Sprint performance is related to muscle fascicle length in male 100-m sprinters

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Sprint performance is related to muscle fascicle length in male 100-m sprinters. J. Appl. Physiol. 88: 811–816, 2000.—The purpose of this study was to investigate the relationship between muscle fascicle length and sprint running performance in 37 male 100-m sprinters. The sample was divided into two performance groups by the personal-best 100-m time: 10.00–10.90 s (S10; n = 22) and 11.00–11.70 s (S11; n = 15). Muscle thickness and fascicle pennation angle of the vastus lateralis and gastrocnemius medialis and lateralis muscles were measured by B-mode ultrasonography, and fascicle length was estimated. Standing height, body weight, and leg length were similar between groups. Muscle thickness was similar between groups for vastus lateralis and gastrocnemius medialis, but S10 had a significantly greater gastrocnemius lateralis muscle thickness. S10 also had a greater muscle thickness in the upper portion of the thigh, which, given similar limb lengths, demonstrates an altered “muscle shape.” Pennation angle was always less in S10 than in S11. In all muscles, S10 had significantly greater fascicle length than did S11, which significantly correlated with 100-m best performance (r values from −0.40 to −0.57). It is concluded that longer fascicle length is associated with greater sprinting performance. Pennation angle; shortening velocity; muscle shape

IT IS USUALLY AGREED THAT sprint running performance requires the ability to generate a high velocity of shortening in the locomotor muscles. Muscle shortening velocity is determined by biochemical (myosin ATPase activity) (7, 28) and architectural (fiber length; the number of sarcomeres in series) (9, 27, 30) characteristics. Most studies concerning the capacity for shortening velocity in leg muscles and sprint running performance have focused on biochemical properties. Shortening velocity of knee extensor muscles is significantly correlated with the percentage of fast-twitch fibers in the vastus lateralis (VL) muscles (32). Several studies have demonstrated that male and female sprinters have a high percentage of fast-twitch muscle fibers in the leg muscles (8, 12). Furthermore, maximum running speed and 100-m sprint running performance are related to the percentage of fast-twitch muscle fibers (23).

Although biochemical properties are important in determining maximal shortening velocity of muscle (7), muscle architectural characteristics have been shown to play an important role in modulating biochemical effects (9, 27, 30). Differences in maximal shortening velocity between muscles were determined, to a much greater extent, by differences in muscle fiber length rather than by biochemical differences (11, 27). However, little other scientific data exist regarding the relationship between fiber length and muscle shortening velocity.

Recently, we showed that elite sprinters, compared with elite distance and marathon runners and untrained controls, had longer fascicle lengths and lesser pennation angles (5). This suggested that differences in sprinting ability may be related to differences in fascicle length. From these data and from previous animal studies, we hypothesized that fascicle length plays an important role in determining sprint running performance in humans. Thus the purpose of the present study was to examine the relationship between architectural characteristics of leg muscles (fascicle length) and sprint running performance within a population of highly trained 100-m sprint specialists.

METHODS

Subjects. Thirty-seven male 100-m sprinters, having 6–15 yr (7.8 ± 1.9 yr) of professional experience, were recruited for the study. Informed consent was obtained from all the subjects, and the study was approved by the department’s ethical commission. Personal-best performance for 100-m sprint was recorded for each sprinter from recent published competition results. Best 100-m sprint times ranged between 10.00 and 11.70 s. For comparison by sprint running performance, the sample was divided into two groups according to the personal-best 100-m record: 10.00–10.90 s (S10; n = 22) and 11.00–11.70 s (S11; n = 15).

Measurement of fat-free mass. Fat-free mass was estimated from body density by using the subcutaneous fat measurements from ultrasound (described in Measurement of skeletal muscle distribution). Our laboratory (1) has reported previously that the SE of the estimate of body density using ultrasound equations is ~0.006 g/ml (~2.5% body fat) for

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men. Body fat percentage was calculated from the body density by using the equation of Brozek et al. (10). Fat-free mass was estimated as the difference between total body mass and fat mass.

