Relationship Between Sprint Performance and Muscle Fascicle Length in Female Sprinters

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Abstract The purpose of this study was to investigate the relationship between sprint performance and architectural characteristics of leg muscles in 26 female 100-m sprinters. Pennation angle and muscle thickness of the vastus lateralis (VL) and gastrocnemius medialis (GM) and lateralis (GL) muscles were measured by B-mode ultrasonography, and fascicle length was estimated. Sprinters had a significantly lower VL pennation angle, but GM and GL pennation angle was similar between sprinters and female control subjects (N=22). There was no significant correlation between pennation angle and 100-m personal best performance. Sprinters had significantly greater absolute fascicle length in VL and GL than controls, which significantly correlated to 100-m best-record (r=–0.51 and r=–0.44, respectively). Relative fascicle length (VL and GL) were also significantly greater in sprinters than controls. However, there were no significant correlation between relative fascicle length and 100-m best-record (r=–0.36 and r=–0.29, respectively). No relationship was found between the sprint performance and fat-free mass (r=–0.26) or body mass index (r=–0.03). However, there was a significant correlation between percent (%) body fat and 100-m best-record (r=0.62, p<0.01). Adjusting the confounding effect of % fat, significant correlations were seen between relative fascicle length and 100-m best-record (VL; r=–0.39 and GL; r=–0.40). Absolute and relative fascicle length were similar in elite female sprinters compared with previous reported values for elite male sprinters (Kumagai et al., 2000). It was concluded that longer fascicle length is associated with greater sprinting performance in sprinters, but there is no gender differences in fascicle length for elite sprinters. J Physiol Anthropol 20 (2): 141-147, 2001 http://www.jstage.jst.go.jp/en/

Keywords: fascicle length, shortening velocity, ultrasonography

Introduction

A substantial gender difference in sprint performance is a common observation. In normal adolescents and college students, mean performances on sprint running tests, such as the 50-m dash, are typically 10–20% greater for men than women (Miyashita and Kanehisa, 1979; Meshizuka et al., 1989). World or junior-world records for males in the 100-m through 400-m events for males exceed those for females by 7–12% (Wilmore and Costill, 1999). Unfortunately, it is not clear whether this phenomenon is due to biological differences or ultimately related to differences in levels of physical training for speed improvement.

Muscle fiber shortening velocity in the locomotor muscles is a reasonable parameter for the determination of sprint running performance. Muscle shortening velocity is determined by biochemical (Barany, 1967; Schluter and Fitts, 1994) (myosin ATPase activity) and architectural (Bodine et al., 1982; Sacks and Roy, 1982; Spector et al., 1980) (fiber length; the number of sarcomeres in series) characteristics. Most studies concerning the capacity for shortening velocity in leg muscles and sprint running performance have focused on biochemical properties. Contraction velocity of knee extensor muscles is significantly correlated with the percentage of fast-twitch fibers in the vastus lateralis muscles (Thorstensson et al., 1976). Maximum running speed and 100-m sprint running time are related to the percentage of fast-twitch fibers in the vastus lateralis muscles (Mero et al., 1981). Furthermore, several studies have demonstrated that male and female sprinters have a
high percentage of fast-twitch muscle fibers in their leg muscles (Bergh et al., 1978; Costill et al., 1976).

Biochemical properties are important in determining maximal shortening velocity of muscle (Barany, 1967; Schluter and Fitts, 1994). However, muscle architectural characteristics have been shown to play an important role in modulating biochemical effects (Bodine et al., 1982; Sacks and Roy, 1982; Spector et al., 1980). Differences in maximal shortening velocity between muscles were more closely associated with differences in muscle fiber length rather than biochemical differences (Burkholder et al., 1994; Sacks and Roy, 1982). Recently, we have shown that elite male sprinters, when compared to elite male distance runners and untrained controls, had longer fascicle lengths and smaller pennation angles (Abe et al., 2000). A significantly negative correlation was observed between 100-m sprint running time and fascicle length of leg muscle in highly-trained male sprinters (Kumagai et al., 2000). However, information on the muscle architectural characteristics of elite female sprinters have not been investigated. Thus, the purpose of the present study was: 1) to examine the relationship between architectural characteristics of leg muscles and sprint running performance in highly-trained female 100-m sprinters, and 2) to test whether there are gender differences in muscle fascicle length (compared with previous reported values for elite male sprinters) that may explain gender differences in sprint performance.

