The Muscle Morphology of Elite Female Sprint Running

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ABSTRACT

MILLER, R., T. G. BALSHAW, G. J. MASSEY, S. MAEO, M. B. LANZA, B. HAUG, M. JOHNSTON, S. J. ALLEN, and J. P. FOLLAND. The Muscle Morphology of Elite Female Sprint Running. Med. Sci. Sports Exerc., Vol. 54, No. 12, pp. 2138–2148, 2022. Introduction: A paucity of research exists examining the importance of muscle morphological and functional characteristics for elite female sprint performance. Purpose: This study aimed to compare lower body muscle volumes and vertical jumping power between elite and subelite female sprinters and assess the relationships of these characteristics with sprint race and acceleration performance. Methods: Five elite (100 m seasons best [SBE100], 11.16 ± 0.06 s) and 17 subelite (SBE100, 11.84 ± 0.42 s) female sprinters underwent: 3T magnetic resonance imaging to determine the volume of 23 individual leg muscles/compartments and five functional muscle groups; countermovement jump and 30 m acceleration tests. Results: Total absolute lower body muscle volume was higher in elite versus subelite sprinters (+15%). Elite females exhibited greater muscle volume of the hip flexors (absolute, +28%; relative [to body mass], +19%), hip extenders (absolute, +22%; relative, +14%), knee extensors (absolute, +21%), demonstrating pronounced anatomically specific muscularity, with relative hip flexor volume alone explaining 48% of sprint performance variability. The relative volume of five individual muscles (sartorius, gluteus maximus, adductor magnus, vastus lateralis, iliopsoas) were both distinct between groups (elite > subelite) and related to SBE100 (r = 0.553–0.639), with the combination of the sartorius (41%) and the adductor magnus (17%) explaining 58% of the variance in SBE100. Elite female sprinters demonstrated greater absolute countermovement jump power versus subelite, and absolute and relative power were related to both SBE100 (r = −0.520 to −0.741) and acceleration performance (r = 0.569 to 0.808). Conclusions: This investigation illustrates the distinctive, anatomically specific muscle volume distribution that facilitates elite sprint running in females, and emphasizes the importance of hip flexor and extensor relative muscle volume. Key Words: FEMALE, SPRINTING, MUSCLE VOLUME, JUMP POWER.

The ability to run at high speeds is a highly sought athletic trait that is exemplified by competitive sprint racing while also being a fundamental aspect of success in many field and team sports. Elite sprint running is a multifaceted athletic event, with various anatomical, environmental, equipment, biomechanical, physiological and psycho-physiological factors influencing performance (1). However, neuromuscular power (the rate of doing mechanical work; [2]), in particular of the lower body, is considered to play a major role in sprint running success (1,3,4). Current scientific knowledge of sprint running has predominantly focused on male performance, although females have a distinctly different sprint performance (100 m World Record: female, 10.49 s vs male, 9.58 s), and fundamentally different sprint running biomechanics, including maximum velocity stride parameters (e.g., stride length and frequency: 2.5–2.8 m and ~4.5 Hz [males] vs 2.1–2.3 m and ~4.9 Hz [females] [5]) compared with males. Furthermore, between-sex differences in a range of anatomical (e.g., stature [6], body composition [7] and limb lengths [8]) and physiological characteristics (e.g., neuromuscular power [7] and fiber type composition [9]), that are thought to influence sprint
performance have also been documented. Although there is a developing body of research examining the physical characteristics underpinning male sprint performance, there is almost no information on the characteristics of elite female sprinters, reflecting a general paucity of research on female athletes (10). Given the extensive differences between males and females the physical qualities important specifically for female sprint running needs to be investigated.

Neuromuscular power is largely determined by muscle volume (11), and thus, it has been widely suggested that high muscle volume is particularly important for sprint running performance (6). In females, however, there is very limited data considering sprint performance and muscle volume. Among female physical education students, total lower body lean mass (analyzed using dual X-ray absorptiometry) has been found to be related to 300-m sprint times ($r = -0.53, P < 0.01$; [12]), but the volume of specific muscles and muscle groups in elite and subelite female sprinters remains unknown. In contrast, in males a number of studies have used magnetic resonance imaging (MRI), the “gold standard” method of measuring muscle volume (13), to examine the importance of specific/regional muscle volumes for sprint performance. For example, our recent comparison of 23 individual muscles/compartments between subelite and elite male sprinters revealed pronounced anatomically specific muscularity was required for fast sprinting, with the hip extensor muscle group (+32%) and three specific muscles (tensor fasciae latae [TFL] +57%, sartorius +47%, gluteus maximus +45%) substantially larger in elite male sprinters. Furthermore, gluteus maximus muscle volume alone explained 33% to 44% of the variance in season’s best race performance among male sprinters (3). However, females have ~1/3 less skeletal muscle mass (14) and a different distribution to their skeletal muscle mass (e.g., disproportionately smaller knee flexors than knee extensors [15]) than males, as well as the extensive biomechanical and physiological differences to males noted above. Therefore, it cannot be assumed that female sprint running performance relies on the same muscle morphology determinants as males. For example, as elite female sprinters may have a higher stride rate than males (5) there could be an increased reliance on hip flexor power, and thus muscle volume, to rapidly recover the leg during swing phase and therefore achieve high stride frequencies (16,17). However, the specific morphological factors that discriminate elite from subelite female sprinters, and/or are related to female sprint performance, have not been investigated. Thus, a comprehensive analysis of lower body muscle volumes and their importance for sprint performance in elite and subelite female sprinters is required.

