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The Muscle Morphology of Elite Sprint Running

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[1]School of Sport, Exercise and Health Sciences, Loughborough University, Leicestershire, UNITED KINGDOM; [2]British Athletics, Loughborough University, Leicestershire, UNITED KINGDOM; [3]School of Sport and Health Sciences, University of Exeter, Devon, UNITED KINGDOM; [4]Research Organization of Science and Technology, Ritsumeikan University, Kusatsu, Shiga, JAPAN; [5]Department of Physical Therapy and Rehabilitation, University of Maryland Baltimore, Baltimore, MD; and [6]Applied Sports Technology Exercise and Medicine Research Centre, Swansea University, Swansea, UNITED KINGDOM

ABSTRACT

MILLER, R., T. G. BALSHAW, G. J. MASSEY, S. MAEO, M. B. LANZA, M. JOHNSTON, S. J. ALLEN, and J. P. FOLLAND. The Muscle Morphology of Elite Sprint Running. *Med. Sci. Sports Exerc.*, Vol. 53, No. 4, pp. 804–815, 2021. The influence of muscle morphology and strength characteristics on sprint running performance, especially at elite level, is unclear. **Purpose:** This study aimed to investigate the differences in muscle volumes and strength between male elite sprinters, sub-elite sprinters, and untrained controls and to assess the relationships of muscle volumes and strength with sprint performance. **Methods:** Five elite sprinters (100-m season's best equivalent [SBE_{100}], 10.10 ± 0.07 s), 26 sub-elite sprinters (SBE_{100}, 10.80 ± 0.30 s), and 11 untrained control participants underwent 1) 3-T magnetic resonance imaging scans to determine the volume of 23 individual lower limb muscles/compartments and 5 functional muscle groups and 2) isometric strength assessment of lower body muscle groups. **Results:** Total lower body muscularity was distinct between the groups (controls < sub-elite +20% < elite +48%). The hip extensors exhibited the largest muscle group differences/relationships (elite, +32% absolute and +15% relative [per kg] volume, vs sub-elite explaining 31%–48% of the variability in SBE_{100}), whereas the plantarflexors showed no differences between sprint groups. Individual muscle differences showed pronounced anatomical specificity (elite vs sub-elite absolute volume range, +57% to −9%). Three hip muscles were consistently larger in elite vs sub-elite (tensor fasciae latae, sartorius, and gluteus maximus; absolute, +45%–57%; relative volume, +25%–37%), and gluteus maximus volume alone explained 34%–44% of the variance in SBE_{100}. The isometric strength of several muscle groups was greater in both sprint groups than controls but similar for the sprint groups and not related to SBE_{100}. **Conclusions:** These findings demonstrate the pronounced inhomogeneity and anatomically specific muscularity required for fast sprinting and provides novel, robust evidence that greater hip extensor and gluteus maximus volumes discriminate between elite and sub-elite sprinters and are strongly associated with sprinting performance. **Key Words:** SPRINTING, MUSCLE VOLUME, ISOMETRIC STRENGTH

Sprint running, including the ability to accelerate quickly and achieve high maximum running speeds, is one of the most revered and long-standing expressions of human athletic performance and is considered a key component of numerous running-based sports. Elite sprinters are capable of achieving impressive gait speeds of over 12 $m \cdot s^{-1}$ (1) because of the generation of extremely high muscular power, particularly from the major muscle groups of the lower body. Theoretically, neuromuscular power is largely determined by muscle volume, and empirical evidence has demonstrated very strong relationships between muscle volume and neuromuscular power of single muscle groups (2). This suggests that muscle volume may be of critical importance for sprint performance, and although it is a common observation that elite sprinters are typically more muscular than untrained populations, the specific muscle groups important for elite sprint running performance remain unclear.

The "gold standard" method of measuring muscle volume is magnetic resonance imaging (MRI [3]); however, to date, only a small number of studies have used MRI to investigate the importance of muscle volumes for sprint running performance. Recent evidence supports the notion that sprinters are generally more muscular (i.e., greater muscle volume) than nonsprinters (controls), but with a nonuniform pattern of muscular hypertrophy such that the hip and biarticular hip and knee joint muscles appear to be larger, whereas the monoarticular knee joint muscles and muscles of the lower leg may be more similar (4,5). Moreover, there are also suggestions that the volume of specific muscles could be related to sprint performance, although with considerable confusion about which muscles/muscle groups may be most important; for example, there are reports that psoas major (6–8), rectus femoris (4), adductors (8,9), hamstrings (7,9), quadriceps (8), or even ratios of

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muscle volumes (psoas major:quadriceps (10), gluteus maximus: quadriceps [7]) may be most important. This confusion may have arisen as most studies have examined only a limited and variable number of muscles or muscle groups (7–11) rather than a complete analysis of the lower body musculature.

Importantly, comparisons to date have also been limited to sprinters versus controls (4,5) or sprinters versus endurance runners (9) rather than what distinguishes elite from sub-elite sprinters. This is because previous studies have not included athletes that are genuinely elite (i.e., internationally competitive), with the fastest personal best 100-m times of participants being 10.68 s (11), 10.67 s (4), 10.23 s (7), 10.95 s (10), division 1 collegiate level sprinters (performance times undefined [5]), and 13.24 s in preadolescent boys (8). Finally, the number of sprinters assessed has typically been relatively small for quantifying the relationship between sprint performance and muscle volumes (n = 8–16 [4,5,8,9,11]). Thus, no comparison between elite and sub-elite sprinters has yet been made, and the muscle groups that need to be particularly large to attain elite running speeds remains to be elucidated.

Similarly, the functional characteristics of specific muscle groups needed for elite sprint running remain largely unknown. Although some studies have assessed strength, during multiple joint exercises (e.g., squatting, isometric mid-thigh pull) in relation to acceleration and/or sprint performance of athletic groups (12,13), this clearly does not allow the identification of which specific muscle groups need to be strong/powerful to enable fast running. Although it has been speculated that hip flexion and extension strength may be critical for fast running (6,7), we are aware of only one preliminary study that reported these muscle groups to be stronger in sprinters and largely predictive of sprint performance (14). In fact, to date, no studies have done a comprehensive assessment of the strength of a range of ankle, knee, and hip joint muscles in elite and/or sub-elite sprinters as well as untrained controls to understand the functional characteristics that may differentiate these groups.

Therefore, the aims of this study were to investigate the differences in muscle volumes and strength between elite sprinters, sub-elite sprinters, and untrained controls and to assess the relationships of both muscle volumes and strength with sprint performance among sprinters. It was hypothesized that the hip flexor and extensor muscles would be progressively larger relative to body mass according to group (controls < sub-elite < elite) and be related to sprint performance among the whole cohort of sprinters. In addition, it was postulated that isometric torque of the hip flexor and extensor muscle groups would be different between groups and related to sprint performance.