Measurement of limb lengths. Limb lengths were measured by using anatomic landmarks; thigh length, the distance between the lateral condyle of the femur and greater trochanter; lower leg length, the distance between the lateral malleolus of the fibula and the lateral condyle of the tibia; upper arm length, the distance between the lateral epicondyle of the humerus and the acromial process of the scapula; and forearm length, the distance between the styloid process and the head of the radius.

Measurement of skeletal muscle distribution. Skeletal muscle architecture of specific muscles within a muscle group were measured in vivo as described previously (18). The estimated coefficient of variation of the image reconstruction have been described and thus would be an index of the muscle size (2). Muscle thickness is significantly correlated with muscle thickness of various muscles across the body. Muscle thickness represents the "depth" or thickness of a muscle measured between fat and bone of a particular muscle group. It is known that muscle thickness is significantly correlated with muscle anatomic cross-sectional area (r = 0.91, P < 0.001) and thus would be an index of the muscle size (2). Muscle thickness was measured by B-mode ultrasound (model SSD-500, Aloka, Tokyo, Japan) at 13 sites (anterior at 30, 50, and 70% thigh length) and posterior (at 50 and 70% thigh, anterior and posterior lower leg at 30%, lateral forearm at 30%, anterior and posterior upper arm at 60%, abdomen, subscapula, and chest) as described previously (1, 3). These measurements are independent of muscle group and are reported by anatomic site. Briefly, the measurements were carried out while the subjects stood with their elbows and knees extended and relaxed. A 5-MHz scanning head was placed perpendicular to the tissue interface. The scanning head was coated with water-soluble transmission gel to provide acoustic contact without depressing the dermal surface. The subcutaneous adipose tissue-muscle interface and the muscle-bone interface were identified from recordings of the ultrasonic image, and the distance from the adipose tissue-muscle interface to the muscle-bone interface was accepted as muscle thickness (Fig. 1A). Precision and linearity of the image reconstruction have been described and confirmed elsewhere (18). The estimated coefficient of variation of this method from test-retest was 0.8%.

Measurement of skeletal muscle architectural characteristics. Skeletal muscle architecture of specific muscles within a muscle group were measured in vivo as described previously (1, 2), by using the B-mode ultrasound apparatus. We studied three specific leg muscles: VL (midway between the lateral condyle of the femur and greater trochanter), gastrocnemius medialis (GM; 30% proximal between the lateral malleolus of the fibula and the lateral condyle of the tibia), and gastrocnemius lateralis (GL; at the same level as GM). Briefly, the ultrasound transducer was placed perpendicularly to the specific muscle to observe a cross-sectional image (Fig. 1A), and then the transducer was shifted to a position that is parallel to the specific muscle resulting in a longitudinal image (Fig. 1B). This is done by manipulating the position of the transducer while viewing the ultrasound image in real time. Again, by using recordings of the ultrasonic images, the distance between subcutaneous adipose tissue-muscle interface and intermuscular interface in the cross-sectional image was accepted as muscle thickness. In the present study we measured only the thickness of the superficial specific muscle (e.g., VL, GM, or GL) and thus use the term isolated muscle thickness. The angles between the echo of the deep aponeurosis of the muscle and interspaces among the fascicles of the muscles in the longitudinal image was measured as pennation angle (see Fig. 1B). From the isolated muscle thickness (MTH) and the pennation angle, the fascicle length across the deep and superficial aponeurosis was estimated from the following equation:

$$\text{Fascicle length} = \text{isolated MTH} \cdot \sin \alpha^{-1}$$

where $\alpha$ is the pennation angle of each muscle determined by ultrasound. Ultrasonic measurements differed from manual measurements of pennation angle in cadavers by only 0–1° (18). The estimated coefficient of variation of this fascicle length determination is 4.7%.