Current research investigating the relationship of MRI measures of muscle volume and sprint performance has focused on overall race performance (e.g., season’s best [SB] race time). This may limit our collective understanding of how muscle morphology is related to the different phases of a sprint race and whether specific muscle volumes may be related to acceleration or maximum speed running ability. To date only one study (18) has collected a specific measure of the first/acceleration phase of the sprint race (i.e., 30 m sprint time) alongside their measures of muscle volume, observing that a larger volume of the adductor muscle group was associated with faster 30 m sprint time in males. Thus, the combination of both SB and a measure of acceleration performance may help reveal if certain muscles are more important for the acceleration phase of the sprint race.

Similar to muscle morphology, whereas several studies have addressed the relationship between power measurements and sprint performance in males, a paucity of research exists in females. Nonetheless, in female games players (soccer and lacrosse) countermovement jump (CMJ) peak power or jump height have been found to be associated with sprint performance (i.e., greater height/power, faster sprint time; $r = -0.434$ to $-0.750, P < 0.05$; [19–21]). One study in female high school sprinters observed relationships between CMJ height and 30, 100, and 300 m sprint times ($r = -0.55$ to $-0.64, P < 0.05$; [22]); however, because of the slow sprint performance standard of this cohort, the relevance of these findings to elite female sprinters remains unknown.

Therefore, the aims of this study were to compare the lower body muscle volumes and vertical jump power of elite versus subelite female sprint athletes; and assess the relationship between these characteristics (muscle volumes and power) with sprint race and acceleration performance in the entire cohort. It was hypothesized that the hip flexor and extensor muscles would be larger in elite than subelite sprinters and related to sprint/acceleration performance, both in absolute and relative to body mass terms. In addition, it was proposed that elite sprinters would be more powerful relative to body mass during jumping, and that lower body power would be related to sprint performance.

METHODS

Participants and sprint performance. Five elite sprinters (age, 25.4 ± 4.0 yr; body mass, 67.7 ± 6.0 kg; height, 1.68 ± 0.05 m) and 17 subelite sprinters (age, 24.2 ± 4.1 yr; body mass, 62.7 ± 6.3 kg; height, 1.68 ± 0.06 m) volunteered to participate and gave informed consent to take part in this investigation. All participants were asymptomatic for leg or back injury, with no minor injury in the previous 4 wk and no major injury in the previous 6 months. Elite sprinters were required to have a season’s best 100 m time of less than 11.35 s (the British Athletics 100 m selection standard for the European Outdoor Championships 2018; [23]). Subelite sprinters were required to have a season’s best time of 11.35 to 12.90 s for 100 m or equivalent (for 60 m/200 m based on World Athletics scoring points [IAAF points]), and to have undergone at least one athletic season of high-intensity sprint-specific training. Sprint performance times were taken from the national governing body database (www.thepowerof10.info) of electronically timed 60 m, 100 m, and 200 m race times with wind readings (≤2.0 m·s$^{-1}$) during the corresponding calendar year in which data collection took place for seasons best time; and throughout the athletes competitive career.
to that point for personal best time. For one individual within the elite group, although they continued to train at the same high-intensity and with no significant personal injury or illness issues, it was not possible to record a season’s best race time because of the COVID-19 global pandemic, and as such the 100-m season’s best sprint time from the previous athletics season was used, which occurred 13 months before data collection. All sprint performances were converted into IAAF points, and the maximum points for each athlete in any of the sprint distances (60, 100, 200 m) was taken as their performance measure, and subsequently converted into 100 m seasons best equivalent (SBE100), or personal best equivalent (PBE100). It should be noted that SBE100 and PBE100 were actual 100 m performances in all of the elite sprinters (SBE100, 11.16 ± 0.06 s; range, 11.10–11.24 s; PBE100, 11.14 ± 0.04 s; range, 11.10–11.19 s), and for 11 participants in the subelite group (SBE100, 11.84 ± 0.42 s; range, 11.44–12.88 s; PBE100, 11.69 ± 0.30 s; range, 11.39–12.51 s), whereas for six subelite sprinters, SBE100 was derived from either 60 m or 200 m season’s best times. Ethical approval was granted by the Loughborough University Ethics Approvals (Human Participants) Subcommittee.

Study overview. A cross-sectional study was conducted where participants were required to attend two measurement sessions: 1) vertical jump and acceleration performance assessment and 2) assessment of muscle morphology (MRI). For each individual, all measurement sessions took place within 2 wk and at least 2 d apart, and were scheduled following a rest day or light training day. One individual from the elite group did not complete the acceleration performance assessment. Participants were given the instruction to arrive at all sessions in a relaxed state (i.e., not following moderate or high intensity activity or active travel) having followed normal daily activity and dietary behaviors. Before commencement of the MRI scans, participants sat quietly for 15 min after arrival. Due to limitations in scheduling and practicalities of data collection with an elite athletic population, it was not possible to control for measurement time of day.

Body composition. Body mass was measured using calibrated ADAM C-150 scales (ADAM equipment, Oxford, CT); and stature was measured using a standing stadiometer (Holtain Ltd., Crymnych, UK). The average of two measurements of skinfold thickness were taken at eight sites (bicep, tricep, subscapular, iliac crest, supraspinale, abdominal, thigh, and calf), using Harpenden skinfold calipers (British Indicators, Ltd, Wolverhampton, UK). All measurements were taken by the same investigator in accordance with the International Society for the Advancement of Kinanthropometry guidelines. From the sum of four skinfolds (bicep, tricep, subscapular and iliac crest), body density was calculated using formula for females age 16 to 19 yr or 20 to 29 yr (depending on each individuals age category) outlined previously (24), and percentage body fat estimated using the Siri (25) equation. Fat-free mass was subsequently derived from the percentage of body fat and body mass values.