METHODS

Participants and sprint performance. All of the participants were healthy young men, asymptomatic for leg or back injury, with no minor injury in the previous 4 wk and no major injury in the previous 6 months. Five elite sprinters (mean ± SD; age, 27 ± 4 y; body mass, 86.4 ± 6.7 kg; height, 1.83 ± 0.06 m), 26 sub-elite sprinters (22 ± 2 yr, 75.4 ± 7.3 kg, 1.78 ± 0.06 m), and 11 control participants (26 ± 3 yr, 75.2 ± 5.6 kg, 1.80 ± 0.08 m; Table 1) volunteered to participate and gave informed consent to take part in this study. Elite sprinters were required to have a season's best 100-m sprint time of <10.25 s (the British Athletics 100 m selection standard for the European Outdoor Championships 2018 [15]). Sub-elite sprinters were required to have a season's best time of 10.35–11.50 s for 100 m or equivalent for 60 m/200 m based on International Association of Athletics Federations (IAAF) points and to have completed at least one season of high-intensity sprint-specific training. Participants in both sprint groups completed a minimum of two sprint-specific training sessions and one resistance training session per week. Control participants had a low to moderate level of physical activity (i.e., vigorous-intensity activity ≤2 times per week, and ≤1500 MET·min·wk^{-1}, overall vigorous and moderate physical activity ≤3000 MET·min·wk^{-1} [16]) and were not involved in systematic physical training or competitive sports (for ≥1 yr). Season's best and personal best sprint (60, 100, and 200 m) times were taken from the national governing body database (www.thepowerof10.info) of electronically timed races with

TABLE 1. Performance, training status and anthropometric characteristics of elite sprinters (n = 5), sub-elite sprinters (n = 26), and untrained controls (n = 11).

	Controls	Sub-elite Sprinters		Elite Sprinters	
	Mean ± SD	Mean ± SD	Range	Mean ± SD	Range
Performance and training status					
SBE_{100} (s)	–	10.80 ± 0.30	10.36–11.50	10.10 ± 0.07**	10.03–10.21
PBE_{100} (s)	–	10.69 ± 0.26	10.34–11.25	9.99 ± 0.07**	9.91–10.08
Sprint training duration (yr)	–	5.3 ± 2.6		9.2 ± 3.4**	
Resistance training duration (yr)	–	3.5 ± 2.0		8.1 ± 2.6**	
Activity level (MET·min·wk^{-1})	2006 ± 825				
Anthropometrics					
Age (yr)	25.8 ± 2.6	22.0 ± 2.2††		27.4 ± 4.1**	
Height (m)	1.80 ± 0.08	1.78 ± 0.06		1.83 ± 0.06	
Body mass (kg)	75.2 ± 5.6	75.4 ± 7.3		86.4 ± 6.7**†	
Body mass index (kg·m^{-2})	23.3 ± 1.8	24.3 ± 2.4		25.0 ± 1.0	
Sum of eight skinfold (mm)	88 ± 32	53 ± 14††		39 ± 4††	
Body fat percentage (%)	15.5 ± 4.3	11.2 ± 3.1††		8.3 ± 1.2††	
Fat-free mass (kg)	63.5 ± 4.7	67.0 ± 6.7		79.8 ± 6.1**††	
Waist–glute ratio (–)	0.81 ± 0.02	0.82 ± 0.04		0.84 ± 0.05	

Data are presented as mean ± SD.
Significantly different to sub-elite: *$P \le 0.05$ and **$P \le 0.01$.
Significantly different to controls: †$P \le 0.05$ and ††$P \le 0.01$.

wind readings (<2.0 $m \cdot s^{-1}$) during the corresponding calendar year in which data collection took place (season's best) or the athletes career at the end of that season (personal best). Sprint performances were converted to IAAF points, a classification system that allows performance comparisons between different events, and each athletes maximum points in any of the sprint events (60, 100, and 200 m) was taken as their performance measure and converted back into 100-m season's best equivalent (SBE_{100}) or personal best equivalent (PBE_{100}) times. For the elite sprint group, SBE_{100} (10.10 ± 0.07; range, 10.03–10.21 s) and PBE_{100} (9.99 ± 0.07; range, 9.91–10.08 s) were actual 100-m performances for all individuals (i.e., 100-m was their best event). For the sub-elite sprint group, SBE_{100} was actual 100-m performances for 73% of these athletes (19 out of 26), whereas for seven athletes, SBE_{100} was derived from either 60- or 200-m season's best times. Consequently, the whole sprint cohort had SBE_{100} ranging from 10.03 to 11.50 s (10.71 ± 0.37 s). Ethical approval was granted by the Loughborough University Ethics Approvals (Human Participants) Sub-Committee.

Study overview. Participants were required to attend two measurement sessions within this cross-sectional study: one for isometric strength measurements and one for assessing muscle morphology (MRI). All measurement sessions were scheduled after a rest day or light training day, and participants were instructed to arrive in a relaxed state having followed normal daily activity and dietary behaviors, where they then sat quietly for 15 min before their MRI scan. Because of limitations in scheduling and practicalities of data collection with elite athletes, it was not feasible to control for measurement time of day.

Anthropometry. Body mass was measured using a calibrated ADAM C-150 weighing scale (ADAM equipment, Oxford, CT), and stature was measured using a wall-mounted stadiometer (Holtain Ltd., Crymmych, UK). Skinfold thickness was measured at eight sites (bicep, tricep, subscapular, iliac crest, supraspinale, abdominal, thigh, and calf) using Harpenden skinfold calipers (British Indicators Ltd., Wolverhampton, UK), and the averages of two measurements at each site were recorded. In addition, waist and gluteal circumferences were collected. All anthropometric measures were done by the same investigator and in accordance with the International Society for the Advancement of Kinanthropometry guidelines (17). The sum of four skinfolds (bicep, tricep, subscapular, and iliac crest) was used to calculate body density using the formula for males 20–29 yr old (18), and percentage body fat was estimated using the Siri (19) equation. Fat-free mass was derived from the percentage body fat and body mass values.

Muscle volume with MRI. T1-weighted axial magnetic resonance (MR) images of the abdomen, thigh, and shank were obtained with a 3-T scanner (Discovery MR750w; GE Healthcare, Chicago, IL) with a receiver 8-channel whole-body coil. Images (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) were obtained from the 12th thoracic vertebra to the calcaneus capturing both legs in five overlapping blocks. Subjects 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°. Oil-filled capsules were placed in equal segments on the right leg of each participant during scanning to facilitate alignment between the blocks during analysis.

The MR images were manually segmented to assess cross-sectional area and to derive the volume of 23 lower limb muscles/compartments. Specifically, every other MR image (i.e., 20 mm between the center of the measured images) starting from the most proximal image in which the muscle appeared was segmented using a public domain DICOM software (Horos, version 2.2.0 www.thehorosproject.org). The average number of images analyzed per muscle is shown in Table 2. Six separate investigators conducted the analysis, with each investigator analyzing the same muscles/compartments for the entire cohort, and blinded to participant identity/group. Fully analyzed images for each participant (i.e., all 26 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 sections. The analyzed muscles/compartments were iliopsoas (psoas major and iliacus combined); sartorius; tensor fasciae latae (TFL); adductor magnus; gracilis; gluteus maximus; gluteus medius; gluteus minimus; rectus femoris; vastus lateralis, medialis, and intermedius; 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 hallux longus (anterior); peroneus longus and brevis (lateral); and plantaris, tibialis posterior, flexor digitorum longus, and flexor hallux 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, and 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 (7):

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

where A_m represents the muscle cross-sectional area calculated from each image, i is the image number, n is the total number of images, and h is the distance between images (20 mm). In addition to absolute muscle volume (cm^3), muscle volume was also expressed relative to body mass ($cm^3 \cdot kg^{-1}$).

Strength measurements. The isometric strength of the five functional muscle groups was assessed with custom-built isometric dynamometers in the following order (for reference

TABLE 2. Absolute and relative muscle volume of all muscles, five functional muscle groups, and 23 individual muscles/compartments of elite sprinters ($n = 5$), sub-elite sprinters ($n = 26$), and untrained controls ($n = 11$).

