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Hip flexor and knee extensor muscularity are associated with sprint performance in sprint-trained preadolescent boys

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Abstract

Purpose: We attempted to determine the relationships between the cross-sectional area (CSA) of the trunk and lower limb muscles and sprint performance in male preadolescent sprinters. ***Methods***: Fifteen sprint-trained preadolescent boys (age, 11.6 ± 0.4 years) participated in this study. The CSAs of the participants' trunk and lower limb muscles were measured using magnetic resonance imaging, and these muscles were normalized with free-fat mass. To assess participants' sprint performance, sprint time and variables during the 50-m sprint test were measured. The sprint variables were expressed as their indices by normalizing with body height. ***Results***: The relative CSAs of psoas major, adductors and quadriceps femoris were significantly correlated with sprint time (r = -0.802, -0.643, and -0.639). Moreover, the relative CSAs of these muscles were significantly correlated with indices of sprint velocity (r = 0.694, 0.612, and 0.630) and step frequency (r = 0.687, 0.740, and 0.590), but did not that of step length. ***Conclusions***: These findings suggest that greater hip flexor and knee extensor muscularity in male preadolescent sprinters may help achieve superior sprint performance by potentially enhancing their moments, which may be induced by increased step frequency rather than step length, during sprinting.

Key words: Magnetic resonance imaging, Muscle cross-sectional area, Hip flexion, Knee extension, Step frequency/length

Introduction

Superior sprint performance is achieved through the generation of large moments by the muscles crossing the hip, knee and ankle joints. The magnitudes of these moments are primarily determined by agonist muscle size (2,12,21,13,34). In fact, trunk and lower limb muscles are larger in sprinters than in non-sprinters (1,14,19,22,26). In addition, previous studies have determined that the sizes of these muscles are associated with sprint performance (8,20,22,23,36). Thus, it is suggested that larger muscles in the trunk and lower limbs may contribute to good sprint performance in sprinters.

Several previous studies attempted to identify the specific muscle(s) that improve performance in sprinters (8,14,20,22,23,36), in order to understand the optimal body structure for successful sprinters. Among these studies, previous studies have reported that the cross-sectional area (CSA) of the psoas major (PM) is associated with sprint performance (8,14,20). The PM is the largest of the hip flexors (7), and its CSA is strongly correlated with maximal hip flexor torque (17), which in turn is correlated to sprint performance (10). Moreover, previous studies have showed that a larger quadriceps femoris (QF) may be related to higher sprint performance because of a strong correlation between maximal knee extensor torque and sprint performance (4,10,14,22). Furthermore, Sugisaki et al. (36) reported that a larger CSA of the adductors (ADD) is correlated with a higher performance in sprinters. Similar to QF, ADD, especially adductors magnus, contributes to producing knee extensor moment during human locomotion, as examined using computer simulation (5). Taken together, although other muscles may also play an important role in sprint performance (4,10,14,23,29), larger hip flexors and knee extensors, including the PM, QF, and ADD, may help improve sprint performance, potentially by enhancing the hip flexor and knee extensor moments during sprinting.

Although the relationship between muscle size and performance in adult sprinters has been frequently examined in previous studies (8,14,22,23,36), this relationship has not been extensively examined in junior sprinters. In only one study, Hoshikawa et al. (20) examined the relationship between muscle size and sprint performance in junior sprinters, and they determined that a larger PM was associated with higher sprint performance. Nevertheless, the authors observed only 3 muscles, the PM, QF, and hamstrings (HAM), and currently there is limited knowledge regarding the relationship between muscle size and sprint performance in junior sprinters. Thus, the relationships between other trunk and limb muscles, including the ADD, and sprint performance in junior sprinters remain unknown. Taken together, it is necessary to research more muscles and obtain further information on the relationship between muscle size and sprint performance. Clarifying this relationship may facilitate the planning of long-term performance enhancing programs in this group of sprinters.

The necessity of a long-term project for developing successful athletes from the junior age has been recognized on a global scale (38). However, although Hoshikawa et al. (20) recruited junior sprinters aged 14 to 17 years, information on the relationship between muscle size and performance in younger sprinters is lacking. Therefore, to identify the muscle(s) improving sprint performance in these younger sprinters, we attempted to determine the relationships between the CSAs of a total of 9 trunk and lower limb muscles and sprint performance in male preadolescent sprinters aged 10 to 12 years.

Methods

Participants

Fifteen sprint-trained preadolescent boys (age, 11.6 ± 0.4 years; body height, 146.0 ± 7.8 cm; body mass, 35.5 ± 5.8 kg) participated in this study. Their maturity status was evaluated using years from peak height velocity estimated by a maturity offset value, which was derived from anthropometric data (27), and was assessed as pre-peak height velocity (mean, −2.57 ± 0.61 years). All participants had belonged to a track-and-field athletic sports club for 1.9 ± 0.9 years, and had trained at least twice a week. The training program in the participants consisted of sprint-specific training such as technical drills, and did not include resistance or plyometric training. The participants had participated in a 100-m race, and their best personal 100-m race times ranged from 13.24 to 16.42 s (15.12 ± 1.04 s), within 1 year prior to this study. All participants and their parents were informed of the experimental procedures and provided written consent to participate in the study. The study was approved by the Ethics Committee of Ritsumeikan University (BKC-IRB-2015-019).

