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Discriminant musculo-skeletal leg characteristics between sprint and endurance elite Caucasian runners

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Excellence in either sprinting or endurance running requires specific musculo-skeletal characteristics of the legs. This study aims to investigate the morphology of the leg of sprinters and endurance runners of Caucasian ethnicity. Eight male sprinters and 11 male endurance runners volunteered to participate in this cross-sectional study. They underwent magnetic resonance imaging and after data collection, digital reconstruction was done to calculate muscle volumes and bone lengths. Sprinters have a higher total upper leg volume compared to endurance runners (7340 vs 6265 cm^3). Specifically, the rectus femoris, vastus lateralis, and hamstrings showed significantly higher muscle volumes in the sprint group. For the lower leg, only a higher muscle volume was found in the gastrocnemius lateralis for the sprinters. No differences were found in muscle volume distribution, center of mass in the different muscles, or relative bone lengths. There was a significant positive correlation between ratio hamstrings/quadriceps volume and best running performance in the sprint group. Sprinters and endurance runners of Caucasian ethnicity showed the greatest distinctions in muscle volumes, rather than in muscle distributions or skeletal measures. Sprinters show higher volumes in mainly the proximal and lateral leg muscles than endurance runners.

The question whether a runner is more suited for sprint vs endurance disciplines and whether he has the talent to obtain national or even international top level, depends in part on the musculo-skeletal characteristics of the legs. Some of these characteristics are almost entirely dependent on genetic predisposition and some are additionally trainable in a certain direction. A main limiting factor for sprinting is power generation, which is directly related to muscle fiber type and muscle volume (Mero et al., 1992; Young et al., 1995). The latter may likely influence the inertial properties of the limb segments. On the other hand, endurance running is characterized by a high muscle oxidative capacity and an excellent running economy, influenced by several factors, such as reduced inertia of the legs (Weyand & Davis, 2005). According to these limiting factors, runners that excel in either sprinting or endurance running should have divergent musculo-skeletal leg characteristics.

This study will provide a direct and extensive morphological comparison between sprint and endurance runners within a single ethnic group (Caucasian), conducted with combined magnetic resonance spectroscopy (MRS) and magnetic resonance imaging (MRI)-based analyses. A first, already well-known, discriminant relevant for sprinting vs endurance running is muscle fiber type composition. Classical studies in the 70s (Gollnick et al., 1972; Costill et al., 1976) indicated that elite level in endurance and sprint running is characterized by a high and low percentage of slow-twitch (type I) fibers, respectively, in the gastrocnemius muscle. In this study, muscle carnosine concentrations were measured by proton magnetic resonance spectroscopy (^{1}H-MRS) to indirectly estimate muscle fiber type composition (Baguet et al., 2011).

A second potential discriminant is muscle volume, which is a dominant determinant of power generation (Bamman et al., 2000; Trappe et al., 2001). For this reason, it can be hypothesized that sprinters should have higher muscle volumes, at least in some critical muscles, particularly recruited during the acceleration phase of sprint running. Abe et al. (2000) showed greater muscle thickness in upper portion of the anterior thigh, but not in the lower portion (70% thigh length) for sprinters compared to endurance runners, which could be a reflection of differences in muscle shape of the upper leg. These data were confirmed by Kumagai et al. (2000) within a population of sprinters, with a greater muscle thickness in the upper thigh (both quadriceps and hamstrings) in the best sprinters. It has been suggested that muscle shape (thicker upper portion of quadriceps and hamstrings) is associated with better sprint performance (Abe et al., 1999, 2000; Kumagai et al., 2000). Also high power of ankle plantar flexors (calf muscles) is required for generating high ground-reaction forces during sprinting (Mero et al., 1992). Endurance running performance, by contrast, is probably hampered by high volumes of the lower leg, because a good mechanical efficiency (economy) is aided by a leg morphology which distributes mass closer to the hip joint, inducing smaller inertia during the swing phase (Saunders et al., 2004).

In addition, the relative contribution of the sizes of the different muscles within the total leg muscle volume in sprinters vs endurance runners is poorly understood. More detailed analyses are essential to complete our knowledge of the different muscle and muscle groups to explore the difference between sprinters and endurance runners (e.g., medial vs lateral, lower leg vs upper leg, anterior vs posterior).

This study aims to directly compare the physiological and functional anatomical characteristics of the leg of male sprinters and endurance runners of Caucasian ethnicity in order to discover the largest discriminants.