Muscle Group/Muscle or Compartment	No. Slices	Absolute Muscle Volume (cm^3)			Relative Muscle Volume ($cm^3 \cdot kg^{-1}$)		
		Control Group	Sub-elite Sprinters	Elite Sprinters	Control Group	Sub-elite Sprinters	Elite Sprinters
All muscles		7628 ± 1548	9164 ± 1207††	11323 ± 1328**††	101.42 ± 7.55	121.51 ± 10.05††	131.26 ± 6.76††
Hip flexors		1031 ± 151	1314 ± 216††	1620 ± 200**††	13.75 ± 2.16	17.42 ± 2.27††	18.82 ± 1.83††
Hip extensors		2257 ± 220	3029 ± 422††	4002 ± 489**††	30.10 ± 3.14	40.16 ± 3.77††	46.39 ± 2.88**††
Knee flexors		1460 ± 196	1859 ± 301††	2304 ± 178**††	19.45 ± 2.72	24.61 ± 2.79††	26.78 ± 0.76††
Knee extensors		2202 ± 315	2636 ± 401††	3218 ± 400**††	29.21 ± 3.09	35.00 ± 4.36††	37.31 ± 2.48††
Plantarflexors		860 ± 172	943 ± 156	1112 ± 181†	11.39 ± 1.92	12.48 ± 1.40	12.92 ± 1.78
Iliopsoas	18	514 ± 75	618 ± 101†	702 ± 97††	6.84 ± 1.03	8.18 ± 0.97††	8.18 ± 1.10
Sartorius	28	142 ± 25	209 ± 50††	306 ± 46**††	1.89 ± 0.28	2.77 ± 0.62††	3.56 ± 0.40*††
TFL	15	73 ± 24	86 ± 25	135 ± 41**††	0.97 ± 0.36	1.14 ± 0.29	1.56 ± 0.39*††
Adductor Magnus	16	624 ± 81	828 ± 128††	1056 ± 83**††	8.30 ± 0.88	10.99 ± 1.46††	12.31 ± 1.05††
Gracilis	17	98 ± 23	142 ± 37††	180 ± 37††	1.31 ± 0.30	1.89 ± 0.45††	2.10 ± 0.39††
Gluteus maximus	16	931 ± 108	1257 ± 197††	1797 ± 376**††	12.40 ± 1.39	16.65 ± 1.82††	20.75 ± 3.15**††
Gluteus medius	10	384 ± 49	405 ± 69	434 ± 92	5.11 ± 0.51	5.38 ± 0.75	5.01 ± 0.75
Gluteus minimus	9	199 ± 39	170 ± 36	192 ± 46	2.66 ± 0.58	2.25 ± 0.44	2.22 ± 0.48
Rectus femoris	21	303 ± 55	401 ± 78††	476 ± 45††	4.05 ± 0.81	5.33 ± 0.98††	5.53 ± 0.38†
Vastus lateralis	22	743 ± 98	925 ± 156††	1132 ± 180†	9.88 ± 1.20	12.26 ± 1.65††	13.07 ± 1.09††
Vastus intermedius	23	680 ± 115	789 ± 140	962 ± 145*††	9.01 ± 1.20	10.48 ± 1.63†	11.17 ± 1.33†
Vastus medialis	19	476 ± 111	521 ± 79	649 ± 97*††	6.28 ± 1.11	6.92 ± 0.89	7.53 ± 0.89
Semimembranosus	17	262 ± 18	327 ± 59††	359 ± 60††	3.50 ± 0.33	4.34 ± 0.63††	4.16 ± 0.56
Semitendinosus	15	219 ± 39	350 ± 79††	449 ± 70*††	2.93 ± 0.64	4.63 ± 0.86††	5.20 ± 0.54††
Biceps femoris long head	18	221 ± 42	267 ± 47†	340 ± 31**††	2.97 ± 0.71	3.55 ± 0.54†	3.96 ± 0.32††
Biceps femoris short head	7	110 ± 28	131 ± 34	167 ± 26††	1.46 ± 0.36	1.73 ± 0.39	1.94 ± 0.29
Popliteus	16	19 ± 6	17 ± 5	23 ± 5	0.26 ± 0.06	0.22 ± 0.07	0.27 ± 0.05
Lateral gastrocnemius	13	156 ± 41	170 ± 37	202 ± 34	2.06 ± 0.47	2.25 ± 0.38	2.36 ± 0.51
Medial gastrocnemius	14	251 ± 52	262 ± 58	300 ± 38	3.33 ± 0.62	3.50 ± 0.42	3.50 ± 0.42
Soleus	22	453 ± 95	510 ± 76	610 ± 137††	6.00 ± 1.08	6.77 ± 0.76	7.05 ± 1.25
Anterior compartment	20	291 ± 47	273 ± 47	302 ± 59	3.87 ± 0.53	3.62 ± 0.52	3.48 ± 0.46
Lateral compartment	21	153 ± 35	161 ± 42	147 ± 32	2.02 ± 0.39	2.13 ± 0.46	1.69 ± 0.27
Posterior compartment	20	326 ± 93	345 ± 71	401 ± 76	4.32 ± 1.12	4.57 ± 0.82	4.63 ± 0.60

The 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). All Muscles is the sum of muscle volumes from all the individual muscles/compartments listed.
Significantly different to sub-elite: $*P \leq 0.05$ and $**P \leq 0.01$.
Significantly different to controls: $\dagger P \leq 0.05$ and $\dagger\dagger P \leq 0.01$.

hip [180°], knee [180°], and ankle [90°] angles in the anatomical position; flexion is lower): hip extensors (upper body prone, hip 145°, knee 150°); hip flexors (upper body supine, hip 180°, knee 150°); knee extensors (sitting, hip 115°, knee 120°); knee flexors (upper body prone, hip 150°, knee 150°); and plantarflexors (sitting, hip 110°, knee 180°, ankle 100°). Measurements were made unilaterally, first with the right leg then the left, before moving to the next dynamometer. Participants were tightly secured to each dynamometer using extensive strapping to minimize extraneous movement. During extension and flexion of the hip and knee, a calibrated S-shaped strain gauge (linear response up to 2000 N) and specific braces were positioned in the movement plane perpendicular to the long axis of femoral/tibial movement and strapped 4 cm proximal to the knee/ankle joints, respectively. During plantarflexion contractions, force data were collected using a portable Kistler force plate (Type 9602A; Kistler Instruments Corp., Winterthur, Switzerland) mounted to a custom-built rig. For all isometric measurements, the force signal was amplified (×500), interfaced with an analog-to-digital converter (CED micro 1401; CED, Cambridge, UK), and sampled at 2000 Hz with a personal computer using Spike 2 software (CED).

With each dynamometer and muscle group, participants first completed a standardized series of warm-up contractions, each of 3-s duration with 15-s rest in between (3 × 50%, 3 × 75%, 1 × 90% perceived maximum) followed by at least two subsequent maximal voluntary contractions of the relevant muscle group, lasting ~4 s with at least 60-s rest in between. A third contraction was completed if the participant scored higher on their second contraction than the first. During the maximal contractions, participants were given strong verbal encouragement, instructed to push as hard as possible for the duration of the contraction, and provided with real-time biofeedback displayed on a computer monitor with a target cursor representing their maximum force in preceding contractions. Maximal voluntary force was the highest instantaneous force achieved, corrected for the force due to gravity (i.e., baseline force at rest), and maximal voluntary torque was calculated as the product of maximal voluntary force and measured lever length (m). For the hip and the knee muscle groups, lever length was manually measured as the distance between the center of the strap and the center of rotation of the respective joint. To calculate plantarflexion lever length, sagittal plane video was recorded synchronous to the force measurement at 60 Hz during the maximal voluntary contractions with a camera (Panasonic HC-V110; Panasonic, Kadoma, Japan) placed 4 m perpendicular to the movement plane, with the field of view maximized with optical zoom and markers on the knee joint, lateral malleolus, and lateral head of the fifth metatarsal. The corners of the force plate and ankle location were manually digitized, and ankle torque was calculated as the perpendicular distance from the normal force vector to the ankle joint center, multiplied by the magnitude of the normal force vector.

