Junge, A., Chomiak, J., Dvorak, J., & Faude, O. (2016). Soccer Injuries in Players Aged 7 to 12 Years: A Descriptive Epidemiological Study Over 2 Seasons. *The American Journal of Sports Medicine*, 44(2), 309–317. <https://doi.org/10.1177/0363546515614816>

Schache, A. G., Dorn, T. W., Blanch, P. D., Brown, N. A. T., & Pandy, M. G. (2012). Mechanics of the Human Hamstring Muscles during Sprinting: *Medicine & Science in Sports & Exercise*, 44(4), 647–658. <https://doi.org/10.1249/MSS.0b013e318236a3d2>

Stevens, T. G. A., de Ruiter, C. J., van Niel, C., van de Rhee, R., Beek, P. J., & Savelsbergh, G. J. P. (2014). Measuring Acceleration and Deceleration in Soccer-Specific Movements Using a Local

Position Measurement (LPM) System. *International Journal of Sports Physiology and Performance*, 9(3), 446–456. <https://doi.org/10.1123/ijsp.2013-0340>

Timmins, R. G., Bourne, M. N., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016). Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. *British Journal of Sports Medicine*, 50(24), 1524–1535. <https://doi.org/10.1136/bjsports-2015-095362>

Valle, X., Malliaropoulos, N., Párraga Botero, J. D., Bikos, G., Pruna, R., Mónaco, M., & Maffulli, N. (2018). Hamstring and other thigh injuries in children and young athletes. *Scandinavian Journal of Medicine & Science in Sports*, 28(12), 2630–2637. <https://doi.org/10.1111/sms.13282>

Venables, W. N., & Ripley, B. D. (2002). *Modern Applied Statistics with S* (4. Edition). Springer. <http://www.stats.ox.ac.uk/pub/MASS4>

Wakeling, J. M., Blake, O. M., Wong, I., Rana, M., & Lee, S. S. M. (2011). Movement mechanics as a determinate of muscle structure, recruitment and coordination. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1570), 1554–1564. <https://doi.org/10.1098/rstb.2010.0294>

Xu, L., Nicholson, P., Wang, Q., Alén, M., & Cheng, S. (2009). Bone and Muscle Development During Puberty in Girls: A Seven-Year Longitudinal Study. *Journal of Bone and Mineral Research*, 24(10), 1693–1698. <https://doi.org/10.1359/jbmr.090405>

Tables and Figures

Table 1: Participant characteristics, sprint and ultrasound data in means and standard deviation (SD) or 95% CI. $v_{\max}$ (maximal velocity over the 40m sprint), $a_{\max}$ (maximal acceleration in the first 10m), mean difference (Δ) with 95% compatibility interval, anatomical cross-sectional area (ACSA), fascicle length (FL) and pennation angle (PA).

