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Sonographic studies of human soleus and gastrocnemius muscle architecture: gender variability

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Abstract The purpose of this study was to establish if there are gender differences in muscle architecture in relaxed human soleus and gastrocnemius muscles of normal, live subjects. Ultrasonography was used to measure fiber bundle length, muscle thickness, and angles of pennation in a total of ten predetermined sites in the medial and lateral heads of gastrocnemius and the anterior and posterior soleus in 19 males and 16 females. Percentage differences between males and females for each parameter were recorded. Gender differences were statistically analyzed using multivariate analysis of variance. In the gastrocnemius and soleus muscles of males and females the differences between the overall fiber bundle length, angle of pennation and muscle thickness were statistically significant ($P < 0.05$). Overall, females were found to have longer average muscle fiber bundle length and males thicker muscles and larger angles of pennation. The greatest percentage differences of the architectural parameters between males and females were in the posterior soleus: 13% difference in fiber length and 26% difference in angle of pennation in the midline of posterior soleus and 26% difference in muscle thickness of the lateral part of posterior soleus. No correlation was found between leg length and fiber length, angle of pennation or muscle thickness. Fiber length (decreased), angle of pennation (greater) and muscle thickness (greater) of most parts of the gastrocnemius and soleus muscles were significantly different in males and females. Leg length of males and females did not correlate to these architectural parameters.

Key words Gastrocnemius · Gender · Muscle architecture · Soleus · Ultrasound

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Introduction

Males tend to have larger muscles and greater absolute strength than females, even when corrections are made for age, body mass and proportion of lean body mass (Maughan et al. 1983; Kanehisa et al. 1994). Conversely, females tend to exhibit greater endurance than males when performing isometric and dynamic contractions at low to medium proportions of their maximum voluntary force of contraction (Maughan et al. 1986; Miller et al. 1993). The mechanisms resulting in the difference in muscle performance in males and females are not well understood. From a morphological perspective, two factors influencing muscle performance are fiber arrangement (architecture) and intracellular structure (Gans and Gaunt 1991; Gans and Bock 1965). While considerable emphasis has been placed on research of the cellular properties of muscle and their influence on performance (Froberg and Pedersen 1984; Green et al. 1984), basic data on human muscle architecture remain scarce (Oxorn et al. 1998). The importance of angles of pennation, fiber length and other muscle fiber architectural parameters with respect to function has been well documented (Spector et al. 1980; Sacks and Roy 1982; Woittiez et al. 1983; Huijing 1985; Huijing et al. 1989; Lieber and Blevins 1989; Legreneur et al. 1996). The architectural data of the human soleus and gastrocnemius muscles are summarized in Table 1. This data are routinely used in calculations of physiological

Table 1 Mean fiber length (*FL*), angle of pennation (θ) and muscle thickness (*MT*) in the gastrocnemius and soleus muscles as reported in the literature (standard deviation when reported) (*C* Cadaveric muscle, *V* in vivo ultrasound study, *M* male, *F* female, *U* sex unspecified, *median* midsagittal.) Maganaris et al. (1998): one data set for the central region of the muscle belly is included

Author (year)	*n*	Source	Location	FL (mm)	θ (deg)	MT (mm)
Medial gastrocnemius						
Alexander and Vernon (1975)	1M	C	–	–	16	16
Friederich and Brand (1990)	1M	C	–	41.9	–	–
	1F	C	–	35.8	6.5	–
Huijing (1985)	8U	C	Proximal	44.3	16.0	–
			Distal	59.8	20.8	–
Narici et al. (1996)	1M	C	Central	36.6	20.5	12.3
			Proximal	39.9	18.5	14.0
			Distal	35.8	17.2	8.0
	6M	V	Central	50.8	17.3	19.8
			Proximal	–	16.2	21.1
			Distal	–	13.0	17.2
Spoor et al. (1991)	3M	C	–	42.6	11	–
Wickiewicz et al. (1983)	3U	C	–	35.3	16.7	–
Kawakami et al. (1998)	6M	V	Central	52 (7)	24 (2)	–
Maganaris et al. (1998)	6M	V	Central:			
			Medial	43.9 (2.2)	21.8 (1.4)	16.6 (1.0)
			Median	45.0 (2.3)	22.3 (2.0)	17.1 (1.3)
			Lateral	45.0 (1.8)	22.1 (1.9)	17.0 (1.4)
Lateral gastrocnemius						
Alexander and Vernon (1975)	1M	C	–	–	8	9
Cutts (1988)	3U	C	–	–	10.7	–
Friederich and Brand (1990)	1M	C	Proximal	76.9	–	–
	1F	C	Distal	44.2	17.5	–
Huijing (1985)	8U	C	–	59.8	7.8	–
			–	65.5	10.8	–
Spoor et al. (1991)	3M	C	–	52.1	7	–
Wickiewicz et al. (1983)	3U	C	–	50.7	8.3	–
Kawakami et al. (1998)	6M	V	Central	56 (8)	13 (1)	–
Maganaris et al. (1998)	6M	V	Central:			
			Medial	72.5 (2.6)	10.9 (1.4)	15.6 (0.7)
			Median	74.0 (3.4)	11.3 (1.2)	15.2 (1.0)
			Lateral	73.0 (2.8)	11.0 (1.9)	16.0 (1.0)
Soleus						
Alexander and Vernon (1975)	1M	C	–	–	20	12
Cutts (1988)	3U	C	–	–	19	–
Friederich and Brand (1990)	1M	C	–	30.8	–	–
	1F	C	–	29.8	32	–
Spoor et al. (1991)	3M	C	Posterior	25.8	34	–
			Anterior	26.7	31	–
Trzenschik and Loetzke (1969)	2M	C	Posterior	26.7	20	–
			Anterior	26.7	25	–
	3F	C	Posterior	30.5	20	–
			Anterior	29.0	25	–
Wickiewicz et al. (1983)	2U	C	–	19.5	25	–
Kawakami et al. (1998)	6M	V	Posterior	38 (4)	21 (3)	–
Maganaris et al. (1998)	6M	V	Posterior (central):			
			Medial	36.9 (2.2)	24.2 (2.4)	13.9 (2.2)
			Median	35.4 (3.5)	25.0 (2.6)	15.1 (2.2)
			Lateral	37.0 (3.0)	23.8 (1.9)	16.0 (3.2)