Statistical analysis. Muscle volume and strength measurements assessed on both legs were averaged to provide unilateral criterion values for each participant. Data are

presented as mean ± SD. The Shapiro–Wilk test was used to assess the normality of distribution and revealed that >90% of the variables were normally distributed, in which case we used parametric statistical tests to provide a consistent approach. One-way ANOVA and subsequent Bonferroni *post hoc* analysis were used to assess differences between groups for muscle volume (absolute, and relative to body mass), torque (absolute, and relative to body mass), and anthropometry. Statistical significance was set at $P < 0.05$. For the whole cohort of sprinters (i.e., elite and sub-elite groups combined, not including the control group), the bivariate relationships between SBE_{100} and measures of muscle volume and strength were assessed using Pearson's product moment correlation. Correlation coefficients were categorized 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–Hochberg (20) method with a false discovery rate of 5%, and the significance level was defined as adjusted $P < 0.05$. Stepwise multiple linear regression was used to calculate the variance in SBE_{100} explained by the best combination of variables in each of the following categories: absolute and relative muscle volume of individual muscles and muscle groups. In practice, based on their significant bivariate correlations with SBE_{100}, the following were entered into four distinct regression analyses for each of these categories of variables: (i) absolute volume of muscle groups (5 muscle groups), (ii) absolute muscle volume of individual muscles (18 specific muscles), (iii) relative volume of muscle groups (2 muscle groups), and (iv) relative volume of individual muscles (1 specific muscle). All statistical procedures were performed with IBM SPSS Statistics Version (IBM Corp., New York, NY).

RESULTS

Anthropometrics. Elite sprinters were similar in stature but heavier (>10 kg) than both sub-elite sprinters and untrained controls ($P = 0.006$ and $P = 0.013$ respectively; Table 1). Both sprint groups had a lower percentage body fat and sum of eight skinfolds compared with controls ($P \leq 0.01$). Fat-free mass was greater in elite sprinters than both sub-elite sprinters (>12 kg, $P \leq 0.01$) and controls (>16 kg, $P \leq 0.01$).

Comparison of absolute muscle volumes. The total unilateral volume of all the measured muscles was greater for both sprint groups vs controls (elite, +48%; sub-elite, +20%; both $P < 0.01$) and for the elite versus sub-elite sprinters (+24%; $P = 0.01$; Table 2). Elite sprinters had greater absolute muscle volume than sub-elite sprinters for four functional muscle groups (hip extensors, +32%; knee flexors, +24%; hip flexors, +23%; knee extensors, +22%; all $P \leq 0.01$; Fig. 1), but not the plantarflexors. Compared with controls, sub-elite sprinters had greater muscle volume of four functional muscle groups (+20%–34%, $P \leq 0.009$, except the plantarflexors; see Figure, Supplemental Digital Content 1, Percentage differences in absolute and relative muscle volumes between sub-elite sprinters vs controls, http://links.lww.com/MSS/C150). The functional muscle groups and individual muscles are ordered according to the magnitude of the percentage differences for absolute muscle volume), and elite sprinters were

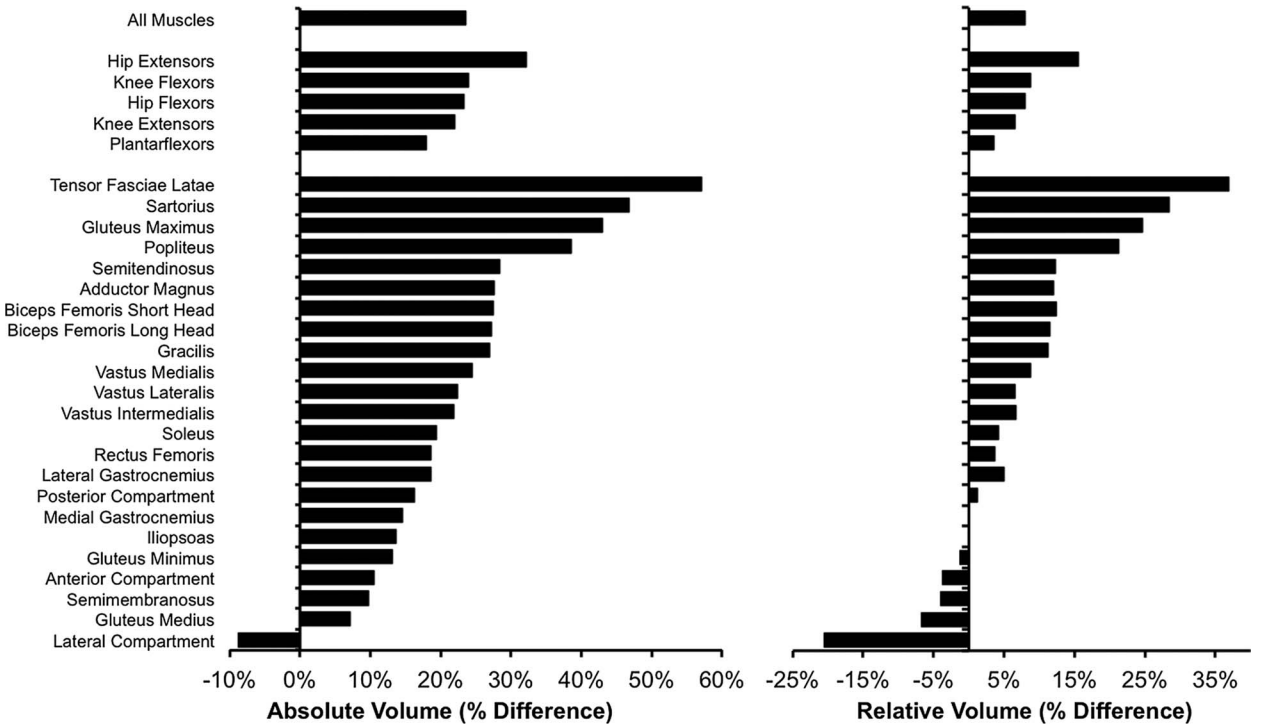

FIGURE 1—Percentage differences in absolute and relative muscle volumes of all muscles, five functional muscle groups, and 23 individual muscles/compartments between elite ($n = 5$) and sub-elite ($n = 26$) sprinters. A positive value indicates greater volume of elite sprinters. The functional muscle groups and individual muscles are ordered according to the magnitude of the percentage differences for absolute muscle volume.

larger in all five functional muscle groups (+29%–77%, all $P \leq 0.020$). When comparing the absolute volume of individual muscles/compartments between groups, there were nonuniform differences and pronounced anatomical specificity, e.g., elite vs sub-elite sprinters ranging from +57% (TFL) to −9% (lateral compartment of the shank). Eight individual muscles were larger in elite vs sub-elite sprinters (all $P \leq 0.035$): TFL (+57%), sartorius (+47%), gluteus maximus (+45%), adductor magnus (+28%), semitendinosis (+28%), biceps femoris long head (+27%), vastus medialis (+24%), and vastus intermedius (+22%). Furthermore, compared with controls, elite sprinters had 15 out of 23 muscles/compartments that were larger (+36%–106%, $P \leq 0.018$), and sub-elite sprinters had 10 muscles/compartments that were larger (+19%–60%, $P \leq 0.019$). In summary, for absolute muscle volumes, similar differences were noted for the two comparisons between sub-elite sprinters vs controls and elite vs sub-elite sprinters (see Table, Supplemental Digital Content 2, A summary table of the observed significant differences between sub-elite sprinters vs controls, and elite sprinters vs sub-elite sprinters, http://links.lww.com/MSS/C151).