Statistical analysis. Results are expressed as means ± SD. A one-way ANOVA was used for comparison between the two performance groups with the priori level of statistical significance set at $P = 0.05$. Relationships between selected architectural variables and 100-m sprint performance time were examined by using Pearson-product moment correlations.

RESULTS

Subject characteristics. There were no significant differences between S10 and S11 in standing height (172 ± 4 vs. 173 ± 6 cm, respectively), body weight (66.3 ± 4.1 vs. 64.7 ± 6.4 kg, respectively), fat-free mass (61.6 ± 3.8 vs. 58.9 ± 5.1 kg, respectively), and thigh (39.2 ± 1.6 vs. 39.4 ± 2.0 cm, respectively) and lower leg (39.3 ± 1.6 vs. 39.9 ± 2.2 cm, respectively).

Fig. 1. Ultrasonographic images representing vastus lateralis (VL) and intermedius (VI) muscles. A: cross-sectional image. B: longitudinal image. White lines in cross-sectional image indicate echoes from deep aponeurosis (APN) and interface among fascicles. AT-M, subcutaneous adipose tissue-muscle; I-M, intermuscular; M-B, muscle-bone.
lengths. Percent body fat was significantly lower in S10 (6.8 ± 1.3%) than in S11 (8.6 ± 2.0%). On average, personal-best 100-m times of S10 and S11 were 10.58 ± 0.23 s (range 10.00–10.90 s) and 11.37 ± 0.22 s (range 11.00–11.70 s), respectively.

Skeletal muscle distribution. All data are summarized in Table 1. Muscle thickness was significantly greater in S10 than in S11 in the upper portion of the thigh (30% anterior and 50% posterior) and in the posterior lower leg. Muscle thickness of anterior upper arm and subscapula were also significantly greater in S10 than in S11. All other sites were comparable between groups.

Skeletal muscle architecture. Isolated muscle thickness of GL muscle was significantly greater in S10 than in S11 (Table 2). There were no group differences in isolated muscle thickness of the VL or GM muscles (Table 2). S10 had a significantly lower pennation angle than did S11 in all selected muscles (Table 2). Fascicle length, absolute and relative to limb length, was significantly greater in S10 than in S11 for all selected muscles (Table 2).

Muscle thickness, absolute and relative to limb length, of 30% anterior upper leg (r = −0.38 and r = −0.39, respectively, both P < 0.05), 50% posterior upper leg (r = −0.45, P < 0.01 and r = −0.41, P < 0.05), and posterior lower leg (r = −0.40, P < 0.05 and r = −0.45, P < 0.01) were negatively correlated with 100-m sprint time. Isolated muscle thickness, absolute and relative to limb length, was negatively correlated with 100-m sprint time in GL muscle thickness (r = −0.36, P < 0.05 and r = −0.42, P < 0.05, respectively), but not in VL (r = −0.17 and r = −0.19) or GM (r = −0.25 and r = −0.29) muscles. Fascicle length, relative to limb length, was positively correlated to isolated muscle thickness (relative to limb length) in VL (r = 0.44, P < 0.01), GM (r = 0.71, P < 0.01), and GL (r = 0.77, P < 0.01) muscles.

Pennation angle had significant correlation with 100-m sprint time in VL (r = 0.34, P < 0.05), GM (r = 0.37, P < 0.05) and GL (r = 0.46, P < 0.01). Fascicle length, relative to limb length, was negatively correlated to pennation angle in VL (r = −0.77, P < 0.01), GM (r = −0.67, P < 0.01) and GL (r = −0.66, P < 0.01) muscles.

There were significant negative correlations between absolute fascicle length and 100-m sprint time in the VL (r = −0.44, P < 0.01), GM (r = −0.40, P < 0.05), and GL (r = −0.54, P < 0.01) muscles. Fascicle length, relative to limb length, was also negatively, and significantly, correlated with 100-m sprint time in the VL, GM, and GL muscles (Fig. 2).