Vertical jump performance. Following completion of their habitual individualized warm-up, each participant performed three maximal effort CMJ with 45-s rest between jumps, on a portable Kistler force plate (Type 9602A; Kistler Instruments Corp; Winterthur; Switzerland), interfaced with a personal computer using a 16-bit analog-to-digital converter (Type 5233A; Kistler Instruments Corp; Winterthur; Switzerland) with a vertical force range of 20 kN and sampling at 1000 Hz. Participants were instructed to stand still on the force plate in an upright posture and keep their hands on their hips throughout the jump (26). Sampling was initiated when they provided an indication they were ready to begin (27). After a 3-s pause to collect the force because of body mass, each participant performed a CMJ for maximal height, with the depth of the countermovement self-selected by the participant.

During off-line analysis, the vertical component of the ground reaction force (vGRF)—time history was exported to a custom-built Excel spreadsheet for subsequent analysis. Previously described methodologies (27) were used to obtain: body mass (calculated from body weight obtained from the average of the first 2 s of quiet standing vGRF data), time-point of CMJ initiation (defined as the first time-point of the vGRF recording to deviate above or below body mass by more than 1.75 times the peak residual found in the 2-s body weight averaging period) and take-off (defined as the first intersection of vGRF and the offset force of the unloaded platform determined by finding the 0.4-s time window during the flight phase with the smallest standard deviation). Acceleration of the center of mass (CoM) was calculated by subtracting body mass from the vGRF data and dividing by body mass, vertical velocity of the CoM was then obtained by time integration of the acceleration signal, and vertical displacement of the CoM was obtained by time integration of the vertical velocity signal (28). The following variables were derived: 1) Absolute peak power (defined as the peak instantaneous power calculated by multiplying vGRF by the vertical velocity of the CoM); 2) Relative peak power (defined as absolute peak power divided by body mass in kg); and 3) jump height (defined as the difference between vertical displacement of the CoM during stance and peak vertical displacement of the CoM) using previously reported methods (28,29). The best of three trials (according to absolute peak power) were taken for each participant.

Acceleration performance. Following CMJ assessment, participants were given time to complete their habitual acceleration-specific warm-up (e.g., stride-outs and runs). Following this, each participant completed a minimum of three separate self-initiated 30 m sprint acceleration trials with the instruction to run as fast as possible from the start line to a finish line 32 m (to ensure participants sprinted maximally for at least 30 m) along an indoor track, beginning from starting blocks and wearing sprinting spikes. Participants were given full, self-selected recovery between efforts. A laser distance measurement (LDM) device (LDM-300C; Jenoptik; Germany; 100 Hz) was used to quantify running speed and distances over the 30-m acceleration trial. The LDM was positioned on a tripod.
at a height of 1 m, 5 m behind the start line. The datum/start line position (i.e., 0 m) was determined using the side of a static box positioned on the start line before each testing session. The device was aimed at the lower part of each participant back for the duration of the trial; initiated manually as the participant rose in the starting blocks, and manually stopped after they had completed 30 m. Raw data files were then imported into a custom-written Matlab (The Mathworks Inc., Natick, MA) script to filter and analyze the data. The script applied a 51-point moving average filter followed by an 11-point moving average filter, and subsequently calculated instantaneous speed throughout the trial. The trial with the highest instantaneous speed at 30 m was taken for each individual.

**Muscle volume with magnetic resonance imaging.**

T1-weighted axial and coronal plane magnetic resonance (MR) images of the abdomen, the thigh and shank were obtained with a 3T scanner (Discovery MR750w, GE Healthcare, Chicago, IL) with a receiver eight-channel whole-body coil. Axial (time of repetition 600 ms, time of echo 8 ms, field of view 450 × 450 mm, image matrix 320 × 320, pixel size 1.4 × 1.4 mm, slice thickness 5 mm, interslice gap 5 mm) and coronal (time of repetition 600 ms, time of echo 8 ms, field of view 450 × 450 mm, pixel size 1.4 × 1.4 mm, slice thickness 5 mm, interslice gap 0 mm) images were obtained from the twelfth thoracic vertebra to the calcaneus capturing both legs in five overlapping blocks for axial images, and three scanning blocks were spliced together to form the coronal plane images. Participants were scanned while in the supine position with arms folded across the chest, with hip and knee joints extended and the ankle joint at −90°. Synchronization of coronal and axial plane scans permitted the objective alignment of crossover between the scanning blocks during analysis, and oil filled capsules were secured to the right leg of each participant in equal segments to confirm the accuracy of block crossover identification.

Six individual investigators carried out analysis of the MR images, with each investigator analyzing the same muscles/compartments for the entire cohort, blinded to participant identity. For muscles that were 200 mm or greater in length every other MR image (i.e., 20 mm between the center of the measured images) were manually segmented, starting from the most proximal image in which that muscle compartment first appeared, to assess cross-sectional area (CSA) and subsequently derive volumes of 23 lower limb muscles/compartments using a public domain DICOM software (Horos, version 2.2.0, www.thehorosproject.org). For muscles shorter than 200 mm, every MR image (i.e., 10 mm between the center of the measured images) was segmented. Fully analyzed images for each participant (i.e., all 23 muscles/compartments) were then checked and quality assured for accuracy by a single investigator (RM), paying particular attention to errors and overlaps between adjacent muscle cross-segments. The analyzed muscles/compartments were: iliopsoas (psosas major and iliacus combined); sartorius; TFL; adductor magnus; gracilis; gastrocnemius; vastus medius; gluteus minimus; rectus femoris; vastus intermedius, medialis and intermedialis; semimembranosus; semitendinosus; biceps femoris long and short heads; popliteus; lateral and medial gastrocnemius; soleus; and the anterior, lateral and deep posterior compartments of the shank. The shank compartments were the combined volume of the following muscles: tibialis anterior, extensor digitorum longus and extensor hallucis longus (anterior); peroneus longus and brevis (lateral); plantaris, tibialis posterior, flexor digitorum longus, flexor hallucis longus (deep posterior). The volume of five functional muscle groups was calculated as the sum of the following muscles; hip extensors (gluteus maximus, adductor magnus, biceps femoris long head, semimembranosus, and semitendinosus); hip flexors (iliopsoas, rectus femoris, sartorius, TFL); knee extensors (rectus femoris, vastus intermedius, medialis and lateralis); knee flexors (gracilis, biceps femoris long and short head, semimembranosus, semitendinosus, sartorius, popliteus and medial, and lateral gastrocnemius); and plantarflexors (medial and lateral gastrocnemius and soleus).