cross-sectional area and muscle force, but are limited by small sample size, lack of consideration of architectural variability in various parts of the muscle, and incomplete data sets, making meaningful comparison of results difficult (Yamaguchi et al. 1990). Gender differences have not been the focus of these studies.

Apart from uncertainties stemming from small sample sizes, there is increasing evidence that fixed cadavers may not accurately (Fukunaga et al. 1997) reflect the fiber arrangement of living muscle because of muscle shrinkage (Cutts 1988; Friederich and Brand 1990) or the deformation that may occur during fixation and storage. Rapid advances in technology have made it possible to study human muscle architecture in vivo non-invasively using ultrasonography (Henriksson-Larsen et al. 1992; Rutherford and Jones 1992; Kawakami et al. 1993; Herbert and Gandevia 1995; Kuno and Fukunaga 1995; Narici et al. 1996; Fukunaga et al. 1997; Ichinose et al. 1997; Maganaris et al. 1998). Ichinose et al. (1998) studied muscle thickness and angle of pennation in the triceps brachii muscles of male and female Olympic athletes.

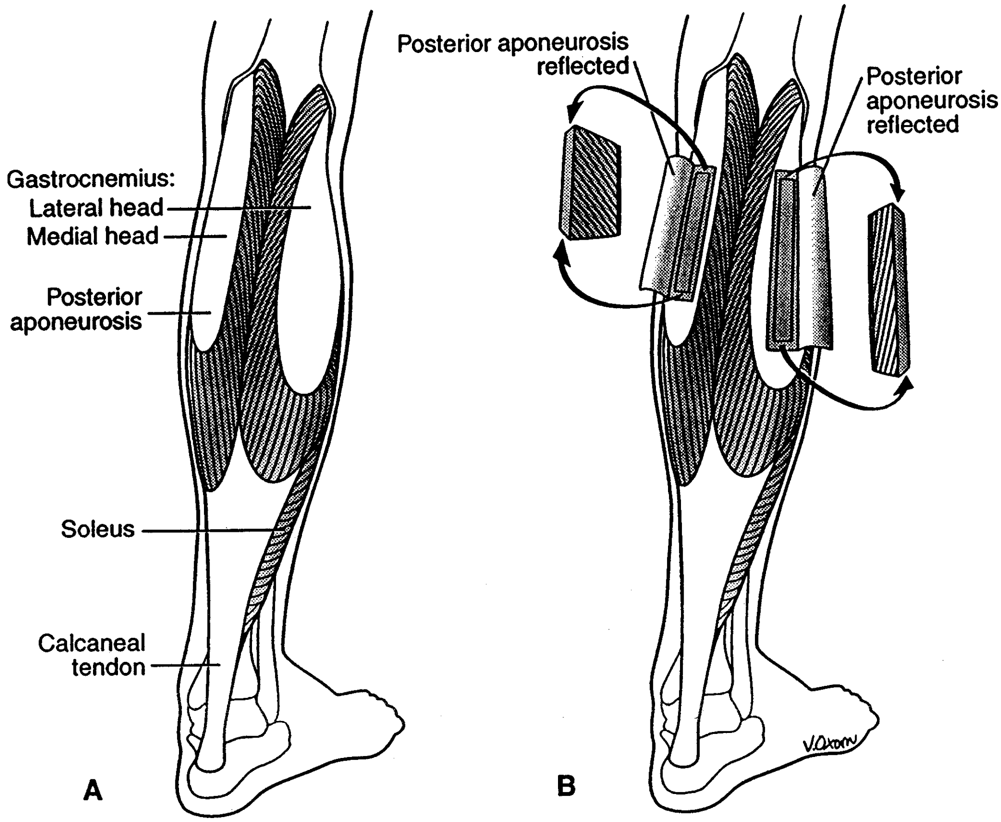

Fig. 1A, B Muscle architecture of the medial and lateral heads of gastrocnemius muscle, posterior views. **A** Superficial, **B** Deep

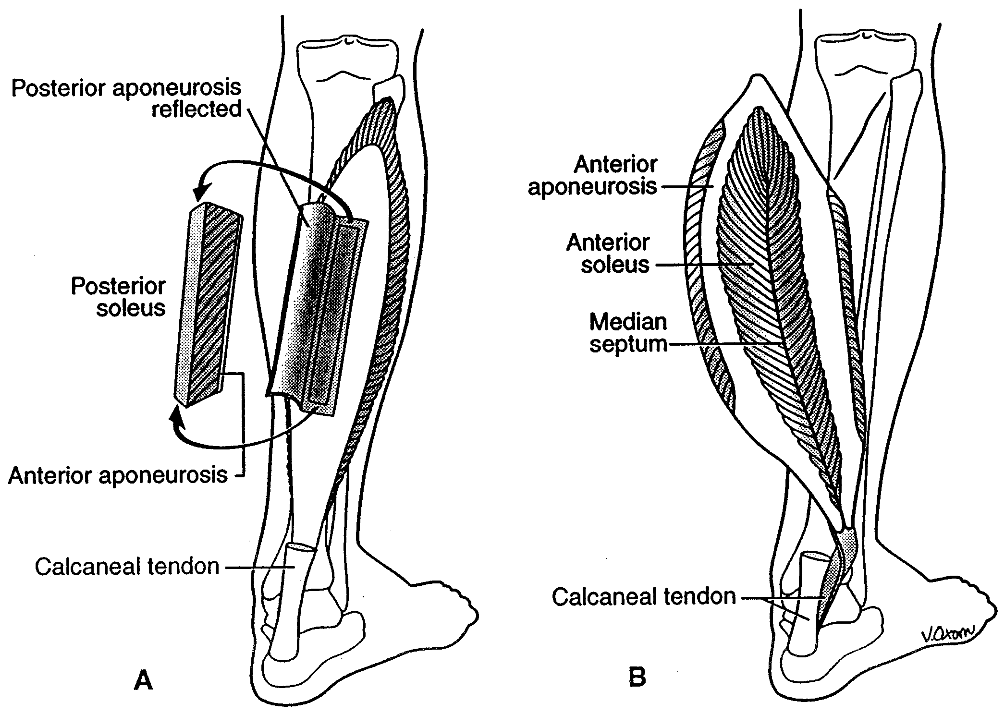

Fig. 2A, B Muscle architecture of the soleus muscle. **A** Posterior soleus, posterior view. **B** Anterior soleus, anterior view

This present ultrasonographic study set out to document and compare in detail the intramuscular architecture of relaxed gastrocnemius and soleus muscles (see Figs. 1 and 2) in normal, healthy men and women.

Methods

Sixteen female [48 (22) years; mean age (SD)] and nineteen male volunteers [44 (22) years] with no history of musculoskeletal injury were recruited for this study. Informed written consent was