**DISCUSSION**

Muscle fibers are packed in bundles, fascicles, which extend from the proximal to distal tendons. In many cases, when investigators refer to muscle fiber length, they are actually referring to fascicle length (13, 16, 29). We have conducted cadaver dissections (unpublished observations) and confirmed that individual fibers run entire length of the fascicles in several muscles in lower limb of humans. However, there is new evidence that suggests that midfascicle connections and fiber tapering are more prevalent than previously believed (24, 33). Therefore, fascicle length and

<table>
<thead>
<tr>
<th>Variable</th>
<th>S10</th>
<th>Range</th>
<th>S11</th>
<th>Range</th>
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<tr>
<td>Isolated muscle thickness, cm</td>
<td>2.75 ± 0.30</td>
<td>2.3–3.3</td>
<td>2.67 ± 0.32</td>
<td>2.2–3.2</td>
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<td>Vastus lateralis</td>
<td>3.27 ± 0.37</td>
<td>1.9–3.1</td>
<td>2.25 ± 0.19</td>
<td>2.0–2.6</td>
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<td>Gastrocnemius medialis</td>
<td>1.93 ± 0.23</td>
<td>1.6–2.6</td>
<td>1.71 ± 0.20</td>
<td>1.3–2.0</td>
</tr>
<tr>
<td>Pennation angle, °</td>
<td></td>
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</tr>
<tr>
<td>Vastus lateralis</td>
<td>19.0 ± 3.2</td>
<td>12–26</td>
<td>21.1 ± 2.1</td>
<td>16–24</td>
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<tr>
<td>Gastrocnemius medialis</td>
<td>21.4 ± 2.9</td>
<td>16–30</td>
<td>23.5 ± 2.6</td>
<td>19–28</td>
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<tr>
<td>Gastrocnemius lateralis</td>
<td>14.0 ± 1.4</td>
<td>12–16</td>
<td>15.2 ± 2.1</td>
<td>12–19</td>
</tr>
<tr>
<td>Muscle fascicle length, cm/cm</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Vastus lateralis</td>
<td>8.63 ± 1.42</td>
<td>5.9–12.0</td>
<td>7.45 ± 1.04</td>
<td>5.8–9.8</td>
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<tr>
<td>Gastrocnemius medialis</td>
<td>6.62 ± 1.35</td>
<td>4.6–10.4</td>
<td>5.70 ± 0.65</td>
<td>4.5–6.8</td>
</tr>
<tr>
<td>Gastrocnemius lateralis</td>
<td>8.07 ± 1.49</td>
<td>6.2–12.8</td>
<td>6.55 ± 0.68</td>
<td>5.5–7.9</td>
</tr>
</tbody>
</table>

*P < 0.05; †P < 0.01, S10 vs. S11.
muscle fiber length may not be synonymous. However, because the preponderance of muscle fibers are connected serially to "create" a functional unit, the fascicle, it is the length of this functional unit that may be the more preferable parameter when considering whole muscle shortening velocity and function (19). Our purpose was not to estimate human muscle fiber length, but rather it was to explore the relationship between fascicle length and sprint performance.

Comparison with other studies. Muscle fiber shortening velocity is determined by muscle fiber type composition (myosin ATPase activity) (7, 28) and muscle fiber length (the number of sarcomeres in series) (9, 27, 30). It is reasonable to predict that these two characteristics would determine sprint running performance. Previously (23), relationships between fiber type composition (percentage of fast-twitch fibers) and sprint running performance (maximum running speed and 100-m sprint performance) have been reported. However, in that study, range of the fiber composition was from 57 to 83% for a 100-m sprint time of ~10.5 s. Although this would be expected, at the same time it indicates that factors other than fiber composition and twitch characteristics may be associated with sprint performance and supports the idea that muscle fascicle length may be an important determinant of sprint running performance. Our previous study (5) reported that the fascicle length (relative to limb length) of the selected locomotor muscles (VL, GM, GL) is significantly greater in elite sprinters than that observed in elite long-distance runners or untrained control subjects. In the present study, we directly demonstrate that sprint performance is related to fascicle length; there were significant correlations between 100-m personal-best performance and absolute and relative fascicle length in selected leg muscles within male 100-m sprint specialists. These findings demonstrate that the differences in muscle fascicle length coincide with differences in sprint performance.