	Under 13 (n=29) mean (SD)	Under 14 (n=25) mean (SD)	Under 15 (n=31) mean (SD)	Under 13 vs Under 14 Δ (95% CI)	Under 14 vs. Under 15 Δ (95% CI)	Under 13 vs. Under 15 Δ (95% CI)
Age (y)	12.5 (0.1)	13.5 (0.3)	14.4 (0.3)	-1.0 (-1.0,-1.0)	-0.9 (-0.9,-0.9)	-1.9 (-1.9,-1.9)
Height (cm)	155.3 (6.2)	160.6 (7.7)	170.0 (7.7)	-3.1 (-10.9,4.7)	-11.0 (-15.9,-6.2)	-14.7 (-21.3,-8.2)
Weight (kg)	43.9 (7.6)	47.0 (6.8)	81.1 (8.8)	-5.3 (-12.4,1.9)	-9.5 (-14.0,-4.9)	-14.1 (-23.3,-5.1)
Sitting height (cm)	83.1 (5.8)	83.4 (5.0)	87.9 (4.3)	-0.3 (-4.8,4.1)	-4.5 (-6.2,-2.9)	-4.9 (-8.3,-1.4)
Leg length	72.2 (5.7)	77.2 (13.8)	82.2 (4.9)	-4.9 (-7.7,-2.2)	-5 (-7.4,-2.5)	-9.9 (-13.6,-6.2)
Maturity Ratio	0.93 (0.05)	0.94 (1.8)	1.06 (0.04)	-0.05 (-0.08,-0.05)	-0.08 (-0.1,-0.05)	-0.13 (-0.13,-0.12)
30m Time (s)	5.01 (0.17)	4.82 (0.2)	4.67 (0.2)	0.19 (0.18,0.19)	0.15 (0.14,0.15)	0.34 (0.33,0.34)
10m Time (s)	2.04 (0.07)	2.01 (0.07)	1.95 (0.08)	0.03 (0.03,0.03)	0.06 (0.05,0.06)	0.09 (0.08,0.09)
$v_{\max}$ (km/h)	25.06 (1.13)	26.27 (1.39)	27.23 (2.16)	-1.21 (-1.45,-0.98)	-0.96 (-1.22,-0.69)	-2.17 (-2.63,-1.84)
$a_{\max}$ (m/s ²)	3.48 (0.19)	3.56 (0.21)	3.72 (0.31)	-0.08 (-0.09,-0.08)	-0.16 (-0.17,-0.15)	-0.24 (-0.64,-0.25)
ACSA (cm ²)	7.78 (2.02)	8.88 (1.56)	10.64 (2.21)	-1.1 (-1.73,-0.48)	-1.77 (-2.11,-1.42)	-2.86 (-3.53,-2.31)
FL (cm)	6.9 (0.8)	7.1 (0.8)	7.6 (0.8)	-0.1 (-0.2,0.0)	-0.6 (-0.6,-0.5)	-0.7 (-0.8,-0.6)
PA (°)	17.9 (2.2)	19.2 (2.0)	19.4 (1.4)	-1.4 (-2.2,-0.5)	-0.2 (-0.4,0.0)	-1.4 (-1.9,-1.0)

Table 2: Pearson's r (95% CI) of sprint ability and architectural parameters tested for correlation. Correlations were calculated using all measured data not divided into age groups.

	BFIh FL	BFIh PA	BFIh ACSA
30m time	-0.25 (0.43,-0.04)	-0.3 (-0.48,-0.09)	-0.61 (-0.73,-0.45)
10m time	-0.13 (-0.33,0.08)	-0.19 (-0.38,0.02)	-0.39 (-0.56,-0.2)
$v_{\max}$	0.26 (.05,0.45)	0.32 (0.11,0.5)	0.61 (0.45,0.72)
$a_{\max}$	0.13 (-0.09,0.33)	0.2 (-0.01,0.4)	0.42 (0.23,0.58)

Table 3: Estimates, standard errors and R² values (95% CI) of multivariate regression analysis calculating the best set of predictors for sprint performance.

Covariates	Estimate	Model		
		Standard error	Standardized β coefficient	R ² (model)
30m sprint time				
Intercept	6.62 (6.01,7.25)	0.31		
ACSA	-0.04 (-0.06,-0.02)	0.01	-0.40	
Age	-0.10 (-0.16,-0.05)	0.03	-0.38	0.47 (0.33,0.62)
10m sprint time				
Intercept	2.48 (2.22,2.74)	0.13		
ACSA	-0.01 (-0.02,0.01)	0.004	-0.23	
Age	-0.03 (-0.05,-0.01)	0.01	-0.32	0.23 (0.08,0.38)
$a_{\max}$				
Intercept	6.61 (3.58,9.65)	1.52		
ACSA	-0.44 (-0.77,-0.11)	0.17		
Age	-0.25 (-0.48,-0.02)	0.11		
ACSA*Age	0.04 (0.01,0.06)	0.01		0.28 (0.13,0.44)
$v_{\max}$				
Intercept	10.45 (4.14,16.77)	3.18		
ACSA	0.25 (0.06,0.44)	0.1	0.30	
Height	0.10 (0.05,0.15)	0.03	0.50	
FL	-0.31 (-0.76,0.13)	0.22	-0.14	0.46 (0.32,0.61)

Figure 1: Transverse and longitudinal ultrasound images of left BFlh with measurement of architectural parameters using the ultrasound device software.

Figure 2: Correlations between 30m sprint time and $v_{\max}$ and BFIh ACSA for different age groups. Pearson's r characterizes overall correlation with no regard to age groups.

Figure 3: Correlations between chronological age and maturity ratio and sprint as well as architectural parameters for different age groups. Pearson's r characterizes overall correlation with no regard to age groups.