Body composition

To exclude difference of whole muscle mass on sprint performance, we measured the free-fat mass (FFM) using a bioelectrical impedance analysis (BIA) with multiple impedance frequencies (InBody720; Biospace Co., CA, USA). The BIA device has been designed to reliably evaluate body composition (37), and unlike dual-energy X-ray absorptiometry, does not expose the participant to radiation (25). BIA measurements were made according to the manufacturer's guidelines. Prior to this measurement, participants emptied their bladders and removed all conductive materials such as watches. During the measurement, participants were still and quiet in undergarments without contact between the torso and arms or between the thighs. The FFM was automatically calculated based on whole body composition from BIA measurement. The value of the FFM in the participants was 31.7 ± 5.7 kg.

Magnetic resonance imaging

The representative images of the CSAs of the trunk and lower limb muscles on magnetic resonance imaging (MRI) are shown in **Figure 1**. The MRI measurement was performed using a 1.5-T magnetic resonance system (Signa HDxt; GE Medical Systems, WI, USA). To measure the CSAs of the trunk and lower limb muscles, the participants were placed in a supine position on the scanner bed, with both knees fully extended and both ankles set at the neutral position (i.e., 0°). For measurement of those CSAs, axial T1-weighted MRI scans of the trunk and lower limb were acquired with an 8-channel coil and a standard body coil, respectively. These scans were performed with a repetition time of 600 ms, echo time of 7.6 ms, slice thickness of 10 mm, field of view of 480 mm, and matrix size of 512 × 256. With regard to the trunk muscles, the CSAs of the rectus abdominis (RA), lateral abdominal wall (LAW), elector spinae (ES), and PM muscles were obtained at the mid-level of the L4−L5 (20,36). The location of L4-L5 was assessed from the sagittal images obtained before the axial images of the trunk. The CSA of the LAW included the external oblique, internal oblique, and transverse oblique. The CSA of the ES was combined with the multifidus lumborum. With regard to the lower limb muscles, the CSAs of the ADD, QF, HAM, dorsiflexors (DF), and plantar flexors (PF) were measured. The images for calculating CSA of the lower limb muscles were obtained based on a method outlined in a previous study (36). In brief, the CSA of the ADD, including the adductor magnus and adductor brevis, was obtained at the proximal 30% of the thigh length (i.e., the distance between the greater trochanter and the lower edge of the femur). The CSA of the QF, including the rectus femoris, vastus intermedius, vastus lateralis, and vastus medialis, was obtained at 50% of the thigh length. The CSA of the HAM, including the biceps femoris, semitendinosus, and semimembranosus, was obtained at 70% of the thigh length. The CSA of the DF, including the tibialis anterior and extensor digitorum longus, was obtained at the proximal 30% of the lower leg length (i.e., the distance between the superior end of the tibia and the lateral malleolus of fibula). The CSA of the PF, including the gastrocnemius medialis, gastrocnemius lateralis, and soleus, was obtained at the same transverse to the DF. The anatomical locations (e.g., of the greater trochanter) for calculating the lengths of the thighs and lower legs were assessed from the coronal images obtained before the axial images of the thighs and lower legs. CSA measurements for all muscles were performed for the right leg. The analyses for measuring CSA were conducted using image analysis software (OsiriX Version 5.6, Switzerland). To reduce the possible influence of the difference in total lean tissue mass among participants, the absolute CSA was normalized to FFM to the two-thirds power, which was converted into the same dimension as the CSA, based on a method described in previous studies (17,19,23,36). The absolute and relative CSAs of a total of 9 trunk and lower limb muscles in the participants are listed in **Table 1**.

The 50-m sprint test

The participants performed two maximal effort 50-m sprints on an all-weather track after sufficient warm-up was performed. They used the standing start from a staggered stance. Start signal was performed using a common sound via the sound system (Digipistol; Molten, Japan). The sprint time in the 50-m sprint test was recorded using photocell (E3G-R13; Omuron Inc, Kyoto, Japan). The fastest sprint of the two maximal effort sprints was used for analysis, and this mean values was 8.19 ± 0.41 s (range, 7.61–8.86). The videos during the sprint were sampled at 300 Hz (JVC; GC-PX1, Japan). The sprint variables were measured using image analysis. To exclude differences in body size among participants, the sprint variables were normalized to body height and were expressed as its index (16). The sprint velocity was calculated as the quotient of the distance and the time, and this mean value was

6.12 ± 0.31 m/s (range, 5.64–6.57). The sprint velocity index was calculated as sprint velocity/(body height × g)1/2, and this mean index value was 1.62 ± 0.06 (range, 1.50–1.69). When calculating the number of the steps, the last step before the 50-m line was considered to be the last step (15). The mean step frequency was 4.08 ± 0.17 Hz (range, 3.83–4.33). The step frequency index was calculated as step frequency × (body height/g)$^{1/2}$, and this mean value was 1.57 ± 0.08 (range, 1.45–1.75). The step length was calculated as the quotient of the distance and the number of steps, and this mean value was 1.50 ± 0.08 m (range, 1.36–1.65). The step length index was calculated as step length/body height, and the mean value was 1.03 ± 0.04 (range, 0.93–1.08).

Statistical analysis

The data are presented as mean ± SD. The relationships between variables were examined using Pearson's product moment correlation coefficient. Statistical significance level was defined at $P < 0.05$. All statistical analyses were conducted using the IBM SPSS software (version 19.0; International Business Machines Corp, NY, USA).

Results

With regard to the relationships among sprint variables during the 50-m sprint test, sprint velocity was significantly correlated with step length (r = -0.664, P < 0.01), but not with the step frequency. Following normalization with body height, the sprint velocity index during the 50-m sprint test was significantly correlated with the step frequency index (r = -0.562, P < 0.05), but not the step length index.