The volume of each muscle ($V_m$) was calculated using previously outlined methods (30):

$$V_m = \sum_{i=1}^{n} \frac{h}{2} (A_{m_i} + A_{m_{i+1}})$$

where $Am$ represents the muscle cross sectional area calculated from each image, $r$ is the image number, $n$ is the total number of images, and $h$ is the distance between images. In addition to absolute muscle volume ($cm^3$), muscle volume was also expressed relative to body mass ($cm^3·kg^{-1}$).

**Statistical analysis.** Muscle volume measurements from both legs were averaged for each participant to provide unilaterial criterion values. Data are presented as mean ± standard deviation (SD). The Shapiro–Wilk test was used to assess the normality of distribution, and revealed that >90% of the variables were normally distributed; therefore parametric statistical tests were used to provide a consistent approach. An independent samples Student’s t test was used to assess differences between groups for sprint race performance (SBE100 and PBE100), vertical jump performance (power [absolute, and relative to body mass]) and jump height), acceleration performance (instantaneous velocity at 30 m), muscle volume (absolute, and relative to body mass), and anthropometry. Statistical significance was set at $P < 0.05$. Cohen’s $d$ effect sizes ($d$) were used to assess the magnitude of any effect and interpreted as follows: trivial, <0.2; small, 0.2 to 0.49; medium, 0.50 to 0.79; and large, >0.8 (31). Pearson’s correlation was used to assess the bivariate relationships between performance measures (sprint race performance and acceleration performance [i.e., instantaneous velocity at 30 m]) and measures of muscle volume for the combined cohort of female sprinters (i.e., elite and subelite). Correlation coefficients were categorized (32,33) as: “weak” ($r \leq 0.40$), “moderate” ($r = 0.40–0.60$), “strong” ($r = 0.60–0.80$), or “very strong” ($r = 0.8–1.0$). Correlation $P$ values were corrected for multiple tests using the Benjamini and Hochberg (34) method with a false discovery rate of 5% and the significance level defined as adjusted $P < 0.05$. If one or more variables were significantly correlated with SBE100 they were subsequently included in a stepwise model.
multiple linear regression to calculate the variance explained by the best combination of predictor variables in each category (i.e., absolute or relative muscle volume). All statistical procedures were performed with IBM SPSS Statistics Version 25 (IBM Corp., New York, NY).

**RESULTS**

**Body composition.** No differences were observed between elite and subelite groups in age, height, or body mass (\(P = 0.134–0.978\); Table 1). Fat free mass was 9% greater in elite versus subelite sprinters (\(P = 0.049\), \(d = 1.07\)).

**Comparison of absolute muscle volumes.** Total unilateral volume for all the measured muscles was greater in elite versus subelite sprinters (+15%; \(P = 0.031\), \(d = 1.18\)), and for three functional muscle groups (hip flexors +28%; hip extensors +22%; knee extensors +21%; all \(P \leq 0.030\), \(d = 1.19–2.29\); Table 2), but not the knee flexors or plantarflexors. When comparing absolute volumes of individual muscles/compartments, eight out of 23 muscles were larger in elite sprinters than subelite (all \(P \leq 0.018\), \(d = 1.21–2.52\); Fig. 1); sartorius (+45%), TFL (+42%), gluteus maximus (+30%), rectus femoris (+29%), vastus lateralis (+27%), adductor magnus (+25%), biceps femoris short head (+24%), and iliotibial band (+20%).

**Comparison of relative muscle volumes.** When considering relative muscle volume, total relative volume of all the measured muscles was not different in elite versus subelite sprinters, but relative muscle volume was greater in two functional muscle groups (hip flexors +18%; hip extensors +14%; both \(P \leq 0.006\), \(d = 2.04\) and 1.55, respectively). Six of 23 individual muscles/compartments had greater relative volume in elite versus subelite sprinters (sartorius +35%; TFL +29%; gluteus maximus +21%; rectus femoris +21%; vastus

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**TABLE 1.** Sprint race, acceleration and vertical jump performance, training history and anthropometric characteristics of elite female sprinters (\(n = 5\)), subelite female sprinters (\(n = 5\))