Comparison of relative muscle volumes. Regarding relative muscle volume, the total volume of the measured muscles was greater in sprint groups vs controls (elite, +29%, $P < 0.001$; sub-elite, +20%, $P = 0.001$), but with no differences between the sprint groups ($P = 0.107$). The hip extensors were the only muscle group to differentiate elite from sub-elite sprinters based on relative muscle volume (+15%, $P = 0.003$), and the only individual muscles that had larger relative muscle volume in the elite vs sub-elite sprinters were the gluteus maximus (+25, $P \leq 0.001$), sartorius (+28%, $P = 0.013$), and TFL (+37%, $P = 0.032$). Compared with controls, both sprint groups had greater relative muscle volume of the flexors and extensors of the hip and knee (i.e., four muscle groups; +20%–54%; all $P \leq 0.001$), but there were no differences for the plantarflexors. In addition, in comparison with controls, the sprint groups had 13 (elite sprinters, +24%–77%) and 12 (sub-elite sprinters, +16%–58%) larger individual muscles relative to body mass. In summary, for relative muscle volumes, although there were many differences between sub-elite sprinters and controls, there were far fewer differences between elite and sub-elite sprinters (see Table, Supplemental Digital Content 2, A summary table of the observed significant differences between sub-elite sprinters vs controls, and elite sprinters vs sub-elite sprinters, http://links.lww.com/MSS/C151).

Relationships between sprint performance and muscle volumes. Among the whole sprint cohort, SBE_{100} showed moderate to strong correlations with absolute muscle volume of all the muscles combined ($r = -0.629$, $P < 0.001$), each of the five muscle groups ($r = -0.495$ to -0.689, $P \leq 0.05$; Table 3), as well as 18 out of 23 individual muscles/compartments ($r = -0.409$ to -0.662; all $P \leq 0.05$), i.e., only five individual muscles were not correlated with SBE_{100}. The highest correlations of absolute muscle volumes with SBE_{100} were the hip extensors from among the muscle groups ($r = -0.689$, $P < 0.001$) and the gluteus maximus from amongst the individual muscles ($r = -0.639$, $P < 0.001$; Fig. 2). Relative to body mass, the combined volumes of all the muscles ($r = -0.422$, $P = 0.036$), two muscle groups (hip extensors $r = -0.560$, $P = 0.005$, and knee flexors $r = -0.522$, $P = 0.006$), and only one individual muscle (gluteus maximus $r = -0.580$, $P = 0.014$) were moderately associated with SBE_{100} (Fig. 2). Two further individual muscle volumes relative to body mass, however, displayed a tendency to be moderately related to SBE_{100} (sartorius $r = -0.484$, $P = 0.066$; TFL $r = -0.454$, $P = 0.079$). The regression models revealed that only the single strongest predictor variable contributed to the explained variance in SBE_{100} within each category of predictor variables: absolute volume of muscle groups, hip extensors explained 47.5% of the variance in SBE_{100}; relative volume of muscle groups, hip extensors explained 31.4% of the variance; absolute volume of individual muscles, gluteus maximus explained 43.8% of the variance; and relative volume of individual muscles, gluteus maximus explained 33.6% of the variance.

TABLE 3. Pearson's product moment correlation coefficients between SBE_{100} and absolute and relative muscle volume of all muscles, five functional muscle groups, and 23 individual muscles in the whole cohort of sprinters ($n = 31$).

Muscle Group/Muscle	Absolute Muscle Volume (cm^3)	Relative Muscle Volume ($cm^3 \cdot kg^{-1}$)
All muscles	−0.629**	−0.422*
Hip flexors	−0.563**	−0.299
Hip extensors	−0.689***	−0.560**
Knee flexors	−0.682***	−0.522**
Knee extensors	−0.495**	−0.178
Plantarflexors	−0.537**	−0.309
Iliopsoas	−0.442*	−0.120
Sartorius	−0.639***	−0.484
TFL	−0.547**	−0.454
Adductor magnus	−0.582**	−0.289
Gracilis	−0.564**	−0.377
Gluteus maximus	−0.662***	−0.580*
Gluteus medius	−0.227	0.152
Gluteus minimus	−0.254	0.040
Rectus femoris	−0.409*	−0.090
Vastus lateralis	−0.475*	−0.199
Vastus intermedius	−0.443*	−0.154
Vastus medialis	−0.431*	−0.114
Semimembranosus	−0.478*	−0.194
Semitendinosus	−0.530**	−0.342
Biceps femoris long head	−0.475*	−0.190
Biceps femoris short head	−0.511*	−0.341
Popliteus	−0.435*	−0.260
Lateral gastrocnemius	−0.578**	−0.398
Medial gastrocnemius	−0.437*	−0.230
Soleus	−0.474*	−0.196
Anterior compartment	−0.272	0.092
Lateral compartment	−0.192	0.045
Posterior compartment	−0.290	0.014

Significant correlations: *$P \leq 0.05$, **$P \leq 0.01$, and ***$P \leq 0.001$, following correction for multiple comparisons.

Isometric strength. Sub-elite sprinters had greater absolute strength of the knee extensors (+26%, $P = 0.001$) and flexors (47%, $P = 0.005$) compared with controls, but with no differences in any other muscle groups. Elite sprinters showed a distinct pattern of differences compared with controls with greater absolute strength of the hip flexors (+55%, $P = 0.002$) and extensors (+63%, $P = 0.002$) and knee flexors (+62%, $P = 0.013$; Fig. 3). When relative torque was compared, sub-elite sprinters outperformed controls across all muscle

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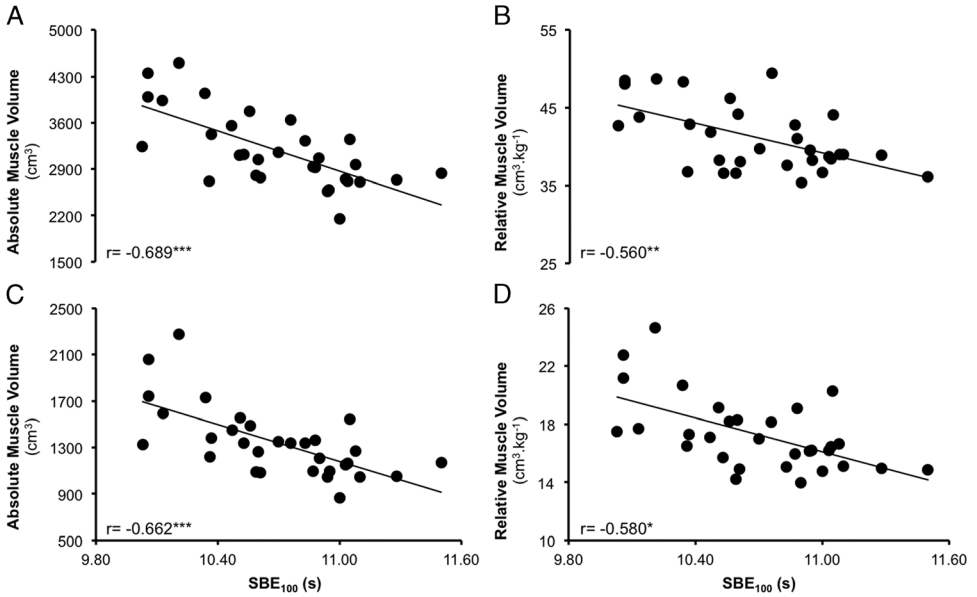