Although there were significant relationships between muscle fascicle length and sprint performance, the correlation coefficients were moderate (r values between −0.40 and −0.57). Furthermore, the muscles investigated in this study are pennate such that muscle shortening velocity would be a function of the cosine of the pennation angle as seen with force-generating characteristics (19). To demonstrate the theoretical impact of greater fascicle length and muscle thickness and lesser pennation angle to sprint performance, we have developed a schematic illustration of a pennate GL muscle (Fig. 3) by using data from Table 2. As the fascicles (fibers) shorten, they pivot about their origin, increasing their pennation angle and pulling the two tendons toward each other, although the distance between the two aponeuroses is kept constant (26).

Fig. 2. Relationships between personal-best 100-m performance and muscle fascicle length of VL (top), gastrocnemius medialis (GM; middle), and gastrocnemius lateralis (GL; bottom) muscles.

![Graph showing relationships between personal-best 100-m performance and muscle fascicle length of VL, GM, and GL muscles.](image)

**Fig. 3.** Schematic illustration of GL muscle representing tendon excursion with fascicle shortening. Mean values of muscle thickness (MTH) and fascicle length (FASL) from male sprinters with personal-best 100-m times of 10.00–10.90 s (S10) and 11.00–11.70 s (S11) are used. Thick solid lines, APN. D, point at which a fascicle attached onto APN; FASL, fascicle length after a 10% shortening. With a 10% shortening of fascicle length [0.81 cm (̅= 8.07–7.26 cm) and 0.66 cm (̅= 6.55–5.89 cm) for S10 and S11, respectively] within 250 ms in each muscle, excursion of attached tendon will be 0.83 cm (D1–D2) for S10 and 0.68 cm (D3–D4) for S11. Finally, muscle shortening velocity would be 3.31 cm/s for S10 and 2.72 cm/s for S11.
model, we will assume an average muscle shortening of 10% of fascicle length in a pennate muscle and a 250-ms duration of muscular shortening activity (6). For S11 the fascicle shortening would be 0.66 cm. This will result in tendon excursion of 0.68 cm, and shortening velocity would be 2.72 cm/s. However, at fascicle length of 8.07 cm for S10, the tendon excursion would be 0.83 cm and shortening velocity would be 3.31 cm/s. Therefore, S10 would shorten ~22% faster than would S11. Thus it seems apparent that greater fascicle length in a pennate muscle would confer greater shortening velocity of the muscle.

The longer fascicle length would also result in greater muscle mass (19). However, greater muscle mass due to the longer fascicle length would not induce an increase in physiological cross-sectional area. There are two possibilities for longer fascicle length leading to faster sprinting. First, the longer fascicle length would result in greater maximal velocity of shortening as discussed above. As a result, the power would be greater and would contribute to sprint performance. Second, the development of force would be influenced by the muscle’s abilities to generate adequate shortening velocities necessary for the dynamics of the movement (30). According to Hill’s equation (14), the velocity of shortening increases with decreasing force. Greater maximal shortening velocity due to longer fascicle length would allow greater force output at an identical shortening velocity. The greater force would result in greater power, which would contribute to sprint performance.