| Subelite Female Sprinters | Elite Female Sprinters | Mean ± SD | Mean ± SD |
|---------------------------|------------------------|-----------|-----------|
| **Sprint race and acceleration performance, and training history** | | | |
| SBE100 (s) | 11.84 ± 0.42 | 11.16 ± 0.06* |
| PBE100 (s) | 11.69 ± 0.30 | 11.14 ± 0.04* |
| Velocity at 30 m (m·s\(^{-1}\)) | 8.83 ± 0.32 | 9.05 ± 0.28 |
| Sprint training history (yr) | 7.1 ± 4.0 | 8.2 ± 5.0 |
| Resistance training history (yr) | 5.6 ± 4.3 | 6.8 ± 2.8 |
| **Vertical jump performance** | | | |
| Peak power (W) | 3814 ± 550 | 4458 ± 624** |
| Relative peak power (W·kg\(^{-1}\)) | 60.0 ± 5.0 | 65.0 ± 6.5 |
| Jump height (m) | 0.48 ± 0.04 | 0.49 ± 0.06 |
| **Anthropometrics** | | | |
| Age (yr) | 24.2 ± 4.1 | 25.4 ± 4.0 |
| Height (m) | 1.68 ± 0.06 | 1.68 ± 0.05 |
| Body mass (kg) | 62.7 ± 6.3 | 67.7 ± 6.0 |
| Body mass index (kg·m\(^{-2}\)) | 22.2 ± 1.5 | 24.00 ± 2.9 |
| Sum of 8 Skinfolds (mm) | 69.3 ± 16.4 | 61.0 ± 9.7 |
| Body fat percentage (%) | 20.0 ± 3.1 | 18.5 ± 4.1 |
| Fat-free mass (kg) | 50.0 ± 4.6 | 55.1 ± 5.2** |

Significantly different to subelite: \(* P \leq 0.01\) and \(** P \leq 0.05\). One individual from the elite group did not complete the acceleration performance assessment, and thus velocity at 30 m represents a sample size of \(n = 4\). Data are presented as mean ± SD. Results are expressed as mean ± SD.

**TABLE 2.** Absolute and relative muscle volume of all muscles, five functional muscle groups and 23 individual muscles/compartments of elite female sprinters (\(n = 5\)), subelite female sprinters (\(n = 17\)).

| Muscle Group/Muscle | No. Slices | Absolute Muscle Volume (cm\(^3\)) | Relative Muscle Volume (cm\(^3\)·kg\(^{-1}\)) |
|---------------------|-----------|----------------------------------|----------------------------------|
| **All muscles** | 6665 ± 899 | 7665 ± 585* | 106.17 ± 7.80 |
| Hip flexors | 826 ± 105 | 1059 ± 87** | 13.19 ± 1.30 |
| Hip extensors | 2172 ± 346 | 2660 ± 209** | 34.55 ± 3.49 |
| Knee flexors | 1446 ± 203 | 1562 ± 79 | 23.05 ± 2.12 |
| Knee extensors | 1810 ± 328 | 2184 ± 253* | 28.80 ± 3.63 |
| Plantarflexors | 821 ± 160 | 756 ± 56 | 13.09 ± 2.08 |
| Iliopsoas | 369 ± 50 | 443 ± 49** | 5.91 ± 0.71 |
| Sartorius | 27 ± 12 | 185 ± 37** | 2.03 ± 0.37 |
| Tensor fasciae latae | 57 ± 12 | 81 ± 24** | 0.92 ± 0.21 |
| Adductor magnus | 585 ± 99 | 732 ± 100** | 9.30 ± 1.02 |
| Gracilis | 101 ± 24 | 113 ± 9 | 1.62 ± 0.35 |
| Gluteus maximus | 1481 ± 160 | 1161 ± 128** | 14.17 ± 1.83 |
| Gluteus medius | 309 ± 51 | 339 ± 53 | 4.94 ± 0.72 |
| Gluteus minimus | 159 ± 32 | 148 ± 38 | 2.54 ± 0.40 |
| Rectus femoris | 272 ± 45 | 350 ± 39** | 4.33 ± 0.56 |
| Vastus lateralis | 619 ± 122 | 788 ± 113* | 8.84 ± 1.41 |
| Vastus intermedius | 21 ± 110 | 607 ± 74 | 8.59 ± 1.34 |
| Vastus medialis | 357 ± 79 | 440 ± 62 | 6.03 ± 0.91 |
| Semimembranosus | 251 ± 40 | 270 ± 65 | 4.00 ± 0.51 |
| Semitendinosus | 242 ± 43 | 287 ± 51 | 3.84 ± 0.44 |
| Biceps femoris long head | 204 ± 42 | 210 ± 26 | 3.25 ± 0.55 |
| Biceps femoris short head | 101 ± 21* | 101 ± 17* | 1.90 ± 0.21 |
| Popliteus | 15 ± 4 | 19 ± 3 | 0.25 ± 0.05 |
| Lateral gastrocnemius | 164 ± 32 | 172 ± 27 | 2.62 ± 0.46 |
| Medial gastrocnemius | 276 ± 71 | 225 ± 25 | 4.40 ± 0.99 |
| Sartorius | 281 ± 73 | 358 ± 64 | 6.07 ± 0.91 |
| Popliteus | 15 ± 4 | 19 ± 3 | 0.25 ± 0.05 |
| Lateral gastrocnemius | 129 ± 21 | 129 ± 17 | 2.06 ± 0.30 |
| Posterior compartment | 18 ± 92 ± 65 | 291 ± 91 | 4.64 ± 0.79 |

Number of axial images/slices used to assess the volume of each muscle were averaged across all participants. Muscle volume data are presented as group mean ± SD, with individual measurements the average of both sides/legs (i.e., unilateral). Significantly different to subelite: \(* P \leq 0.05\) and \(** P \leq 0.01\).
lateralis +19%; adductor magnus +16%; all \( P \leq 0.032, \ d = 1.17–1.85 \). In contrast, the relative volume of the medial gastrocnemius was smaller in elite versus subelite sprinters (−24%, \( P = 0.031, \ d = -1.18 \)).