Methods

Subjects

Eight male sprinters (60 m indoor – 200 m) and 11 male endurance runners (3000–5000 m) volunteered to participate in this cross-sectional study. All athletes were competing in major Belgian national and/or international running competitions. The runners were classified based on their best running performance according to the International Amateur Athletic Federation (IAAF) scoring system. This IAAF classification allows intra- and inter-individual comparisons of performance obtained in different events. The best IAAF score of each runner was used as the individual running performance. Personal best performances ranged between 6.95 and 7.07 s for 60 m or 10.68 and 10.99 s for 100 m in sprinters and 7.54 and 8.53 min for 3000 m or 13.32 and 14.55 min for 5000 m in endurance runners. Personal best performances were reached within 2 years before or after the measurement and none of the athletes was long-term injured in the last year before the measurement. A four-site skinfold test (biceps, triceps, subscapula, and suprailiac) was used to calculate the body fat percentage using the Durnin and Womersley (1974) table. The study was approved by the local ethical committee (Ghent University Hospital, Ghent, Belgium) and all subjects gave their written informed consent.

MRI

Axial spin-echo T1-weighted MR images were acquired of both legs simultaneously while subjects lay supine in a 3-T whole body MRI scanner (Siemens Trio, Erlangen, Germany). Images were collected using a repetition time of 9.64 ms, echo time of 2.45 ms, and slice thickness of 1.20 mm. A matrix size of 440 × 269 mm was used for all scans. Three overlapping series (a total of 224 slices) covered a field of view starting proximally at the iliac crest and running down to the distal part of the calcaneus. After data collection, the MR images were transferred to 3D slicer for digital reconstruction.

Two-dimensional measurements

The 3D Slicer software version 3.6 (www.slicer.org; an open source software; Brigham and Womens Hospital, Boston, MA) was used to measure length of thigh, shank, and leg length. *Thigh length* was defined as the distance between the tips of greater trochanter and lateral condyle of the femur (Fig. 1a). *Shank length* was defined as the distance between the medial condyle of the tibia to the tip of the medial malleolus (Fig. 1a). *Leg length* was defined as the distance between the tip of greater trochanter of femur to the tip of the medial malleolus of the tibia.

Three-dimensional measurements

The MRI images were displayed and manually segmented into anatomically significant structures. Muscle volumes

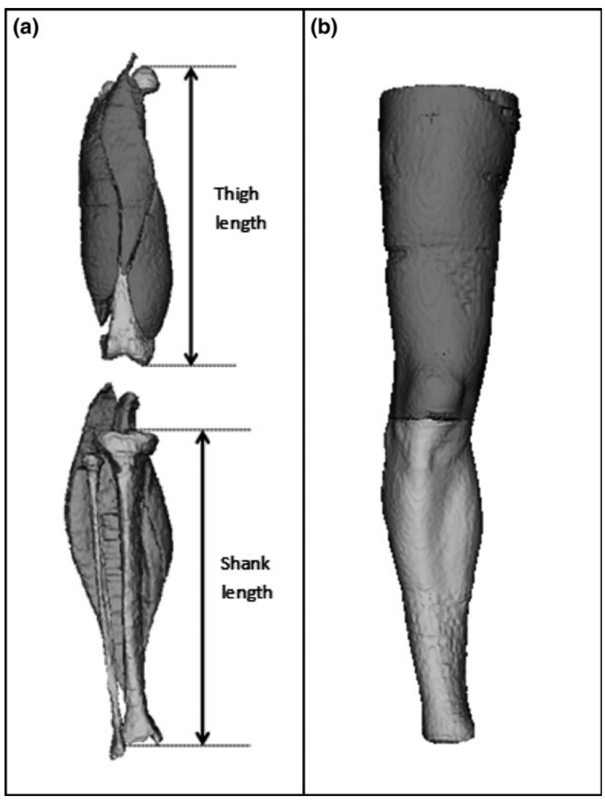

Fig. 1. 3D reconstructions of upper and lower leg with the different muscles (a) and total leg (b). Thigh length and shank length are defined (right leg, ventral view).