FIGURE 2—The relationships between SBE_{100} and absolute hip extensor volume (A); relative hip extensor volume (B); absolute gluteus maximus volume (C); and relative gluteus maximus volume (D). Significant correlations: *$P \leq 0.05$; **$P \leq 0.01$; and ***$P \leq 0.001$ following correction for multiple comparisons.

groups (mean difference + 34%, $P \leq 0.027$). Similar to absolute torque, the elite group produced greater relative torque than the controls during hip extension (+48%, $P = 0.002$), hip flexion (+40%, $P = 0.007$), and knee flexion (+49%, $P = 0.049$) than the controls. However, there were no differences observed in absolute or relative torque between elite and sub-elite sprinters across any of the five muscle groups (Fig. 3).

Absolute strength of all five muscle groups was unrelated to sprint performance. For relative strength, counterintuitively one muscle group, relative knee extensor strength, was positively correlated with SBE_{100} ($r = 0.485$, $P = 0.033$; i.e., greater knee extension torque, slower sprint time), but there were no relationships for other muscle groups ($r = -0.265$ to 0.139, $P > 0.105$).

DISCUSSION

The aims of this study were to compare the lower body muscle volumes and strength characteristics between a group of genuinely elite sprinters with sub-elite sprinters and untrained controls and to assess the relationships of these measures with sprint performance among sprinters. MRI analysis revealed that total lower body muscularity was distinct between all three groups (vs controls: sub-elite, +20%; elite, +48%), such that the elite sprinters had ~3.7 kg and ~2.2 kg of extra muscle mass per leg than controls and sub-elite sprinters, respectively. However, the differences in muscle volume between the groups were highly nonuniform with substantial anatomical specificity according to muscle group and especially individual muscle. For elite vs sub-elite sprinters, the largest muscle group–specific effects were found primarily for the hip extensors (differences of +32% absolute and +15% relative volume, explaining 47.5% [absolute volume] to 31.4% [relative volume] of the variability in performance) and secondarily for the knee flexors (differences of +24% absolute volume; performance correlations for absolute [$r = -0.682$] and relative [$r = -0.522$] volume), whereas the plantarflexors showed no differences between the sprint groups. Individual muscles showed even greater anatomical specificity with three muscles being larger in elite vs sub-elite sprinters in both absolute and relative terms (TFL: absolute, +57%; relative, +37%; sartorius: absolute, +47%; relative, +28%; gluteus maximus: absolute, +45%; relative, +25%), and the gluteus maximus alone explained 33.6% (relative volume) to 43.8% (absolute volume) of the variance in performance among sprinters. Although both sprint groups had stronger hip and knee muscle groups than controls, isometric strength did not differentiate between sprint groups and was unrelated to sprint performance. Therefore, this study provides novel and robust evidence highlighting the importance of specific morphological characteristics, principally hip extensor and gluteus maximus volume, for elite sprint running.

For the control group in this study, both muscle volume and knee joint muscular strength were comparable with previously published investigations using similar measurements in analogous populations (21–23). Both sprint groups demonstrated relatively large muscle volumes when compared with previous studies; however, comparison with previous literature is confounded by differences in performance standard, the inclusion of both male and female sprinters in some studies (5), and potential ethnic differences (7). The performance standards of the elite sprinters in this study ($n = 5$; SBE_{100}, 10.03–10.21 s; PBE_{100}, 9.91–10.08 s) were all faster than any previously studied individual sprinter or cohort (e.g., fastest personal best 10.23–11.71 s [4,7,9]). The sub-elite group in the current study (PBE_{100}, 10.34–11.24 s) was of a comparable, if not higher, performance standard to previous research. Hence, this

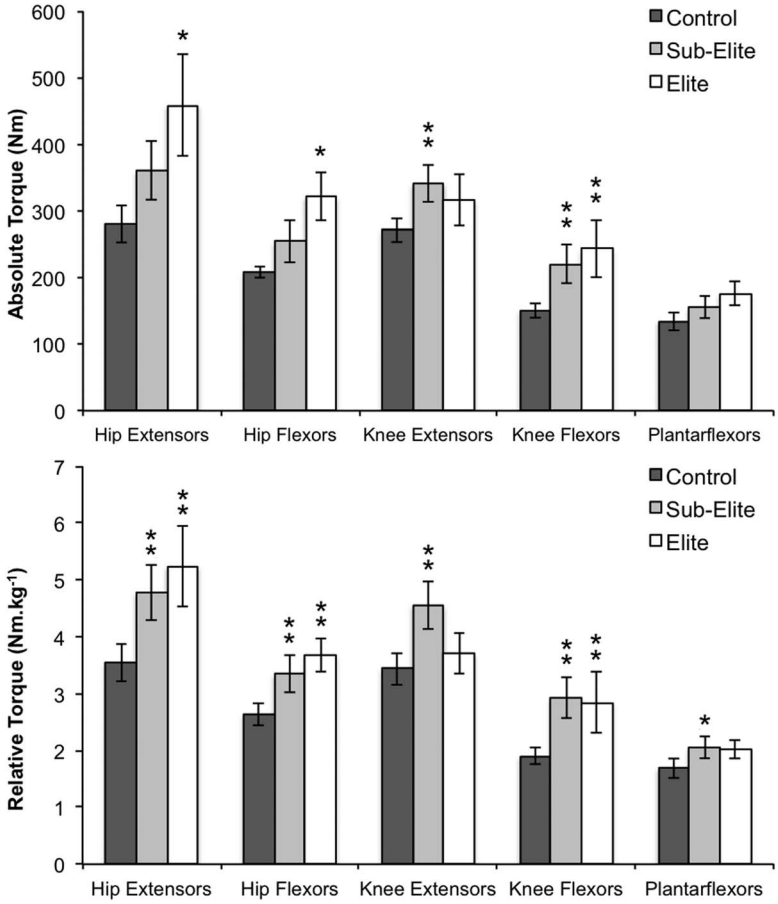

FIGURE 3—Comparison of absolute and relative isometric maximum voluntary torque of five functional muscle groups between elite (n = 5) vs sub-elite (n = 26) sprinters vs untrained controls (n = 11). Data are presented as group mean ± SD, with individual measurements the average of both legs. Significantly different to controls: *$P \leq 0.05$ and **$P \leq 0.01$.

appears to be the first comprehensive comparison of muscle morphology and strength between genuinely elite sprinters with sub-elite sprinters and controls.

Absolute muscle volume. Preliminary anthropometrics revealed that the three groups had similar stature and BMI. However, both sprint groups were leaner than controls, and the elite group was heavier (>11 kg) and had greater fat-free mass (>12 kg) than both the other groups. From the MRI analysis, the total muscle volume of all the muscles was distinct and progressively larger according to sprint performance (controls < sub-elite +20% < elite +48%) with elite sprinters having ~4.4 kg (vs sub-elite) and ~7.4 kg (vs controls) of extra muscle mass across both legs. These differences in lower limb muscularity are in accordance with, but more pronounced than, previous studies of sub-elite sprinters (5,7). The mechanistic reasons for the greater muscularity of elite > sub-elite > controls in the current study are not possible to discern from this investigation, although it seems likely that the sprint and resistance training history of the groups, which shows a similar pattern, would contribute to these differences in muscularity.