**Relationships between sprint performance and muscle volumes.** Among the entire cohort of female sprinters, SBE\(_{100}\) was not related to the absolute muscle volume of any functional muscle group (strongest correlation: hip flexors, \( r = -0.580, \ P = 0.055 \)) or individual muscle/compartment volume (strongest correlation: sartorius, \( r = -0.577, \ P = 0.114 \)) following family wise correction for multiple correlations (Table 3). Relative to body mass, the total volume of all the muscles (\( r = -0.483, \ P = 0.042 \)), and three functional muscle groups (hip flexors, \( r = -0.689 \); knee extensors, \( r = -0.583 \); hip extensors, \( r = -0.577 \); all \( P \leq 0.025 \)) showed moderate to strong negative relationships with SBE\(_{100}\) (i.e., larger muscles, faster/shorter time). In contrast, the relative volume of the plantarflexors was positively associated with SBE\(_{100}\) (\( r = 0.531, \ P = 0.011 \); i.e., larger plantarflexors, slower/longer time). The regression models revealed that for the relative volume of functional muscle groups, only the hip flexors contributed to the explained variance in SBE\(_{100}\) alone explaining 47.5% of the variance. Relative muscle volume was associated with faster SBE\(_{100}\) in five individual muscles (sartorius, \( r = -0.639 \); vastus lateralis, \( r = -0.634 \); gluteus maximus, \( r = -0.596 \); adductor magnus, \( r = -0.582 \); iliopsoas, \( r = -0.553 \); all \( P \leq 0.029 \)). Conversely, three muscles were associated with slower SBE\(_{100}\) (gluteus minimus, \( r = 0.555 \); medial gastrocnemius, \( r = 0.526 \); soleus, \( r = 0.521 \); all \( P \leq 0.037 \)). For the relative volume of individual muscles/compartments, the regression model found 57.8% of the variance in SBE\(_{100}\) was explained by the combination of two muscles (sartorius 40.9% and adductor magnus 16.9%; Fig. 2).

**Relationships between speed at 30 m and muscle volumes.** No relationships were observed between acceleration speed and absolute volume of functional muscle groups or individual muscle/compartment volume. Relative to body mass, the volume of only the knee extensor muscle group showed a moderate relationship to speed at 30 m (\( r = 0.584, \ P = 0.032 \)). No relationships were found between the relative volume of any other functional muscle group or individual muscle and acceleration performance.

**Vertical jump performance.** Absolute peak power was greater in elite versus subelite sprinters (4458 W vs 3814 W, \( P = 0.037, d = 1.14 \); Table 4). No differences between groups were observed for relative peak power (\( P = 0.077 \)) or jump height (\( P = 0.646 \)). Moderate to strong relationships were observed between SBE\(_{100}\) and all CMJ metrics (absolute power, \( r = -0.520, P = 0.020 \); relative power, \( r = -0.741; P < 0.0001 \); jump height, \( r = -0.477, P = 0.025 \)). Moderate to very strong relationships were observed between speed at 30 m and relative peak power (\( r = 0.808, P < 0.0001 \); Table 4). jump height...
The aim of this study was to compare the lower body muscle volumes and vertical jump power between elite and subelite female sprinters, and to assess the relationship of these measures with sprint and acceleration performance in the whole cohort. Elite sprinters had greater total absolute, but not relative, lower body muscle volume (absolute +15%) than subelite sprinters, with nonuniform, anatomically specific differences in the volume of muscle groups and individual muscles. Specifically, there were between group differences in volume of the hip flexors (absolute +28%, relative +29%), the hip extensors (absolute +22%, relative +19%) and the knee extensors (absolute +21%), whereas the knee flexors and plantarflexors were not different. Greater relative volume of the same three muscle groups (hip flexors, hip extensors, knee extensors) were associated with faster sprint performance, and regression modeling revealed that the relative volume of the hip flexors explained 47.5% of the variance in SBE_{100}. Elite sprinters were larger in eight (absolute) and six (relative) out of 23 individual muscles compared with subelite sprinters, notably the sartorius, TFL and gluteus maximus. The relative volume of five individual muscles (sartorius, ilioptsoas, adductor magnus, gluteus maximus, vastus lateralis) were associated with faster sprint performance, and multiple regression revealed that 57.8% of the variance in sprint performance was explained by the combination of the relative volume of the sartorius (40.9%) and adductor magnus (16.9%). Sprint acceleration, assessed as speed at 30 m, was related to the relative volume of the knee extensors. This study provides novel and robust evidence highlighting the particular importance of the relative muscle volume of the hip flexors and extensors and the knee extensor muscle groups and sartorius, TFL and gluteus maximus muscles for female sprint running performance.

The muscle volume values presented in this study are similar to previously published data in a mixed-sex group of male and female Division I NCAA sprinters (35) and in male Japanese sprinters (30), which may be due to the broadly similar body mass of these groups (subelite females, 62.7 ± 6.3 kg; elite females, 67.7 ± 6.0 kg; 68.9 ± 8.5 kg, [35]; 67.0 ± 4.9 kg, [30]). However, muscle volumes of the female sprinters in the current study were markedly smaller than the notably heavier elite and subelite male sprinters in our previous investigation (86.4 ± 6.7 kg, and 75.4 ± 7.3 kg, respectively; [3]). The standard of elite female sprinters in the current study exceeded that of any other previous male or female sprint group by an average 268 IAAF points. Given the very limited data available on female sprinters, the current study appears to be the first evaluation of anthropometrics, body composition, muscle morphology and power in a group of genuinely elite, and subelite female sprinters.