were measured using the LabelStatistics module of Slicer 3.6, after manually selecting the muscles on transverse slices (the contrast of muscle tissue is too low for fully automatic segmentation). Figure 2 demonstrates how the different muscles were determined on a axial slice in upper leg (Fig. 2a) and lower leg (Fig. 2b) and on a coronal slice (Fig. 2c). The volume measurements for the muscles were expressed in centimeters cubed (cm^3). We focused on the major flexor and extensor muscle groups. The seven muscles or muscle groups traced were the vastus lateralis and intermedius (VL + VI), vastus medialis (VM), rectus femoris (RF), hamstrings (HAMSTR) (semimembranosus, semitendinosus, biceps femoris long head, biceps femoris short head), gastrocnemius medialis (GM), gastrocnemius lateralis (GL), and soleus (SOL). Total upper leg volume (combined bone and muscle volume) was defined from the tip of the pelvis to the tip of the lateral condyle of the femur (Fig. 1b). Total lower leg volume (combined bone and muscle volume) was defined from the tip of the tibia to the tip of the medial malleolus of the tibia (Fig. 1b). The open source software pyFormex was used to determine moments of inertia. Due to the lack of direct measurements of the tissue densities, we first computed the homogenized density y^i_{home} with i being the index identifying upper and lower leg. Calculation was based on one subject from which both bone and entire limb surfaces were segmented. All muscles were assumed to have the same density (γ_{musc} = 1059.7 kg/m^3) (Mendez & Keys, 1960). The apparent density of the bones was also taken from literature (γ_{bone} = 1700 kg/m^3) (Nigg & Herzog, 1994). All centers of mass (COM) were computed on the volume embedded by each surface. Each volume was filled with tetrahedrons, so the center of mass can be calculated by the centroids of each element weighted on the volumes. The inertia I_{limb} was computed with respect to a transverse axis through the center of mass of each limb assumed fully filled with muscles from which we then subtracted the inertia I_{bone} of the bone geometry having a fictitious density equal to the difference between the muscles density and the apparent density of the bone $\gamma^*_{bone} = \gamma_{bone} - \gamma_{musc}$.

Determination of muscle carnosine content

Carnosine content was measured in SOL and GM by ^{1}H-MRS, as previously described by Baguet et al. (2010). These muscles were chosen because carnosine in the calf muscles could be determined by ^{1}H-MRS, which is not the case for upper leg muscles. The subjects were lying in supine position and the lower leg was fixed in a spherical knee coil. All the measurements were performed on a 3-T whole body MRI scanner (Siemens Trio, Erlangen, Germany). Single voxel point-resolved spectroscopy (PRESS) sequence with the following parameters was used: repetition time (TR) = 2000 ms, echo time (TE) = 30 ms, number of excitations = 128, 1024 data points, spectral bandwidth of 1200 Hz, and a total acquisition time of 4.24 min. The average voxel size for SOL and GM was 40 × 12 × 30 mm and 40 × 12 × 30 mm, respectively. Following shimming procedures, the linewidth of the water signal was on average 24.0 and 25.5 Hz for SOL and GM, respectively. The absolute carnosine content (mM) was calculated as described before by Baguet et al. (2010).

Statistics

An independent sample T-test was performed to compare the different parameters between the sprinters and endurance runners. Pearson correlation was calculated between the IAAF scores and the different parameters. Z-scores of all parameters were calculated based on the mean and standard deviation of the total group (sprinters and endurance runners together). All analyses were done with SPSS statistical software (SPSS 21, Chicago, Illinois, USA). All values are reported as mean ± SD and statistical significance was set at $P < 0.05$.

Results

Anthropometric characteristics

Sprinters and endurance runners were similar in performance level (IAAF score) and body height, but