Methods

Subjects

Twenty-six female 100-m sprinters (SPR), with 6–17 yrs (9.1 ± 2.8 yrs) of professional experience, and 22 control students (CON) 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. Control students had not participated in any recreational sports for at least a year prior to testing.

Measurement of percent body fat

Percentage body fat (% fat) was estimated from body density (BD) using the subcutaneous fat measurements from ultrasound (described Measurement of skeletal muscle distribution). We have reported previously that the standard error of the estimate (SEE) of BD using ultrasound equations is ~0.006 g/ml (~2.5% body fat) for female (Abe et al., 1994). Body fat percentage was calculated from the BD using the equation of Brozek et al. (1963). Fat-free mass (FFM) was derived by subtracting fat mass from total body mass.

Measurement of skeletal muscle distribution

Skeletal muscle distribution was determined by measurement of muscle layer thickness across the body. As described previously (Abe et al., 1994, 1998), muscle thickness was measured across the muscle group by B-mode ultrasound (SSD-500, Aloka, Japan) at 13 sites (anterior [at 30, 50, and 70% thigh length, starting at the greater trochanter] and posterior [at 50 and 70% thigh length] thigh, anterior and posterior lower leg [at 30% proximal of the lower leg length], lateral forearm [at 30% proximal of the forearm], anterior and posterior upper arm [at 60% distal of the upper arm length], abdomen, subscapula and chest). These measurements are independent of muscle group and are reported by anatomical 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. Precision and linearity of the image reconstruction have been described and confirmed elsewhere (Kawakami et al., 1993). The estimated coefficient of variation (CV) of this method from test-retest was 0.8%. The same investigator (TA) made all of the ultrasound measurements.

Measurement of skeletal muscle architectural characteristics

Skeletal muscle architecture of specific muscles within a muscle group, termed isolated, was determined by placing the ultrasound transducer over the specific muscle. Isolated muscle thickness and fascicle pennation angle of the three specific leg muscles; vastus lateralis (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) were measured in
vivo, as described previously (Abe et al., 1998, 2000), using the B-mode ultrasound apparatus. Briefly, the ultrasound transducer was placed perpendicular to isolated muscle thickness and parallel to pennation angle for each muscle. This is done by placing the transducer over the specific muscle. For the determination of pennation angle, the position of the transducer is manipulated while viewing the ultrasonic image in real time. Again, using the ultrasonic images, the distance between subcutaneous adipose tissue-muscle interface and inter-muscular interface was accepted as muscle thickness, here termed isolated muscle thickness. The angles between the echo of the deep aponeurosis of the muscle and interspaces among the fascicles of the muscles was measured as pennation angle. From the muscle and inter-muscular interface was accepted as muscle thickness, here termed isolated muscle thickness. The angles between the echo of the deep aponeurosis of the muscle and interspaces among the fascicles of the muscles was measured as pennation angle. From the isolated muscle thickness (MTH) and the pennation angle, the length of fascicle (lf) across the deep and superficial aponeurosis was estimated from the following equation:

\[ l_f = \text{isolated MTH} \times \sin \alpha^{-1} \]

where \( \alpha \) is the pennation angle of each muscle, as determined by ultrasound. Ultrasonic measurements differed from manual measurements of pennation angle in cadavers by only 0-1 degree (Kawakami et al., 1993; Narici et al., 1996). The estimated CV of this \( l_f \) determination is 4.7%.

**Statistical analysis**

Results are expressed as mean \( \pm \) standard deviations (SD). A one-way ANOVA was used for comparison between sprinters and controls. Relationships between selected architectural variables and 100-m sprint performance time were examined using Pearson-product correlations. Partial correlations between fascicle length in the selected leg muscles and 100-m sprint time was calculated to eliminate the effect of body fat percentage. In each statistical analysis the level of significance was set at \( P<0.05 \).

**Results**

**Subject characteristics**

The mean age was similar between SPR (21.5 \( \pm \) 2.7 yr) and CON (20.5 \( \pm \) 2.0 yr). Standing height [SPR; 163 \( \pm \) 6 and CON; 158 \( \pm \) 4 cm, respectively], body weight [54.9 \( \pm \) 4.9 and 49.9 \( \pm \) 4.5 kg], percentage body fat [16.7 \( \pm \) 1.8 and 22.7 \( \pm \) 3.1%], fat-free mass [45.8 \( \pm \) 3.9 and 38.5 \( \pm \) 2.9 kg], and thigh [38.7 \( \pm \) 2.2 and 36.2 \( \pm \) 1.4 cm] lengths were significant differences \((p<0.01)\) between groups. On average, personal best 100-m times of SPR was 12.21 \( \pm \) 0.70 second (range 11.04–13.42).