**Muscle volume.** Initial analysis revealed no differences in stature, body mass, or body fat percentage between elite and subelite female sprinters, but fat free mass was greater (+5 kg) in elite versus subelite sprinters. More precise MRI analysis indicated that elite sprinters had greater volume for all muscles combined (+15%), the hip flexors (absolute, +28%; relative, +19%), hip extensors (absolute +22%, relative +14%) and the knee extensors (absolute +21%). This pattern of lower limb musculature with the proximal hip muscle groups being disproportionately larger than the distal plantarflexors was similar to the only other comparison of elite versus subelite sprint athletes that involved males (3). Furthermore, the relative volumes of the hip flexors and extensors were related to sprint race performance (r = −0.689 and −0.577, respectively). During the running stride, it has been widely proposed that the hip flexors are critical to the rapid recovery of the leg during swing phase and therefore in achieving high stride frequencies (16,17), whereas the hip extensors are regarded as critical in facilitating the back swing of the leg during late swing (36,37), horizontal force application to the ground during the stance phase (38,39) and thus forward propulsion. Therefore, both of these muscle groups were hypothesized to be larger in elite female sprinters, which were found to be true.

The association of hip extensor relative volume and female sprint performance in the current study (r = −0.577) was strikingly similar to the relationship we previously found in male sprinters (r = −0.560, [3]); however, the association between relative hip flexor volume and sprint performance

TABLE 3. Pearson’s product moment correlation coefficients between seasons best equivalent 100 m (SBE_{100}) and absolute and relative muscle volume of all muscles, five functional muscle groups and 23 individual muscles in the whole cohort of female sprinters (n = 22).

| Muscle Group/Muscle                | Absolute Muscle Volume (cm³) | Relative Muscle Volume (cm³·kg⁻¹) |
|-----------------------------------|-----------------------------|----------------------------------|
| All muscles                       | −0.340                      | −0.483                           |
| Hip flexors                       | −0.580                      | −0.689*                          |
| Hip extensors                     | −0.426                      | −0.577*                          |
| Knee flexors                      | −0.089                      | 0.036                            |
| Knee extensors                    | −0.484                      | −0.583*                          |
| Plantarflexors                   | 0.434                       | 0.532                            |
| Iliopsoas                        | −0.497                      | −0.553*                          |
| Sartorius                        | −0.577                      | −0.639*                          |
| Tensor fasciae laterae           | −0.363                      | 0.324                            |
| Adductor magnus                  | −0.445                      | −0.582*                          |
| Gracilis                         | −0.304                      | 0.293                            |
| Gluteus maximus                  | −0.480                      | −0.596**                         |
| Gluteus medius                   | −0.202                      | 0.180                            |
| Gluteus minimus                  | 0.466                       | 0.555*                           |
| Rectus femoris                   | −0.450                      | −0.459                           |
| Vastus lateralis                 | −0.532                      | −0.634**                         |
| Vastus intermedius               | −0.378                      | 0.413                            |
| Vastus medialis                  | −0.387                      | 0.448                            |
| Semimembranosus                 | −0.165                      | 0.141                            |
| Semitendinosus                  | −0.242                      | 0.245                            |
| Biceps femoris long head        | 0.004                       | 0.029                            |
| Biceps femoris short head       | −0.235                      | −0.189                           |
| Popliteus                        | −0.277                      | −0.302                           |
| Lateral gastrocnemius           | 0.083                       | 0.142                            |
| Medial gastrocnemius            | 0.482                       | 0.526*                           |
| Soleus                           | 0.400                       | 0.521*                           |
| Anterior compartment             | 0.019                       | 0.059                            |
| Lateral compartment             | 0.102                       | 0.155                            |
| Posterior compartment           | 0.165                       | 0.235                            |

Significant correlations: *P ≤ 0.05; and **P ≤ 0.01 following correction for multiple correlations.

(r = 0.691, P = 0.004), and absolute peak power (r = 0.569, P = 0.007).
in females ($r = -0.689$), such that relative hip flexor volume alone explained 47.5% of variance in sprint performance within the current investigation, was not observed in male sprinters ($r = -0.299$; nonsignificant). In a similar contrast as for the whole hip flexors, the relative volumes of two of the individual hip flexors (sartorius, $r = -0.639$; iliopsoas, $r = -0.553$) were associated with sprint performance in the current female. Cohort, whereas comparable data in men suggests no association of the relative volume of the individual hip flexor muscles with performance (3,40). It has been found that higher stride frequencies are associated with faster sprint times in females, whereas longer stride lengths were associated with male sprint performance (6). This may emphasize the requirement for faster leg recovery during sprinting in female sprinters, and as such the relative volume of the hip flexors (and therefore hip flexor power) may be particularly important for sprint performance in females compared with males.

Considering individual muscle volumes, there was a distinct anatomical distribution between elite and subelite female sprinters, akin to our previous research in males (3). Specifically, for 6 of 23 individual muscles compartments, both absolute and relative muscle volumes were larger in elite versus subelite sprinters: sartorius (absolute, +45%; relative, +35%), TFL (absolute, +42%; relative, +29%), gluteus maximus (absolute, +30%; relative, +21%), rectus femoris (absolute, +29%; relative, +21%), vastus lateralis (absolute, +27%; relative, +19%), and adductor magnus (absolute, +25%; relative, +16%). The observation that the sartorius, TFL, and gluteus maximus were the muscles found to have the largest between-group differences is remarkably consistent with our previous work in male sprinters where the same three muscles displayed the largest percentage differences between elite and subelite sprinters in absolute and relative terms (3). As the gluteus maximus is the largest muscle in the human body, and also the biggest and strongest of the hip extensors (36,41), given our findings for the importance of the hip extensor muscle group, it is unsurprising that the gluteus maximus appears to be a key differentiator of sprint level in both females (current study) and males (3). Furthermore, the TFL and

![FIGURE 2](image-url)
sartorius are both significant contributors to hip flexion (42), and although the sartorius is the only simultaneous flexor of the knee and hip joints, it has been reported that the TFL also acts as an accessory knee flexor (43). As such the findings of the current investigation confirm and reinforce the importance of the gluteus maximus, sartorius and TFL for elite sprint performance and their likely role in propulsion and leg recovery, respectively.