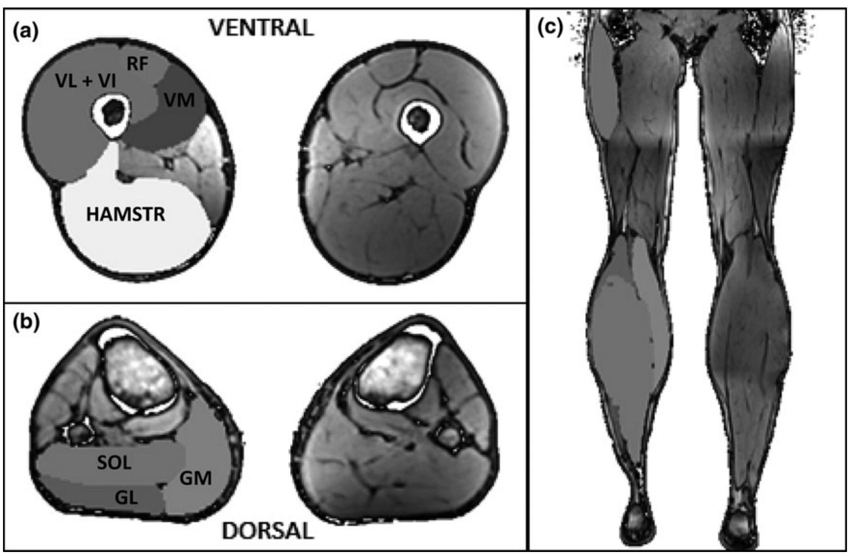

Fig. 2. Axial slice in upper leg (a) and lower leg (b) and coronal slice of total leg (c, dorsal view). VL + VI, vastus lateralis and intermedius; RF, rectus femoris; VM, vastus medialis; HAMSTR, hamstrings; SOL, soleus; GM, gastrocnemius medialis; GL, gastrocnemius lateralis.

the sprinters' body mass, BMI, and fat percentage were higher (Table 1). As indicated in Table 2, sprinters and endurance runners showed no differences in length of neither the body segments thigh and shank, nor the total leg. The ratio of these body segments to body height and the ratio of thigh and shank length to leg length were similar in both groups. Due to a comparable body height and comparable body segments lengths, there was no need to normalize other parameters to body height and further analyses could be done with absolute values.

Muscle volumes parameters

The total upper leg volume was significantly higher for the sprinters compared to the endurance runners (17%, $P = 0.002$). Specifically, the RF, VL + VI, and HAMSTR showed significantly higher muscle volumes (Table 3A). The RF contributed to an average 11%, the VL + VI 44%, the VM 16%, and the HAMSTR 29% of the total analyzed thigh muscle volume, with no differences between the two groups. Center of mass (COM) was defined in the direction of gravity and expressed in percentage of the total leg length. COM of the different muscles of the upper leg showed no differences between the groups (Table 3A).

Table 1. Physical characteristics and running performance

	Sprinters ($n = 8$)	Endurance runners ($n = 11$)
Age (year)	23.6 ± 4.2	23.5 ± 3.7
Height (cm)	178.0 ± 5.6	180.4 ± 3.5
Body mass (kg)	74.8 ± 6.4	64.0 ± 4.7*
Body mass index	23.6 ± 1.8	19.7 ± 1.2*
Fat percentage (%)	9.0 ± 1.5	7.2 ± 1.9†
Running performance (IAAF score)	984.6 ± 77.4	1013.2 ± 107.2

Data are means ± SD.
*$P < 0.05$ vs sprinters; †P = between 0.05 and 0.10 vs sprinters.

Table 2. Body segments and ratio of different body segments

	Sprinters ($n = 8$)	Endurance runners ($n = 11$)
Leg length (cm)	86.4 ± 4.3	87.6 ± 2.3
Length thigh (cm)	47.2 ± 2.7	48.1 ± 1.2
Length shank (cm)	39.6 ± 2.0	40.0 ± 1.3
Ratio leg length/height	0.485 ± 0.012	0.486 ± 0.011
Ratio length thigh/height	0.265 ± 0.008	0.267 ± 0.006
Ratio length shank/height	0.222 ± 0.007	0.222 ± 0.006

Data are means ± SD.

Table 3B shows the data of the lower leg. Sprinters had a significantly higher muscle volume in the GL (21%, $P = 0.017$) and a tendency to a higher muscle volume in SOL (17%, $P = 0.091$) compared to endurance runners. Total lower leg volume and GM volume were similar in both groups. No differences were found in muscle distribution or COM in the different muscles of the lower leg. The percentage differences between sprinters and endurance runners in the different muscles volumes were 26% for RF, 23% for VL, 21% for GL and HAMSTR, 17% for soleus, 14% for VM, and 9% for GM. The transverse moment of inertia of the lower leg at knee joint and the upper leg at hip joint were not significantly different between sprinters and endurance runners [0.13 ± 0.02 vs 0.12 ± 0.02 kg/m^2, $P = 0.102$ (lower leg) and 0.59 ± 0.10 vs 0.52 ± 0.07 kg/m^2, $P = 0.105$ (upper leg)].