With regard to the relationships between the CSA variables and sprint time during the 50-m sprint test, the absolute CSAs of most trunk and lower limb muscles, excluding the PF, were significantly correlated with the sprint time (r = −0.827 to −0.603, P < 0.05 for all). After normalization with the FFM to the two-third power, the relative CSAs of the PM, ADD, and QF were significantly correlated with the sprint time (**Figure 2**; r = −0.802, −0.643, and −0.639; $P \leq 0.010$, respectively)

The correlation coefficients between the CSA variables and indices of sprint variables during the 50-m sprint test are shown in **Table 2**. With regard to the relationships between the absolute CSA and sprint variables, the absolute CSAs of the LAW, PM, ADD, QF, and HAM were significantly correlated with sprint velocity index (r = 0.545 to 0.598, P < 0.05 for all). Only a trend against such significance was observed in the ES (r = 0.511, P = 0.051). In addition, the absolute CSAs of most trunk and lower limb muscles, excluding the ES, were significantly correlated with step frequency index (r = 0.580 to 0.811, P < 0.05 for all). In contrast, although only a trend against the significance relationship between the absolute CSA and step length index was observed in the ADD (r = −0.478, P = 0.072) and PF (r = −0.511, P = 0.051), there were no other significant correlations.

With regard to the relationships between the relative CSA and sprint variables, the relative CSAs of the PM, ADD, and QF were significantly correlated with sprint velocity (r = 0.694, 0.612, and 0.630; P < 0.05 respectively) and step frequency (r = 0.687, 0.740, and 0.590; P < 0.05, respectively) indices during the 50-m sprint test (**Figure 3**). In contrast, although only a trend against such significance was observed in the RA (r = 0.506, P = 0.054), there were no other significant correlations.

Discussion

The present study showed that larger CSAs of the trunk and lower limb muscles in 10- to 12-year-old boy sprinters are strongly correlated with higher sprint performance, as assessed by sprint time and variables during the 50-m sprint test. After the CSAs were normalized with FFM, we further found that the relative CSAs of PM, QF, and ADD demonstrated correlation with sprint velocity and step frequency, but not step length. Thus, the findings of the present study suggest that larger trunk and lower limb muscles, especially the hip flexors and knee extensors, may contribute to superior sprint performance in male preadolescent sprinters.

The relationships between trunk and limb muscularity and sprint performance in junior sprinters are poorly understood. In only one study, Hoshikwa et al. (20) examined the relationships between the CSAs of three muscles (i.e., the PM, QF, and HAM) and the mean velocity for a 100-m race in junior sprinters; however, the relationships between other muscles of the trunk and lower limbs and sprint performance in junior sprinters remains unclear. Thus, the present study examined the relationships between a total of 9 trunk and lower limb muscles and sprint performance in junior sprinters and identified significant relationships between the hip flexor and knee extensor muscles and sprint performance. With regard to the knee extensor muscles, previous studies have determined that the larger CSAs of the QF and ADD are related to higher sprint performance in adult sprinters (4,10,14,22); however, these relationships had not been determined in junior sprinters. With regard to the hip flexor muscle, previous studies have determined that the magnitude of the PM CSA is associated with sprint performance in sprinters (8,14,20). Of these previous studies, Hoshikawa et al. (20) demonstrated that a larger PM CSA was correlated with a higher personal best 100-m race time in junior sprinters aged 14 to 17 years. Thus, for the first time, we demonstrated the important roles of greater knee extensor muscles on sprint performance in junior sprinters. In addition, we identified a close relationship between hip flexor muscle size and sprint performance in preadolescent sprinters aged 10 to 12 years.

The sprint velocity is expressed as the product of step frequency and step length. The present findings showed that, after normalization with the body height, sprinting velocity index during the 50-m sprint test is correlated with step frequency index, but not with step length index. Moreover, we showed that the step frequency index, but not the step length index, is correlated with the CSA relative to FFM of the PM, ADD, and QF. This suggests that larger CSA of the hip flexor and knee extensor muscles may contribute to accelerated sprint velocity by enhancing the step frequency rather than step length. Step frequency can be increased by decreasing the contact and aerial times. Weyand et al. (39) determined that an increase in running velocity induces a shortened contact time, but not aerial time. Moreover, Morin et al. (28) reported that shorter contact time is closely related to higher maximal sprinting velocity during 100-m sprint. Thus, although previous observations were made in adult sprinters, the relationship between the greater relative CSA and higher step frequency index observed in the present study might be a reflection of shorter contact time during sprinting.

A large vertical ground reaction force (VGRF) during the stance phase is strongly related to maximal speed in sprinters, and increasing peak VGRF results in decreased contact time in sprinting (28,39). Increased hip flexion moment contributes to enhancing the VGRF during the late stance phase with eccentric contraction, while increased knee extension moment contributes to the early stance phase with eccentric contraction and the late stance phase with concentric contraction (6,9,33). Although hip flexor and knee extensor muscles have different actions during the stance phase while spiriting, both muscles play an important role in increasing peak VGRF in sprinting. Thus, in the present study, larger CSA of the hip flexor and knee extensor muscles in preadolescent sprinters could contribute to the production of a large VGRF during the stance phase while sprinting. On the basis of these results, we propose that greater hip flexor and knee extensor muscularity in junior sprinters may help achieve a higher sprint velocity by a higher step frequency and shorter contact time, which is enhanced by larger VGRF production.

The present findings showed that a greater CSA of the ADD may help achieve higher sprint performance by enhancing the knee extension moment while sprinting. However, as assessed using computer simulation, the contribution of the ADD is observed not only in knee extension but also in hip extension during human locomotion (5); however, the behavior of the ADD during sprinting remains unknown. In the present study, the CSA of the ADD included the adductor magnus and adductor brevis. Using computer simulation, Arnold et al. (5) demonstrated that the adductor magnus contributes to knee extension and hip extension during human locomotion, while the adductor brevis contributes to hip flexion. From our findings, we cannot clarify whether a larger ADD strongly contributed to enhancing the knee extension moment while sprinting; nevertheless, the adductor magnus in the ADD was largest (3), and therefore it is more likely to contribute to knee extension than hip extension.