The current study found no relationship between absolute muscle volume and race performance in female sprinters, whereas our previous work in male sprinters revealed that the absolute volume of five muscle groups and 18 of 23 individual muscles were associated with sprint performance (3). It has been shown that male sprinters have lower body fat compared with females (12), and that additional or excess body fat may have a negative influence on sprint performance due to adding to body mass without contribution to power production (7). As such, it may be speculated that in order for female sprinters to counteract the negative impact of higher relative fat mass, muscle volume relative to body mass may be more important than absolute muscle volume for female sprint performance. However, in the current study, correlations as strong as \( r = -0.58 \) (hip flexors and sartorius) were considered nonsignificant, in part because of the correction for multiple correlations (34), including a conservative false discovery rate (5%) that was used to decrease the likelihood of type-I error (44). It is possible that reducing the risk of a type-I error for null associations increases the risk of a type-II error for those associations that are not null (45), and it may be possible that the lack of association of absolute muscle volume and SBE\(_{100}\) could be due to type-II error.

This study revealed that the relative volume of the knee extensor muscle group was related to both SBE\(_{100}\) \((r = -0.547)\) and acceleration performance \((r = 0.584)\), and that the volume of two individual quadriceps muscles were greater in elite versus subelite sprinters (vastus lateralis: absolute, +27%; relative, +19%; rectus femoris: absolute, +29%; relative, +21%). This contrasts with recent evidence in males suggesting that knee extensor muscleularity is not related to sprint performance (3,30,46). Nonetheless, during ground contact the knee extensors play an important role in the vertical deceleration and subsequent acceleration of the CoM, as well as stabilizing the knee joint (36). In addition, the current study observed that the relative volume of the plantarflexors, the soleus and the medial gastrocnemius were associated with slower sprint times \((r = 0.521–532)\). This may be attributed to the proposition that enlarged distal leg muscles may substantially increase the moment of inertia of the leg, impeding limb angular acceleration and subsequently sprint performance (30). This study indicates that the relative volume of the knee extensors (larger was beneficial) and plantarflexors (larger was detrimental) are important for female sprint performance, and the comparison with previous findings in males may indicate that these are sex-specific influences on female sprint performance only.

**Vertical jumps and power.** The elite group produced higher absolute power output during vertical jumping than the subelite group, with only a tendency \((P = 0.076)\) for a difference in relative peak power, and no difference in jump height. Muscle power is considered an important determinant of sprint performance (1), and therefore we hypothesized that the elite sprinters would have greater absolute and relative peak power than subelite sprinters. As such elite sprinters displaying greater power output than subelite sprinters may be an unsurprising finding. In addition, all CMJ metrics were moderately to strongly associated with faster sprint running, with relative peak power in particular showing the strongest associations to SBE\(_{100}\) \((r = -0.741)\) and 30 m acceleration performance \((r = 0.808)\). Previous research has highlighted associations between CMJ relative peak power and measures of acceleration performance in well-trained female soccer players \((r = -0.434 to -0.466, (20). However, it appears that this is the first time these variables have been examined in a group of elite sprinters, and the current study highlights significantly stronger relationships than have been previously reported, suggesting that CMJ metrics may be a useful indicator of sprint performance among sprinters. This may be of particular interest to sprint athletes and their coaches, as the CMJ is an easily administered monitoring tool we have found to be strongly related to sprint running ability.

**Limitations.** For six members of the subelite sprint group, SBE\(_{100}\) was an estimation based on their best IAAF points from either 60 m or 200 m season’s best time, and as such may have overestimated their sprint ability. Nevertheless, any impact of this estimation on group sprint time was trivial (i.e., less than 0.5% change to subelite group race performance), and this method ensured a consistent measure of each athlete’s best performance. In addition, the temporal separation between race performance (SBE\(_{100}\)) and the morphology, jump and acceleration measurements within this study is a potential confounder that may have weakened the observed effects. Despite this, the continuity of habitual training throughout the study in both sprint groups is likely to have reduced the possibility of significant changes in muscle volumes or power between the dates of race performance and assessment. Finally, to define functional muscle groups, this study used a relatively simplistic categorization of the musculature able to contribute to muscular power production in a specific direction about each joint. This categorization could potentially misrepresent the role and contribution of some individual muscles, and potentially confound the influence of functional muscle groups. However, the functional muscle groups defined in the current study were based on accepted anatomical/biomechanical contributions of each individual muscle and thus appeared a useful way to group muscles with similar functional roles. Nonetheless, given a larger data set, more sophisticated statistical techniques could be used to search the data for optimal combinations of muscles that may explain a greater proportion of the variability in sprint performance.

**Conclusions**

In conclusion, this investigation illustrates for the first time the lower body muscle volume characteristics that facilitate
genuinely elite sprint running in females. It emphasizes the particular importance of a distinctive and specific distribution of relative (to body mass) muscle volume specifically for female sprint performance, in particular, the beneficial effect of larger hip flexors (alone explaining 47.5% of the variance in performance), hip extensors and knee extensors, whereas the larger plantarflexors were associated with slower performance. Furthermore, greater relative volumes of five individual lower body muscles were beneficial for fast sprinting (sartorius, vastus lateralis, gluteus maximus, adductor magnus, and iliopsoas). In light of this novel evidence, it is recommended that coaches and female sprinters aspiring to compete at the elite level consider emphasis in their training to increase the muscle volumes of the hip flexors and extensors in order to enhance sprint running performance.

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Conflicts of Interest: No conflicts of interest are relevant to this article. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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