Previous studies (16, 19, 34) have reported that differences in maximum force and maximum shortening velocity between GM and GL muscles would be principally determined by their architectural properties. GL muscle has the longest fascicle length in the triceps surae group. Given that fiber type composition is similar between GL and GM muscles (17), the longer fascicle length in GL distinguishes them for greater shortening velocity potential. On the other hand, GM muscle was characterized by shorter fascicle length and larger pennation angle than other triceps surae muscles, which means GM can pack more fibers within a given volume; this distinguishes them for force generation. Our present data confirm these architectural observations and now extend them to partially explain differences in sprint performance. Our data show that GL muscle thickness was greater in the faster 100-m sprint (S10) group, whereas GM muscle thickness was similar between groups. Greater GL muscle thickness and smaller pennation angle, in S10 group, is due to longer fascicle length and perhaps larger fiber cross-sectional area (12).

Another interesting and consistent finding in our data is an apparent difference in “muscle shape,” which like fascicle length appears to associate with sprint performance. Our data show that S10 had significantly greater muscle thickness in upper portion of the thigh (at 30 and 50% thigh length for anterior and posterior thigh, respectively) but not in the lower portion (at 50 and 70% thigh length for anterior thigh and at 70% thigh length for posterior thigh) compared with S11.

Given that thigh length was similar between groups, the shape of the quadriceps and hamstrings muscles is different in S10. Our laboratory (2) has shown previously that among black football players an advantage for sprint performance, faster 40-yard dash times compared with white football players, appeared to be related to a greater deposition of muscle in the upper portion of the quadriceps muscle group (greater muscle thickness), whereas in the lower portion muscle thickness was similar between blacks and whites. In a comparison of sprinters with long-distance runners and untrained controls (5) a similar observation was made; sprinters had a greater muscle thickness in the upper portion of the quadriceps muscle group when limb length was similar. Our present data confirm these observations. Even within a population of highly trained sprinters, the best sprinters had a greater muscle thickness in the upper thigh (in the present study, both quadriceps and hamstrings) compared with other trained sprinters who were <1 s slower in performing the 100-m sprint. Furthermore, muscle thickness, absolute and relative to limb length, of upper anterior (30%) and upper posterior (50%) thigh was positively correlated with 100-m sprint time. Thus it would seem that muscle shape is an important variable in determining sprint performance; however, more work is needed to clarify this phenomenon.

Origin of architectural differences. The remaining questioning regarding these data is the origin of the architectural differences among sprinters. It is quite possible that greater fascicle length and altered muscle shape are genetically conferred, which predisposes individuals to sprint performance. However, a second possibility is that fascicle lengthening and muscle shape are specific adaptations to high-intensity, sprint training and/or high-intensity resistance training used by sprinters. The possibility of muscle fascicle lengthening in humans as a result of muscle enlargement and/or chronic and acute stretch is still only speculative, although there is evidence of fiber lengthening in animal models (15, 22, 31). Recently, our laboratory (20) reported that fascicle length is significantly greater in cross-section of Japanese sumo wrestlers compared with untrained Japanese male controls. The muscle enlargement in the sumo wrestlers was associated with greater fascicle length (significant positive correlation between muscle fascicle length and isolated muscle thickness). In the present study, we also found that fascicle length is positively correlated to isolated muscle thickness for all selected leg muscles in the 100-m sprint specialists. The relationship between fascicle length and increased muscle thickness lends intriguing support to the possibility that fascicle lengthening may occur in humans as an adaptation to training (21), but more data are needed. Regarding muscle shape, Narici et al. (26) reported nonuniform changes in cross-sectional area along the length of the quadriceps muscle after high-intensity resistance training. They suggested that each of the muscles of the quadriceps group may have varying degrees of hypertrophic responsiveness. However, differences could be simply related to
specific motor unit recruitment patterns involved in the specific type of training. Regardless, it appears that differences or changes in muscle shape, especially in the quadriceps and hamstring muscle groups, are associated with sprint performance. The possible genetic or training-specific origin of these architectural differences will require further study.

In conclusion, it appears that greater fascicle length and altered muscle shape, whether a genetic predisposition or a specific consequence of training, are associated with superior sprint performance.

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REFERENCES