Table 3. Muscle volumes, ratios, and center of mass (COM) of upper leg (A) en lower leg (B). Ratios were expressed in percentage of the total analyzed thigh volume (RF, VL + VI, VM, and HAMSTR). COM was defined in the direction of gravity and expressed in percentage of the total leg length

A	Upper leg	Sprinters ($n = 8$)	Endurance runners ($n = 11$)
Volume (cm^3)	RF	372.92 ± 27.58	295.10 ± 44.97*
	VL + VI	1478.25 ± 172.05	1204.48 ± 159.92*
	VM	530.80 ± 88.02	464.64 ± 77.43
	HAMSTR	966.83 ± 132.08	799.31 ± 117.92*
	Total volume	7339.67 ± 652.04	6265.06 ± 584.53*
Ratio (%)	RF	11.23 ± 1.24	10.74 ± 1.67
	VL + VI	44.14 ± 1.77	43.59 ± 2.06
	VM	15.79 ± 1.33	16.77 ± 1.43
	HAMSTR	28.83 ± 1.95	28.91 ± 2.04
COM (%)	RF	23.73 ± 3.74	23.06 ± 2.33
	VL + VI	30.68 ± 4.06	30.32 ± 2.00
	VM	35.51 ± 4.20	35.38 ± 2.35
	HAMSTR	36.48 ± 3.96	36.26 ± 1.78
	Total volume	37.29 ± 3.76	36.87 ± 2.03
B	**Lower leg**	**Sprinters ($n = 8$)**	**Endurance runners ($n = 11$)**
Volume (cm^3)	SOL	496.46 ± 76.29	424.91 ± 92.05†
	GM	281.88 ± 60.18	259.14 ± 52.45
	GL	206.20 ± 32.15	170.08 ± 27.49*
	Total volume	2815.89 ± 195.14	2662.31 ± 302.09
Ratio (%)	SOL	50.45 ± 4.28	49.56 ± 3.54
	GM	28.55 ± 3.66	30.42 ± 3.59
	GL	21.00 ± 2.48	20.01 ± 1.23
COM (%)	SOL	82.01 ± 2.82	82.26 ± 1.76
	GM	69.73 ± 3.57	69.65 ± 1.89
	GL	67.86 ± 3.67	67.83 ± 1.67
	Total volume	83.28 ± 2.99	83.83 ± 1.57

Data are means ± SD.
*$P < 0.05$ vs sprinters; †P = between 0.05 and 0.10 vs sprinters.

There were significant positive correlations between ratio HAMSTR/QUADS muscle volume and IAAF scores in the sprint group ($R = 0.811$, $P = 0.015$) and in the group with all athletes together ($R = 0.532$, $P = 0.019$), but no correlation was found in the endurance group alone.

Muscle carnosine concentration

Muscle carnosine concentration was approximately 60% higher in sprinters compared to endurance runners for SOL (5.74 ± 2.14 vs 3.62 ± 0.94 mM, $P = 0.035$) and for GM (10.82 ± 2.57 vs 6.61 ± 1.15 mM, $P = 0.002$).

Figure 3 shows all individual *Z*-scores of sprinters and endurance runners on the different musculo-skeletal parameters, with muscle carnosine in GM as the most discriminant feature.

Discussion

Excellence in sprint or endurance running requires specific musculo-skeletal properties of the leg. At cellular level, it is well known that skeletal muscles of sprinters are characterized by a high percentage fast-twitch fibers and that endurance runners possess a high proportion of slow-twitch fibers. In this study, muscle carnosine concentration, as indirect estimation of percentage area occupied by type II fibers (Baguet et al., 2011), was 60% higher in sprinters. However, the question remains at macroscopic morphological level, which of the characteristics are specifically divergent between sprint and endurance runners.

In sprinting, the determining factor for performance is power production, which is regulated by the combination of force and velocity (Mero et al., 1992). To optimize power generation, the muscles specifically recruited during sprint running should be primarily developed, with greater volumes as result. This is in contrast to endurance running where lower volumes in upper and lower leg were expected to ensure low energy cost for the swinging phase. The results of this study showed indeed higher muscles volumes in the sprint specific muscles (e.g., VL + VI, RF, HAMSTR), which resulted in higher total upper leg volume. However, at individual muscle level no differences were found in VM. This is in contrast to the results in the study of Kubo et al. (2011) who found greater thickness of the medial side of the knee extensors, but this was compared to untrained subjects. It has been suggested that the VM muscle among the knee extensor muscles is important for stabilizing functions both during sprinting and endurance running (Toumi et al., 2007). The VL is a more power delivering muscle, suggesting an important role for this muscle during sprinting and therefore the VL is more distinguished between sprinters and endurance runners than the VM.