Furthermore, there was extensive anatomical variability in the magnitude of differences between muscle groups and particularly individual muscles/compartments. Specifically there were differences between all three groups (elite>sub-elite>controls) for four out of five muscle groups, with the greatest differences in hip extensors (sub-elite, +34%; elite, +77% vs controls) followed by the knee flexors (+27%; +58%), hip flexors (+27%; +57%), and knee extensors (+20%; +46%), but only the elite sprinters > controls for the plantarflexors (+29%). The broad pattern of these findings, with the largest differences in the hip and knee joint muscles but less pronounced differences for the ankle joint muscles, is in accordance with previous research comparing sub-elite sprinters with nonsprinters (4,5). The current study has extended those findings, with elite runners found to have particularly pronounced muscularity of the hip extensors and flexors, and knee flexors, and thus to our knowledge, this is the only research study to date highlighting the morphological characteristics important for elite-level sprinting. At running speeds >7.5 $m \cdot s^{-1}$, there appears to be a disproportionate requirement for power generation by the hip flexors, hip extensors, and knee flexor muscle groups (24). Biomechanically, the hip extensors are primarily responsible for the back swing of the legs during stance (25), and both the hip extensor and the

knee flexors facilitate the application of horizontal forces to the ground (26), and thus these muscle groups are considered critical for propulsion (27). However, the hip flexors are thought crucial to the rapid acceleration of the legs during swing phase to achieve high stride frequencies (24,28). From this perspective, it is logical that elite sprinters would be larger in these muscle groups.

Individual muscle differences between the groups showed pronounced anatomical specificity with the muscles of elite vs sub-elite sprinters ranging from +57% (TFL) to −9% (lateral compartment of the shank). Elite sprinters had 8 out of 23 larger muscles/compartments versus sub-elite (+22%–57%: TFL, sartorius, gluteus maximus, semitendinosus, adductor magnus, biceps femoris long head, vastus intermedius, and vastus medialis), with 6 of these being hip muscles. Furthermore, both sprint groups had 10 (sub-elite, +20%–47%) and 15 (elite, +35%–115%) larger muscles/compartments than controls. Strikingly, among the sprinters total muscle volume, the volume of all five muscle groups and 18/23 individual muscles were all found to be related to SBE_{100} (i.e., greater volume, faster sprint time). However, strong relationships ($r > 0.60$), and in fact the highest correlations in this study, were observed between SBE_{100} and volume of the hip extensor ($r = -0.689$) and knee flexor muscle groups ($r = -0.682$) as well as two constituent muscles from within these groups (gluteus maximus $r = -0.662$; and sartorius $r = -0.639$). The largest previous study of muscle morphology in sub-elite sprinters also reported the absolute volume of 4/12 individual muscles, including the gluteus maximus and hamstrings, to be related to 100 m time (r = 0.37–0.42 [7]). Inclusion of elite-level sprinters in the current investigation and the somewhat higher average performance standard of our cohort (10.71 vs 10.94 s [7]) might explain the more pronounced relationships we have found. Subsequently, regression analyses revealed that the absolute volume of the hip extensors explained 47.5% and gluteus maximus 43.8% of the variance in sprint running performance, respectively. Given the multifactorial nature of sprint running performance, widely considered to depend on an array of anatomical, biomechanical, physiological, technical, and psychological variables (29), the apparent importance of these specific muscle morphology characteristics in explaining >40% of the variance in performance is remarkable.

Overall, these findings highlight the importance of the absolute size of specific muscle groups (primarily the hip extensors and secondarily knee flexors) and muscles (gluteus maximus and sartorius) for sprint performance. The consistency of our findings/differences between sub-elite sprinters versus controls and elite sprinters versus sub-elite sprinters for absolute muscle volumes (see Table, Supplemental Digital Content 2, A summary table of the observed significant differences between sub-elite sprinters vs controls, and elite sprinters vs sub-elite sprinters, http://links.lww.com/MSS/C151), and the most distinct muscle groups/muscles explaining substantial proportions of the variance in sprint performance, reinforces the apparent veracity of these findings. The primary importance of the hip extensors (the largest muscle group differences for both elite vs sub-elite, +32%, and sub-elite vs controls, +34%, explaining 47.5% of the variance in SBE_{100}) and gluteus maximus (greater for both elite vs sub-elite, +45%, and sub-elite vs controls, +35%, explaining 43.8% of the variance in SBE_{100}) are original findings. Previous literature has reported contradictory findings for the primary importance of various muscle groups and muscles (4,6,8–10), without highlighting the importance of the hip extensors and gluteus maximus. These investigations typically used smaller numbers (n = 8–16) of sub-elite sprinters (fastest individual 100-m personal best = 10.33 s) and have performed less comprehensive morphological analyses (i.e., a limited number of lower body muscles). As discussed above, given the key role of the hip extensors and gluteus maximus in propulsion (25,26), it is surprising that until now there has been little empirical evidence to support their importance for sprint running performance.

The importance of absolute muscularity would certainly be expected to be beneficial for absolute power production given the strong association of these variables (R^2 ~0.80 [2]), but it may be surprising given that sprint running has often been considered to depend on power per unit body mass (i.e., relative muscle volume [30]). However, theoretical analysis has shown that among runners of similar stature, having greater absolute muscle mass is biologically necessary to attain faster sprinting speeds (31). The current experiment adds to the data indicating that absolute muscularity, particularly of key muscle groups and individual muscles, is highly important for sprint running performance. Although it seems unlikely, an alternative possibility is that the elite sprinters in this study were coincidentally larger, and therefore the apparent abundance of differences between groups and associations with sprint performance we have observed for absolute muscle volumes could be an artifact of their coincidentally greater body mass. In this case, relative muscle volume (per kilogram) facilitates body mass–independent comparisons, without this potential confounding difference in body mass between the groups.

Relative muscle volume. Relative muscle volume was greater for both sprint groups compared with controls for the flexors and extensors of the hip and knee. For individual muscles, the differences in relative muscle volume also showed marked anatomical variability/specificity between the three groups (e.g., elite vs sub-elite; range, +37% TFL to −21% lateral compartment of the shank). Interestingly, however, only one muscle group (hip extensors, +15%) and three individual muscles (gluteus maximus, +25%; sartorius, +28%; and TFL, +37%) were larger in the elite vs sub-elite sprinters. The TFL and the sartorius have been highlighted as having large differences in volume between sprinters and controls (5), but this is the first study where these muscles have been found to be relatively larger in elite vs sub-elite sprinters. Although these muscles have received very little attention to date with regard to their influence on sprint performance, both the TFL and the sartorius are key contributors to hip flexion (32). In addition, the sartorius is the only simultaneous knee and hip flexor (33), an important combination of actions in changing limb

momentum from down and back at the end of stance, to upward and forward during swing, and therefore may be important for early swing phase mechanics and thus sprint performance (5,25).