The present study showed that larger CSA of the hip flexor and knee extensor muscles, such as the PM, ADD, and QF, are correlated with higher sprint performance in preadolescent sprinters, which corresponds with previous findings in adults (8,14,20,22,36). Several previous studies reported that the magnitude of other muscles, especially the HAM, may also play an important role for superior performance in adult sprinters (10,29). However, in the present study, although the absolute CSA of the HAM was correlated with sprint variables during the 50-m sprint test, we did not observe such correlations between the relative CSA of the HAM and sprint variables in preadolescent sprinters. Similarly, Hoshikawa et al. (20) reported that the relative CSA of the HAM in junior sprinters did not correlate to sprint performance. Previous studies demonstrated less development of the HAM relative to the QF in junior athletes (18,32). Hoshikawa et al. (18) reported that the percentage of CSA relative to the total thigh muscle compartment in the HAM was greater in senior soccer players than in junior soccer players, while that of the QF was greater in junior soccer players than in senior soccer players. These results suggest that, in junior athletes, the HAM may be underdeveloped compared to the QF. Thus, although we cannot completely explain the age-related discrepancies between the findings of our study and those of previous studies, the maturation of the HAM relative to the QF in junior athletes revealed by previous studies may somewhat explain the results of the present study.

Kumagai et al. (24) reported that, in adult sprinters, muscle thickness in the PF was larger in sprinters who have a faster personal best 100-m race time than 11 s than in sprinters who have a slower personal best 100-m race time than 11 s. In contrast, Stafilidis and Arampatzis (35) reported that no difference in the thickness of PF (assessed by the gastrocnemius medialis) has been identified between faster and slower adult sprinters based on their personal best 100-m race time. Moreover, others reported that the size of PF (assessed by the thickness or CSA) was not related to the sprint performance in adult sprinters (22,36). Thus, results of the relationship between the size of PF and sprint performance is inconsistent with previous findings. In the present study, although the absolute CSA of the PF was correlated with sprint variables during the 50-m sprint test, we could not obtain a significant correlation between the relative CSA of the PF and sprint performance in junior sprinters. With regard to the DF, to the best of our knowledge, a significant relationship between DF size and sprint performance has not yet been observed in either junior or adult sprinters. In the present study, although the absolute CSA of the DF was correlated with sprint variables during the 50-m sprint test, we could not obtain a significant correlation between the relative CSA of the DF and sprint performance in preadolescent sprinters. Taken together, the present findings suggest that the trunk and thigh muscles, rather than the lower leg muscles, may play an important role in sprint performance in junior athletes.

A limitation in the present study is that CSAs of the trunk and lower limb muscles were based on results of previous studies in the same anatomical locations (20,36). However, whether the locations for these CSA measurements would be appropriate to assess the size of each muscle is poorly understood. Moreover, the results of previous studies were derived in adults. Although CSA is strongly related to muscle strength, muscle volume (MV) is known to be more appropriate for assessing muscle strength than CSA (2,12). Additionally, the MV is associated with muscle force and contractile velocity, which are closely related to superior sprint performance. Thus, to clearly determine the relationship between muscle size and sprint performance, MV is a more appropriate parameter than the CSA; however, the present study did not calculate the muscle volume. Further studies are needed to examine the relationships between MVs of the trunk and lower limb and sprint performance in junior sprinters.

Another limitation of the present study was that we found that larger hip flexor and knee extensor muscles in preadolescent sprinters were correlated with sprint velocity depending on the step frequency, but not on the step length, during a 50-m sprint test. Moreover, we speculated that a higher step frequency may be derived from a shorter contact time, potentially by the larger moments from the hip flexor and knee extensor muscles. However, in addition to shortening the contact time, larger hip flexor and knee extensor forces might contribute to performing rapid leg movement during the swing phase (10,33), suggesting a reduction in aerial time. In the present study, we did not perform a detailed analysis of kinematic and kinetic data in sprinting. Thus, further studies are needed to examine the relationships between the size of the trunk and lower limb muscles and various sprint variables, including the contact time and aerial time.

In conclusion, the present study showed that larger CSAs of the trunk and lower limb muscles, especially the PM, ADD, and QF, are correlated with higher sprint performance in 10- to 12-year-old boy sprinters, and was dependent on enhancement of the step frequency rather than the step length. Thus, to our knowledge, the present findings are the first to suggest that greater muscularity of the hip flexors and knee extensors may help improve sprint performance in preadolescent sprinters. Although childhood participation in competitive sports has increased, there is poor scientific information regarding the enhancement of performance in junior athletes, especially preadolescent athletes or younger athletes than it. Taken together, the scientific information derived from the present study may be useful in understanding individual features that improve the outcomes of sprinters.

References

1. Abe T, Kumagai K, Brechue WF. Fascicle length of leg muscles is greater in sprinters than distance runners. *Med Sci Sports Exrec*. 2000; 32:1125-1129.

2. Akagi R, Takai Y, Ohta M, Kanehisa H, Kawakami Y, Fukunaga T. Muscle volume compared to cross-sectional area is more appropriate for evaluating muscle strength in young and elderly individuals. *Age Ageing*. 2009; 38:564-569.

3. Akima H, Ushiyama J, Kubo J, Fukuoka H, Kanehisa H, Fukunaga T. Effect of unloading on muscle volume with and without resistance training. *Acta Astronaut*. 2007; 60:728-736.