No significant correlation was observed between 100-m best-record and fat-free mass \((r=0.26)\) or body mass index \((r=-0.03)\). However, there was a significant correlation between percentage body fat and 100-m best-record \((r=0.62, p<0.01)\).

**Skeletal muscle distribution**

Muscle thickness (both absolute and relative to limb length) of upper and lower limb muscles were significantly greater in SPR than in CON except the anterior lower leg. Muscle thickness of abdomen and subscapula were also significantly greater in SPR than in CON (Table 1). Absolute and relative (to limb length) muscle thickness of GM and GL muscles were significantly higher in SPR than CON (Table 2). VL absolute muscle thickness was

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**Table 1 Absolute and relative muscle thickness distributions in female 100-m sprinters (SPR) and control subjects (CON)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Muscle thickness (cm)</th>
<th>Relative muscle thickness</th>
<th>Relative to standing height (cm/m)</th>
<th>Relative to limb length (cm/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPR (N=26)</td>
<td>CON (N=22)</td>
<td>SPR (N=26)</td>
<td>CON (N=22)</td>
</tr>
<tr>
<td>Forearm lateral</td>
<td>1.85 ( \pm ) 0.22(^\dagger)</td>
<td>1.62 ( \pm ) 0.20</td>
<td>0.82 ( \pm ) 0.08(^\dagger)</td>
<td>0.74 ( \pm ) 0.09</td>
</tr>
<tr>
<td>Upper arm anterior</td>
<td>2.45 ( \pm ) 0.29(^\dagger)</td>
<td>1.97 ( \pm ) 0.20</td>
<td>0.81 ( \pm ) 0.09(^\dagger)</td>
<td>0.68 ( \pm ) 0.06</td>
</tr>
<tr>
<td>posterior</td>
<td>2.63 ( \pm ) 0.39(^\dagger)</td>
<td>1.97 ( \pm ) 0.32</td>
<td>0.87 ( \pm ) 0.14(^\dagger)</td>
<td>0.68 ( \pm ) 0.12</td>
</tr>
<tr>
<td>Thigh anterior 30%</td>
<td>5.71 ( \pm ) 0.46(^\dagger)</td>
<td>4.70 ( \pm ) 0.43</td>
<td>1.48 ( \pm ) 0.11(^\dagger)</td>
<td>1.33 ( \pm ) 0.12</td>
</tr>
<tr>
<td>50%</td>
<td>5.01 ( \pm ) 0.50(^\dagger)</td>
<td>4.10 ( \pm ) 0.44</td>
<td>1.29 ( \pm ) 0.13(^\dagger)</td>
<td>1.14 ( \pm ) 0.13</td>
</tr>
<tr>
<td>70%</td>
<td>3.82 ( \pm ) 0.43(^\dagger)</td>
<td>3.20 ( \pm ) 0.38</td>
<td>0.99 ( \pm ) 0.12(^\dagger)</td>
<td>0.89 ( \pm ) 0.11</td>
</tr>
<tr>
<td>posterior 50%</td>
<td>6.25 ( \pm ) 0.57(^\dagger)</td>
<td>5.07 ( \pm ) 0.42</td>
<td>1.62 ( \pm ) 0.15(^\dagger)</td>
<td>1.40 ( \pm ) 0.12</td>
</tr>
<tr>
<td>70%</td>
<td>5.80 ( \pm ) 0.54(^\dagger)</td>
<td>4.97 ( \pm ) 0.33</td>
<td>1.50 ( \pm ) 0.16(^\dagger)</td>
<td>1.38 ( \pm ) 0.09</td>
</tr>
<tr>
<td>Lower leg anterior</td>
<td>2.72 ( \pm ) 0.22</td>
<td>2.68 ( \pm ) 0.26</td>
<td>0.72 ( \pm ) 0.08(^\dagger)</td>
<td>0.71 ( \pm ) 0.17</td>
</tr>
<tr>
<td>posterior</td>
<td>6.66 ( \pm ) 0.37(^\dagger)</td>
<td>5.97 ( \pm ) 0.44</td>
<td>1.77 ( \pm ) 0.16(^\dagger)</td>
<td>1.66 ( \pm ) 0.14</td>
</tr>
</tbody>
</table>

\(^\dagger\)p<0.05, \(^\ddagger\)p<0.01; SPR vs. CON.
significantly greater in SPR than CON (Table 2), however, there was no group differences in relative (to limb length) muscle thickness of the VL muscle (SPR; 0.65 ± 0.10 and CON; 0.60 ± 0.09, respectively).