Furthermore, strong relationships were observed between the SBE_{100} and the relative muscle volume of the hip extensor ($r = -0.560$) and knee flexor ($r = -0.522$) muscle groups, and specifically in only one individual muscle (gluteus maximus $r = -0.580$). Consequently, separate regression analyses for muscle groups and individual muscles revealed that the relative volume of the hip extensors explained 31.4% and gluteus maximus 33.6% of the variance in sprint performance, respectively. During sprint running, the gluteus maximus is activated from late swing phase to midstance (26), accelerating the leg underneath the body (34) and making a major contribution to the generation of propulsive forces along with the hamstring muscles (26,35). Thus, greater gluteus maximus volume would be expected to facilitate greater propulsion forces and, therefore, greater sprinting speeds. It is interesting that the gluteus maximus, the largest individual muscle in the human body, appears to be particularly important for fast running. The biologically expensive process of developing a large gluteus maximus represents a significant evolutionary investment that presumably confers an advantage for survival. It is possible that the role of the gluteus maximus in facilitating humans to run fast explains the evolution of the gluteus maximus as the largest muscle in the human body.

Isometric strength. The elite sprinters (absolute and relative 3/5 muscle groups [hip extensors and flexors, and knee flexors] and sub-elite sprinters (absolute 2/5 [knee flexors and extensors]; relative 5/5 muscle groups) were stronger than controls. Because of the observed sprint and resistance training history of the sprint groups, and their greater muscle volume, it is unsurprising that both sprint groups were found to be stronger than controls in several muscle groups. Unexpected findings of this study were that no strength measurements for any muscle group were discriminatory between sprint groups or negatively associated with sprint performance. This contrasts with previous research demonstrating that measures of isokinetic hip flexion strength were related to aspects of sprint performance (14). Furthermore, the speculated importance of hip extension and plantarflexion force during the stance phase (24,26) and hip flexion force during swing phase (24,28) for fast running might also make the current results surprising. However, task/contraction specificity may be an important factor influencing the association between strength/power of the hip muscles and sprint performance (6). Therefore, the findings of this study could be a consequence of a lack of specificity between the isometric strength measures of the current study and the dynamic nature of sprint running (36). It is acknowledged, however, that isometric strength was only measured on one occasion and with no familiarization because of the difficulty in recruiting elite-level sprinters for even a single assessment session. Although the protocol was clearly the same for all three groups, this may have introduced some noise into the data potentially, reducing the likelihood of finding more subtle differences between groups, especially given the small sample size of the elite sprint group ($n = 5$).

No strength measures were found to be related to faster sprint performance, although a counterintuitive finding was the positive relationship between relative knee extensor strength and SBE_{100} ($r = 0.485$; i.e., the greater the torque, the slower the sprint time). Previous contrary reports include a negative correlation (37) or no relationship (38) between knee extensor strength and sprint performance in team sports players, rather than the elite-level and the sub-elite sprinters of the current study. In addition, work by Dorn and colleagues (24) found that the force requirement of the vastii plateaus as running velocity increases past 5 $m \cdot s^{-1}$, perhaps suggesting that knee extensor torque is not a particular limitation of fast running.

Limitations. There are some limitations associated with the present investigation. First, for some of the sub-elite sprinters (7/26), SBE_{100} was an estimation based on their superior IAAF points at either 60 or 200 m and as such may have overestimated their 100-m performance. However, the difference in group sprint performance time as a result of this estimation was trivial, and this method ensured that the best sprint performance for each individual was used consistently. Second, there was a temporal separation between the performance (i.e., SBE_{100}) and the laboratory morphology and strength measurements within this study. Although this is clearly a potential confounder that might have reduced the strength of the effects we have observed, the continuity of training in the sprint groups would have reduced the likelihood of large differences in muscle volume or strength between the dates of laboratory assessment and the sprint performance. Third, it may be argued that the use of isometric force lacks specificity in relation to sprint running (39), where the joint angular velocities can be very high (e.g., knee extension at ~850°·s^{-1} [1]). However, the aim of the current study was to accurately assess the isolated strength of five distinct functional muscle groups (i.e., individual joint torques), given the paucity of data on the function, and particularly comparative strength, of these muscle groups in sprinters versus controls. Isometric measurements are also known to be highly reliable, sensitive, and relatively easy to conduct and also require limited familiarization time (36). In contrast performing these isolated muscle group measurements dynamically, especially at high velocity, in a consistent and reliable manner would be highly challenging. Finally, the cross-sectional nature of this study means that definitive cause and effect relationships remain unknown. However, on the basis of the pronounced differences and relationships we have observed, and the logical rationale for the importance of the muscle groups (hip extensors and knee flexors) and individual muscles (gluteus maximus) identified, it seems likely that there is a large causal component to these relationships.

Practical summary and implications. The extensive differences in muscle morphology between elite and sub-elite sprinters and the strength of the relationships we have observed have clear implications for coaches and practitioners.

Although overall muscularity appeared important for performance (all muscles: absolute volume + 24% for elite vs sub-elite; performance correlations for absolute [$r = -0.629$] and relative [$r = -0.422$] volume), this belied the fact that there were highly variable and nonuniform effects for specific muscle groups and muscles. The largest muscle group–specific effects were found primarily for the hip extensors (differences of +32% absolute and +15% relative volume; explaining 47.5% [absolute volume] to 31.4% [relative volume] of the variability in performance) and secondarily for the knee flexors (differences of +24% absolute volume; performance correlations for absolute [$r = -0.682$] and relative [$r = -0.522$] volume), whereas the plantarflexors showed no differences between the sprint groups. This evidence strongly supports the idea that developing large hip extensors and knee flexors, for example, through resistance training, would be valuable for the sprint athlete looking to enhance performance (27).

For absolute muscle volumes, very similar factors differentiated both sub-elite sprinters from controls as well as elite versus sub-elite sprinters (e.g., total muscle volume, four muscle groups in the same order of magnitude, and five individual muscles; see Table, Supplemental Digital Content 2, A summary table of the observed significant differences between sub-elite sprinters vs controls, and elite sprinters vs sub-elite sprinters, http://links.lww.com/MSS/C151), indicating that the progressive development of these same variables may continuously improve performance up to elite level. By contrast, for relative volumes, although a wide range of factors distinguished sub-elite sprinters from controls, elite sprinters were differentiated by only four variables (volume of the hip extensor muscle group, TFL, sartorius, and gluteus maximus), indicating that a more targeted development may be needed for elite performance. Moreover, the need for targeted hypertrophy even within muscle groups is emphasized by the individual muscle findings with three muscles being larger in elite vs sub-elite sprinters in both absolute and relative terms (TFL: absolute, +57%; relative, +37%; sartorius: absolute, +47%; relative, +28%; gluteus maximus: absolute, +45%; relative, +25%) with the gluteus maximus alone explaining 33.6% (relative volume) to 43.8% (absolute volume) of the variance in performance among sprinters. However, our knowledge of the exercises needed to facilitate hypertrophy of these individual muscles (TFL, sartorius, and gluteus maximus) is relatively limited. Given the greater sprint training experience of the elite group in this study, it is also possible that regular, prolonged sprint training may stimulate many of the morphological characteristics we have observed (40).

CONCLUSION

In conclusion, this investigation highlights for the first time the importance of highly inhomogeneous muscularity, with a specific pattern of distribution for elite sprint running performance compared with sub-elite sprinters and controls. Specifically, this experiment revealed for the first time that the hip extensors of elite sprinters were of a greater absolute and relative size and both these measurements were related to performance, such that hip extensor absolute volume explained 47.5% of the variability in sprint running performance. Individual muscles showed particularly pronounced differences in the muscle distribution of elite sprinters, with three hip muscles (TFL, sartorius, and gluteus maximus) consistently larger in absolute and relative terms, and the absolute volume of the gluteus maximus alone explained 43.8% of the variance in sprint performance. Based on this novel evidence, it is therefore recommended that coaches and athletes be attentive to the development of muscle volume in these specific lower body muscles to enhance sprint running performance.

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

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