4. Alexander MJ. The relationship between muscle strength and sprint kinematics in elite sprinters. *Can J Sport Sci*. 1989; 14:148-157.

5. Arnold AS, Anderson FC, Pandy MG, Delp SL. Muscular contributions to hip and knee extension during the single limb stance phase of normal gait: a framework for investigating the causes of crouch gait. *J Biomech*. 2005; 38:2181-2189.

6. Belli A, Kyröläinen H, Komi PV. Moment and power of lower limb joints in running. *Int J Sports Med*. 2002; 23:136-141.

7. Bogduk N, Pearcy M, Hadfield G. Anatomy and biomechanics of psoas major. *Clin Biomech*. 1992; 7:109-119.

8. Copaver K, Hertogh C, Hue O. The effects of psoas major and lumbar lordosis on hip flexion and sprint performance. *Res Q Exerc Sport*. 2012; 83:160-167.

9. Dorn TW, Schache AG, Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. *J Exp Biol*. 2012; 215:1944-1956.

10. Dowson MN, Nevill ME, Lakomy HK, Nevill AM, Hazeldine RJ. Modelling the relationship between isokinetic muscle strength and sprint running performance. *J Sports Sci*. 1998; 16:257-265.

11. Ema R, Wakahara T, Yanaka T, Kanehisa H, Kawakami Y. Unique muscularity in cyclists' thigh and trunk: A cross-sectional and longitudinal study. *Scand J Med Sci Sports*. 2016; 26:782-793.

12. Fukunaga T. Miyatani M, Tachi M, Kouzaki M, Kawakami Y, Kanehisa H. Muscle volume is a major determinant of joint torque in humans. *Acta Physiol Scand*. 2001; 172:249-255.

13. Häkkinen K, Keskinen KL. Muscle cross-sectional area and voluntary force production characteristics in elite strength- and endurance-trained athletes and sprinters. *Eur J Appl Physiol Occup Physiol*. 1989; 59:215-220.

14. Handsfield GG, Knausl KR, Fiorentino NM, Meyer CH, Hart JM, Blemker SS. Adding muscle where you need it: non-uniform hypertrophy patterns in elite sprinters. *Scand J Med Sci Sports*. 2016; in press

15. Hobara H, Sano Y, Kobayashi Y, Heldoorn TA, Mochimaru M. Step frequency and step length of 200-m sprint in able-bodied and amputee sprinters. *Int J Sports Med*. 2016; 37:165-168.

16. Hof AL. Scaling gait data to body size. *Gait Posture*. 1996; 4:222-223.

17. Hoshikawa Y, Iida T, Ii N, Muramatsu M, Nakajima Y, Chumank K, Kanehisa H. Cross-sectional area of psoas major muscle and hip flexion strength in youth soccer players. *Eur J Appl Physiol*. 2012; 112:3487-3494.

18. Hoshikawa Y, Iida T, Muramatsu M, Nakajima Y, Fukunaga T, Kanehisa H. Differences in thigh muscularity and dynamic torque between junior and senior soccer players. *J Sports Sci*. 2009; 27:129-138.

19. Hoshikawa Y, Muramatsu M, Iida T, Ii N, Nakajima Y, Kanehisa H. Sex differences in the cross-sectional areas of psoas major and thigh muscles in high school track and field athletes and nonathletes. *J Physiol Anthropol*. 2011; 30:47-53.

20. Hoshikawa Y, Muramatsu M, Iida T, Uchiyama A, Nakajima Y, Kanehisa H, Fukunaga T. Influence of the psoas major and thigh muscularity on 100-m times in junior sprinters. *Med Sci Sports Exerc*. 2006; 38:2138-2143.

21. Kanehisa H, Ikegawa S, Fukunaga T. Comparison of muscle cross-sectional area and strength between untrained women and men. *Eur J Appl Physiol Occup Physiol*. 1994; 68:148-154.

22. Kubo K, Ikebukuro T, Yata H, Tomita M, Okada M. Morphological and mechanical properties of muscle and tendon in highly trained sprinters. *J Appl Biomech*. 2011; 27:336-344.

23. Kubo T, Hoshikawa Y, Muramatsu M, Iida T, Komori S, Shibukawa K, Kanehisa H. Contribution of trunk muscularity on sprint run. *Int J Sports Med*. 2011; 32:223-228.

24. Kumagai K, Abe T, Brechue WF, Ryushi T, Takano S, Mizuno M. Sprint performance is related to muscle fascicle length in male 100-m sprinters. *J Appl Physiol*. 2000; 88:811-816.

25. Kyle UG, Bosaeus I, De Lorenzo AD, et al. Bioelectrical impedance analysis-part II: utilization in clinical practice. *Clin Nutr*. 2004; 23:1430-1453.

26. Maughan RJ, Watson JS, Weir J. Relationships between muscle strength and muscle cross-sectional area in male sprinters and endurance runners. *Eur J Appl Physiol Occup Physiol*. 1983; 50:309-318.

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

28. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour JR. Mechanical determinants of 100-m sprint running performance. *Eur J Appl Physiol*. 2012; 112:3921-3930.

29. Morin JB, Gimenez P, Edouard P, et al. Sprint acceleration mechanics: The major role of hamstrings in horizontal force production. *Front Physiol*. 2015; 6:404.

30. Novacheck TF. The biomechanics of running. *Gait Posture*. 1998; 7:77-95.

31. O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN. Strong relationships exist between muscle volume, joint power and whole-body external mechanical power in adults and children. *Exp Physiol*. 2009; 94:731-738.