Furthermore, a significantly higher GL and a clear trend for larger volume in SOL was found in the lower leg, but with surprisingly no significant greater total lower leg volume between sprinters and endurance runners. A possible explanation for finding no differences in total lower leg volume between these athlete populations is that both sprint and endurance running require optimal muscle volumes in the lower leg with a positive effect toward power delivering (Mero et al., 1992; Trappe et al., 2001), but not too heavy for swinging the legs (Saunders et al., 2004).

Additionally, some studies suggested a different shape of the upper leg between sprinters and endurance runners (Abe et al., 1999, 2000; Kumagai et al., 2000), but this cannot be confirmed by our results, as there were no differences in distribution of the different muscles or in the position of the center of mass of the different muscles. It has to be mentioned that earlier studies were done with ultrasonography, which gives an estimation of muscle volume, while in this study muscle volumes were calculated on MRI-based 3D reconstructions of serial 2D slices.

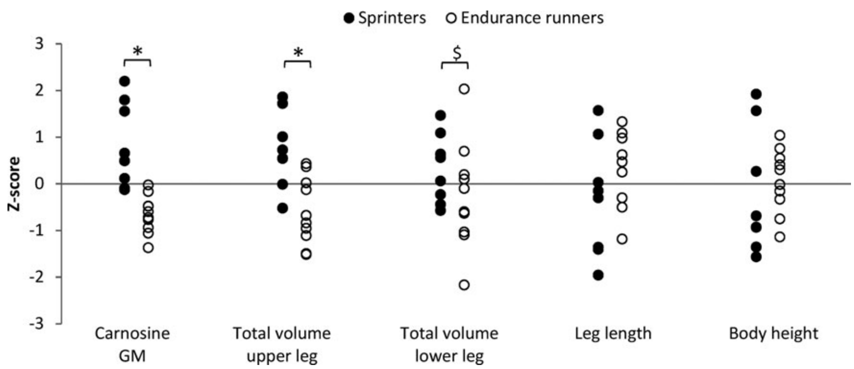

Fig. 3. All individual *Z*-scores of sprinters (black circles) and endurance runners (open circles) for the different musculo-skeletal parameters. $*P \leq 0.05$ and $^{\$}P$ = between 0.05 and 0.10.

It has already been suggested that the hamstring and psoas major muscles play an important role during sprinting (Mero et al., 1992; Hoshikawa et al., 2006; Schache et al., 2012). Hamstrings volume is indeed larger in sprinters than in endurance runners. Hamstrings eccentrically deliver large power peaks when decelerating the swing leg just before ground contact (Schache et al., 2012). A positive correlation between HAMSTR/QUADS ratio and IAAF scores in sprinters was found. Although causality of this relationship is uncertain, it could mean that a high hamstring muscle mass, relative to quadriceps muscle mass, is advantageous for sprint running performance, more than for endurance running performance.

Nevertheless, the ratio of total hamstrings volume to total quadriceps volume averaged nearly 1:3 in earlier studies (Tate et al., 2006). This study found 2.5-fold lower volumes in hamstrings compared to quadriceps in both sprinters and endurance runners. This means that, although very strong hamstrings are required for sprinting, H/Q ratio is about equal in sprinters and endurance runners to ensure functional knee stability.

It can be concluded that the results in this study, generated by MRI-based anatomical 3D reconstruction, indicate that the differences between sprint and endurance Caucasian runners are situated in muscle volumes, rather than muscle shape or skeletal measures. Higher muscle volumes were mainly found in proximal and lateral leg muscles for the sprinters. However, the major discriminant between these athlete populations of the same ethnicity remains estimated muscle fiber type composition. Our data also support the notion that the hamstrings muscles are an important factor in sprint running performance.

Perspectives

The current study is the first to describe the musculoskeletal leg characteristics between sprinters and endurance runners of the same ethnicity (Caucasian) with MRI, allowing single bone and single muscle level analysis. This information source should allow more accurate biomechanical simulations of running, based on true athletic legs of sprinters and endurance runners. Until now, most biomechanics analysis software (e.g., Visual 3D) is based on Dempster's anthropometic data (Dempster, 1955). Further research on a higher level of athletes is required on whether body morphology shows more distinctions between sprinters and endurance runners. This can create some new insights to the main musculo-skeletal characteristics contributing in sprint or endurance performance.

Key words: Running, morphological properties, performance.

Acknowledgements

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Conflict of interest

There are no conflicts of interest.

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