Skeletal muscle architecture

Pennation angle was similar between SPR and CON in the GM and GL. SPR had a significantly lower pennation angle than CON in the VL muscle. Fascicle length, absolute or relative to limb length, was significantly greater in SPR than CON for VL and GL muscles (Table 2). Relative GM fascicle length was similar between groups, however, absolute fascicle length was greater in SPR than in CON. Absolute and relative fascicle length of the selected leg muscles were similar between female sprinters (present study) and previous reported (Kumagai et al., 2000) values for elite male sprinters (Table 3).

There were significant negative correlations between absolute fascicle length and 100-m sprint time in the VL (r=-0.51, P<0.01) and GL (r=-0.44, P<0.05) muscles, but not in GM (r=-0.22) (Fig. 1). Fascicle length, relative to limb length, tended to be correlated with 100-m sprint time in the VL (r=-0.36, P=0.07) and LG (r=-0.29) muscles. Adjusting the confounding effect of percent body fat in relation to 100-m sprint performance, a significant correlation was seen between relative fascicle length and 100-m sprint time (VL; r=-0.39, GL; r=-0.40, both P<0.05).

Pennation angle tended to be correlated with 100-m sprint time in VL (r=0.36, P=0.07) and LG (r=0.34, P=0.10). Fascicle length, relative to limb length, was negatively correlated to pennation angle in VL (r=-0.43, P<0.05) and GL (r=-0.40, P<0.05) for SPR and in VL (r=-0.67, P<0.01) for CON.

Discussion

Comparison of fascicle length between female and male sprinters

It is known that muscle fascicle length plays a significant role in determining the maximum shortening velocity of muscle (Bodine et al., 1982; Sacks and Roy, 1982) and sprint running performance (Kumagai et al., 2000). However, it is unknown whether there are gender differences in muscle fascicle length that may explain gender differences in sprint performance. Recently, our laboratory reported that there were no differences in fascicle length seen between female and male strength trained athletes (Abe et al., 1998). The finding in the present study demonstrated that the fascicle lengths (absolute and relative to limb length) in female 100-m sprinters are similar to previous reported values for elite male sprinters (Kumagai et al., 2000) (Table 3). Also, the relative fascicle length of leg muscles is similar between female and male control subjects (Table 3). Therefore, the differences in sprint running time between female and male sprinters do not appear to be a result of gender differences in fascicle length of locomotor muscles.

<table>
<thead>
<tr>
<th>Subject (N)</th>
<th>Vastus lateralis (cm) Mean Range</th>
<th>Gastrocnemius medialis (cm) Mean Range</th>
<th>Gastrocnemius lateralis (cm) Mean Range</th>
<th>Authors (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>female (N=26)</td>
<td>0.22 0.12–0.29</td>
<td>0.16 0.12–0.20</td>
<td>0.20 0.16–0.25</td>
<td>Present study</td>
</tr>
<tr>
<td>male (N=23)</td>
<td>0.22 0.15–0.33</td>
<td>0.17 0.12–0.24</td>
<td>0.20 0.16–0.32</td>
<td>Abe et al. (2000)</td>
</tr>
<tr>
<td>male (N=37)</td>
<td>0.21 0.15–0.32</td>
<td>0.16 0.12–0.24</td>
<td>0.19 0.13–0.32</td>
<td>Kumagai et al. (2000)</td>
</tr>
<tr>
<td>Untrained</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>female (N=22)</td>
<td>0.17 0.12–0.24</td>
<td>0.15 0.12–0.20</td>
<td>0.17 0.12–0.22</td>
<td>Present study</td>
</tr>
<tr>
<td>male (N=30)</td>
<td>0.18 0.12–0.23</td>
<td>0.14 0.10–0.19</td>
<td>0.18 0.12–0.27</td>
<td>Kearns et al. (2000)</td>
</tr>
<tr>
<td>male (N=24)</td>
<td>0.18 0.13–0.23</td>
<td>0.14 0.12–0.19</td>
<td>0.18 0.12–0.26</td>
<td>Abe et al. (2000)</td>
</tr>
<tr>
<td>male (N=6)</td>
<td>0.13 0.12–0.24</td>
<td>0.14 0.12–0.19</td>
<td>0.14 0.12–0.26</td>
<td>Kawakami et al. (1998)</td>
</tr>
</tbody>
</table>
Relationship between sprint performance and muscle architecture