32. Quatman-Yates CC, Myer GD, Ford KR, Hewett TE. A longitudinal evaluation of maturational effects on lower extremity strength in female adolescent athletes. *Pediatr Phys Ther*. 2013; 25:271-276.

33. Schache AG, Blanch PD, Dorn TW, Brown NA, Rosemond D, Pandy MG. Effect of running speed on lower limb joint kinetics. *Med Sci Sports Exerc*. 2011; 43:1260-1271.

34. Schantz P, Randall-Fox E, Hutchison W, Tydén A, Astrand PO. Muscle fibre type distribution, muscle cross-sectional area and maximal voluntary strength in humans. *Acta Physiol Scand*. 1983; 117:219-226.

35. Stafilidis S, Arampatzis A. Muscle-tendon unit mechanical and morphological properties and sprint performance. *J Sports Sci*. 2007; 25:1035-1046.

36. Sugisaki N, Kanehisa H, Tauchi K, Okazaki S, Iso S, Okada J. The relationship between 30-m sprint running time and muscle cross-sectional areas of the psoas major and lower limb muscles in male college short and middle distance runners. *Int J Sport Health Sci*. 2011; 9:1-7.

37. Tompuri TT, Lakka TA, Hakulinen M, et al. Assessment of body composition by dual-energy X-ray absorptiometry, bioimpedance analysis and anthropometrics in children: the Physical Activity and Nutrition in Children study. *Clin Physiol Functi Imaging*. 2015; 35:21-33.

38. Vaeyens R, Lenoir M, Williams AM, Philippaerts RM. Talent identification and development programmes in sport: current models and future directions. *Sports Med*. 2008; 38:703-714.

39. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol*. 2000; 89:1991-1999.

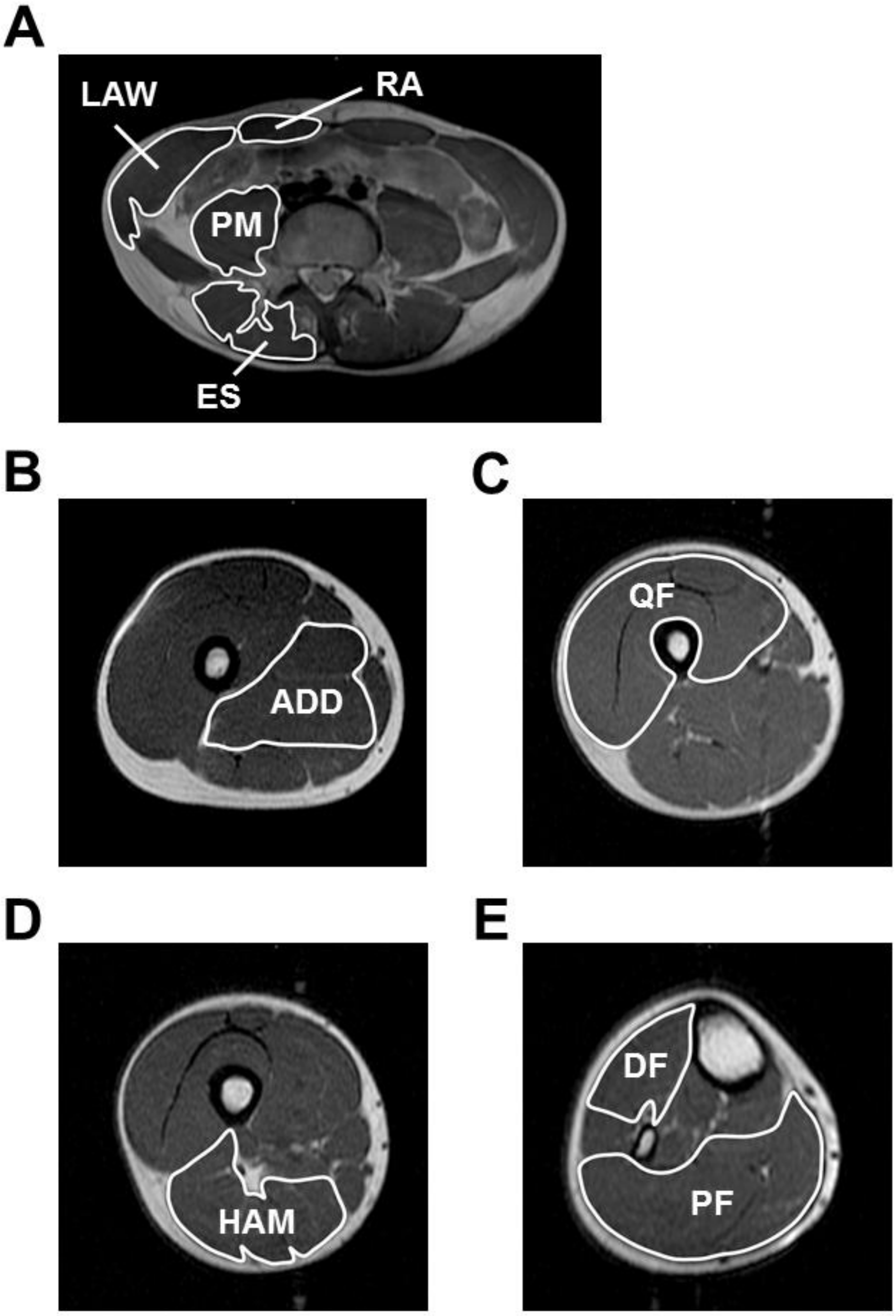

Figure 1. Representative magnetic resonance imaging scans used for measuring cross-sectional area (CSA) of the trunk and lower limb muscles in a preadolescent sprinter.

The CSA of the rectus abdominis (RA), lateral abdominal wall (LAW), elector spinae (ES), and psoas major (PM) were obtained at the mid-level of the L4–L5 (A). The CSA of the adductors (ADD) was obtained at the proximal 30% of the thigh length (B). The CSA of the quadriceps femoris (QF) was obtained at 50% of the thigh length (C). The CSA of the hamstrings (HAM) was obtained at 70% of the thigh length (D). The CSA of the dorsiflexors (DF) and plantar flexors (PF) were obtained at the proximal 30% of the lower leg length (E).

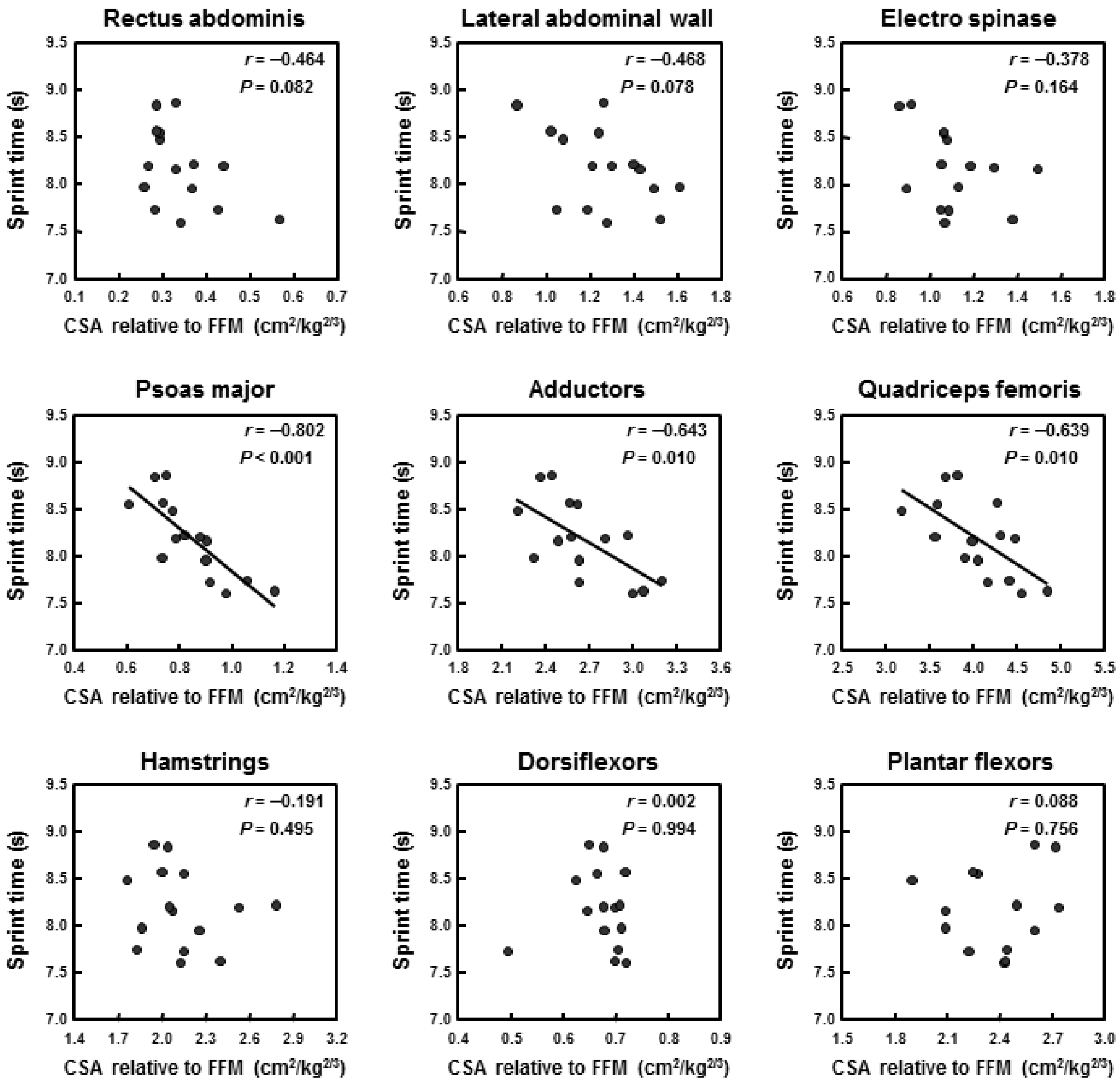

Figure 2. Relationships between relative CSA and sprint time during a 50-m sprint test.