It is reasonable to predict that fiber type composition (myosin ATPase activity) (Barany, 1967; Schluter and Fitts, 1994) and muscle fiber length (the number of sarcomeres in series) (Bodine et al., 1982; Sacks and Roy, 1982; Spector et al., 1980) would determine sprint running performance. Previously, relationships between fiber type composition (percentage of fast-twitch fibers in the VL) and sprint running performance (maximum running speed and 100-m sprint time) have been reported (Mero et al., 1981). However, in that study, range of the percent fiber composition ranged from 57% to 83% for a 100-m sprint time of ~10.5 sec. Although this would be expected, it indicates that factors other than fiber composition and twitch characteristics may be associated with sprint performance. It suggests the idea that muscle fascicle length may be an important determinant of sprint running performance. Our previous study reported that the fascicle length of the selected locomotor muscles is significantly greater in elite sprinters than that observed in elite distance runners (Abe et al., 2000). Furthermore, a significantly negative correlation was observed between 100-m personal best performance and fascicle length of locomotor muscles in highly-trained male 100-m sprinters (Kumagai et al., 2000). In the present study, we also demonstrated that sprint running performance is related to fascicle length in selected leg muscles within female 100-m sprint specialists. These findings demonstrate that...
the differences in muscle fascicle length for both gender coincide with differences in sprint performance.

To demonstrate the theoretical impact of greater fascicle length to sprint performance, we have developed a schematic illustration of a muscle-joint torque generating system and sarcomeres force-velocity relationship (Fig. 2). For a given tendon excursion at a muscle fascicle shortening 1 cm per second, fascicle (B) would need to shorten it single sarcomere 1.0 µm while fascicle (A) could share the shortening distance between its sarcomeres and each sarcomere would need to shorten only 0.5 µm. The physiological implication is that fascicle (A) could shorten at a slower velocity (0.5 µm/sec) than fascicle (B) (1.0 µm/sec), and be at a stronger portion of the sarcomeres force-velocity curve (Kawakami, 2000, personal communication). Therefore, greater fascicle length would confer greater force generating capacity during identical tendon excursion. As a result, the power would be greater and would potentially enhance sprint performance.

Previous studies (Huijing, 1985; Kawakami et al., 1998; Wickiewicz et al., 1983) 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 has the longest fascicle length in the triceps surae group. Given that fiber type composition is similar between GL and GM muscles (Johnson et al., 1973), the longer fascicle length in GL distinguishes them for greater potential shortening velocity. On the other hand, GM was characterized by shorter fascicle length and larger pennation angle than other triceps surae muscles, this means GM can pack more fibers within a given volume; distinguishing them for force generation. In the present study, GL muscle thickness and fascicle length were greater in SPR. Although GM fascicle length was similar between groups, GM muscle thickness was also greater in SPR. GL fascicle length was correlated with 100-m sprint time. However, there were no significant correlations between absolute and relative GM fascicle lengths and 100-m sprint time. Thus it seems that GL fascicle length and muscle thickness are more important variables in determining sprint performance. However, future work is needed to clarify this phenomenon.

Origin of architectural differences

An important question regarding these data is the origin of the architectural differences among sprinters. It is quite possible that greater fascicle length is genetically conferred, which predisposes individuals to sprint performance. Recently, however, a monozygous twin study (Abe, 2000) showed that there was a non-significant within-twin-pair resemblance for muscle fascicle length in the GM muscle, but that for the GL was significant.

A second possibility is that fascicle lengthening is a specific adaptations to high-intensity, sprint training and/or high intensity resistance training used by sprinters. The possibility of human muscle fascicle lengthening 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 (Holly et al., 1980; Lynn et al., 1998; Tarbary et al., 1972). Recently, we (Kearns et al., 2000) reported that fascicle length is significantly greater in a cross-section of Japanese sumo wrestlers compared to 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 female sprinters. 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 (Kearns et al., 1998, 2000), but more data are needed.

In conclusion, it appears that greater fascicle length, whether a genetic predisposition or a specific consequence of training, is associated with superior sprint running performance in both genders, but there is no gender differences in fascicle length for elite sprinters.

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