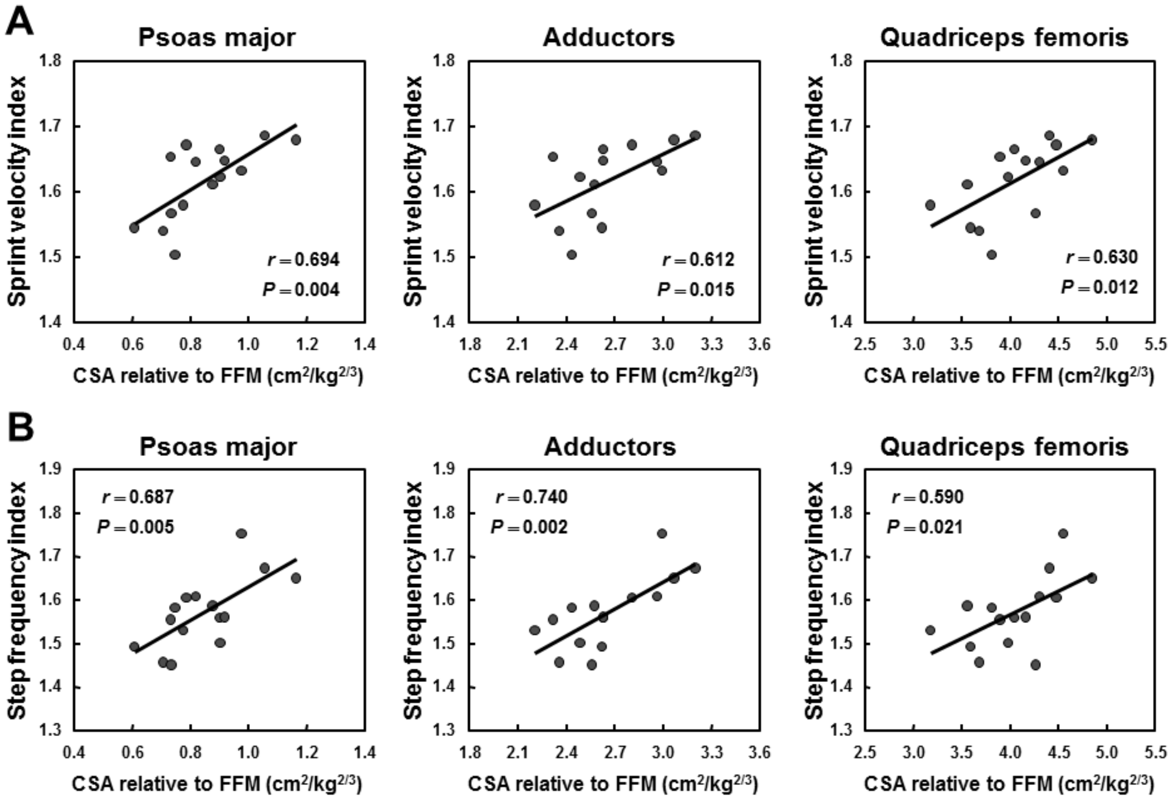

Figure 3. Relationships between relative CSA and indices of sprint velocity (A) and step frequency (B) during a 50-m sprint test.

Sprint velocity index was calculated as sprint velocity/(body height × g)$^{1/2}$. Step frequency index was calculated as step frequency × (body height /g)$^{1/2}$.

Table 1. Cross-sectional area (CSA) variables in the trunk and lower limb muscles

	Mean ± SD	Range
Absolute CSA (cm^2)		
Rectus abdominis	3.5 ± 1.2	2.4–6.9
Lateral abdominal wall	12.6 ± 2.8	7.7–18.4
Elector spinae	11.1 ± 2.5	7.7–16.7
Psoas major	8.6 ± 2.4	5.8–14.1
Adductors	26.7 ± 5.6	19.6–37.9
Quadriceps femoris	40.7 ± 2.8	28.2–58.9
Hamstrings	21.2 ± 3.7	15.6–29.1
Dorsiflexors	6.7 ± 1.0	5.3–9.1
Plantar flexors	24.3 ± 4.3	16.8–33.3
Relative CSA ($cm^2/kg^{2/3}$)		
Rectus abdominis	0.34 ± 0.08	0.26–0.57
Lateral abdominal wall	1.26 ± 0.21	0.86–1.61
Elector spinae	1.10 ± 0.17	0.86–1.49
Psoas major	0.84 ± 0.15	0.61–1.16
Adductors	2.65 ± 0.29	2.20–3.20
Quadriceps femoris	4.04 ± 0.44	3.17–4.84
Hamstrings	2.13 ± 0.27	1.76–2.78
Dorsiflexors	0.67 ± 0.06	0.49–0.72
Plantar flexors	2.44 ± 0.35	1.89–3.36

Values are presented as the Mean ± SD. The relative CSA was calculated as absolute value of CSA (cm^2)/free-fat mass ($kg^{2/3}$).

Table 2. Correlation coefficients between cross-sectional area variables and indices of sprint variables during the 50-m sprint test

	Sprint velocity index		Step frequency index		Step length index	
	r	*P* value	*r*	*P* value	*r*	*P* value
Absolute value						
RA	0.445	0.097	**0.617**	**0.014**	–0.350	0.201
LAW	**0.560**	**0.030**	**0.580**	**0.023**	–0.240	0.388
ES	0.511	0.051	0.461	0.084	–0.112	0.692
PM	**0.598**	**0.019**	**0.738**	**0.002**	–0.355	0.195
ADD	**0.563**	**0.029**	**0.811**	**<0.001**	–0.478	0.072
QF	**0.570**	**0.026**	**0.735**	**0.002**	–0.371	0.173
HAM	**0.545**	**0.036**	**0.635**	**0.011**	–0.303	0.272
DF	0.409	0.130	**0.718**	**0.003**	–0.471	0.076
PF	0.273	0.325	**0.638**	**0.010**	–0.511	0.051
Relative value						
RA	0.398	0.142	0.506	0.054	–0.295	0.286
LAW	0.465	0.081	0.293	0.289	0.018	0.948
ES	0.431	0.109	0.130	0.644	0.197	0.482
PM	**0.694**	**0.004**	**0.687**	**0.005**	–0.253	0.363
ADD	**0.612**	**0.015**	**0.740**	**0.002**	–0.383	0.158
QF	**0.630**	**0.012**	**0.590**	**0.021**	–0.178	0.526
HAM	0.367	0.178	0.227	0.415	0.019	0.945
DF	0.131	0.642	0.242	0.385	–0.169	0.548
PF	0.002	0.996	0.207	0.459	–0.260	0.349

RA, rectus abdominis; LAW, lateral abdominal wall; ES, elector spinae; PM, psoas major; ADD, adductors; QF, quadriceps femoris; HAM, hamstrings; DF, dorsiflexors; PF, plantar flexors.