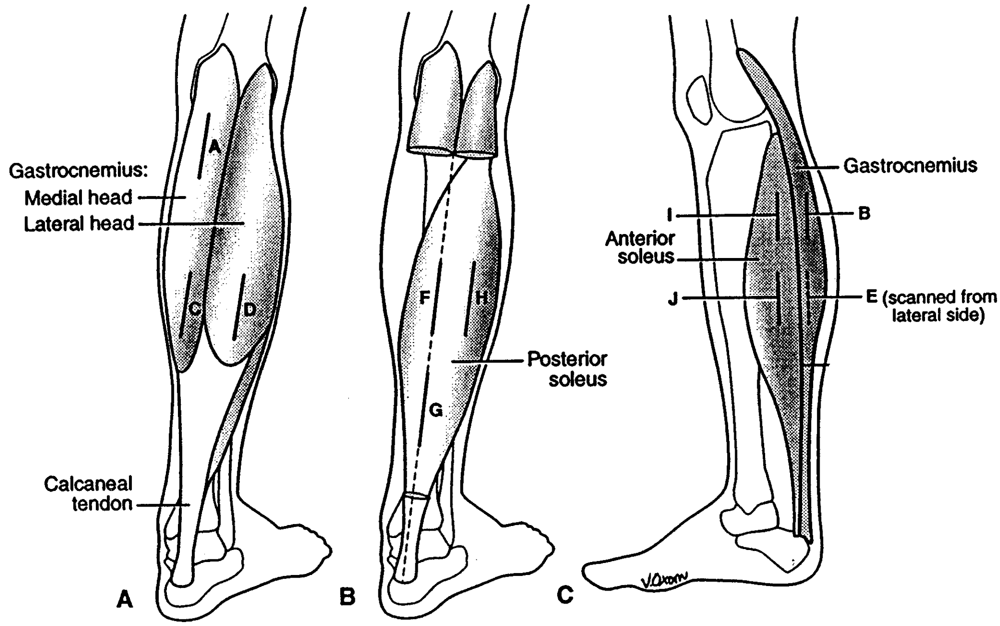

Fig. 3A–C Locations of sonographic scanning sites. **A** Medial and lateral heads of gastrocnemius, posterior view. **B** Posterior soleus, posterior view. **C** Gastrocnemius and anterior soleus. Sites scanned are labelled *A–J*. These sites are referred to by letter designation in Tables 2, 3, 4, 5, 6

obtained from each subject. The University of Toronto Human Subjects Review Committee approved this study.

For the sonographic study of the right and left gastrocnemius and soleus muscles, subjects lay prone on an examining table. Their lower limbs were extended, muscles relaxed and their feet rested over the edge of the table at an angle of 90° to the leg. Scanning was carried out in the sagittal and/or coronal planes to optimize visualization of entire fiber bundles lying between two aponeuroses. Ten predetermined sites were scanned in the gastrocnemius/soleus muscle complex. Three sites were imaged in the medial gastrocnemius, two in the lateral gastrocnemius, three in the posterior soleus, and two in the anterior soleus, as shown in Fig. 3.

A Toshiba SSH-140A real time ultrasound scanner with 5 MHz or 7.5 MHz linear array transducer was used for the study. Information was processed with the Agfa Impax System (Pax System).

Three architectural parameters, fiber bundle length, muscle thickness, and angle of pennation, were measured on each ultrasound scan using a scaled ruler and a protractor. A clearly visible fiber bundle lying between two aponeuroses was identified on each scan (see Fig. 4). The fiber bundle and the aponeuroses of attachment were taped using thin Letraset tape. Fiber bundle length was measured, in mm, along the marked fiber bundle as the distance between its aponeurotic attachments (see Fig. 5). In the medial and lateral heads of the gastrocnemius and the posterior soleus, two angles of pennation were measured, in degrees, for each fiber bundle. Angle θ_A is the angle of insertion of the fiber bundle into the anterior aponeurosis and angle θ_P is the angle of insertion into the posterior aponeurosis. The θ_A and θ_P angles of pennation of the anterior soleus were measured as the angle between the point of insertion of a fiber bundle into the median septum and anterior aponeurosis respectively (see Fig. 5). Muscle thickness was measured, at the center of each scan in millimeters, as the perpendicular distance between the two aponeuroses to which the muscle fiber

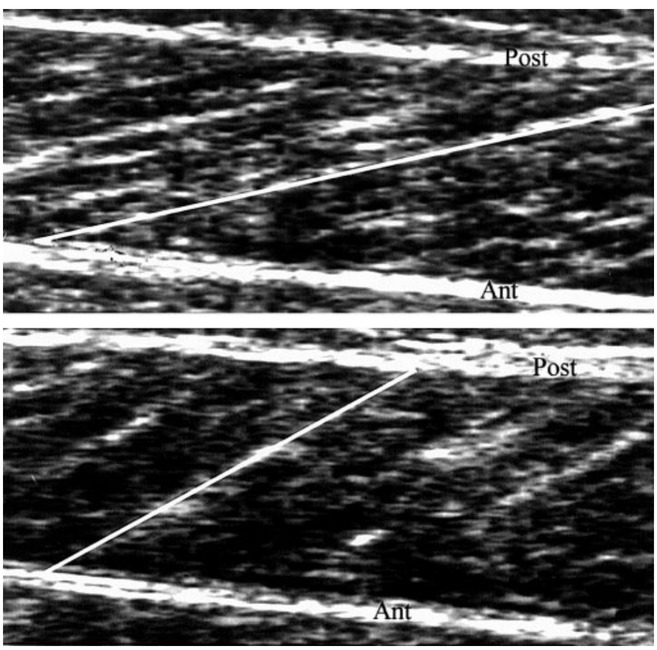

Fig. 4 Relaxed (*upper*) and contracted (*lower*) ultrasound scans of the medial head of gastrocnemius. (*White line* Muscle fiber bundle, *Ant* anterior aponeurosis, *Post* posterior aponeurosis)

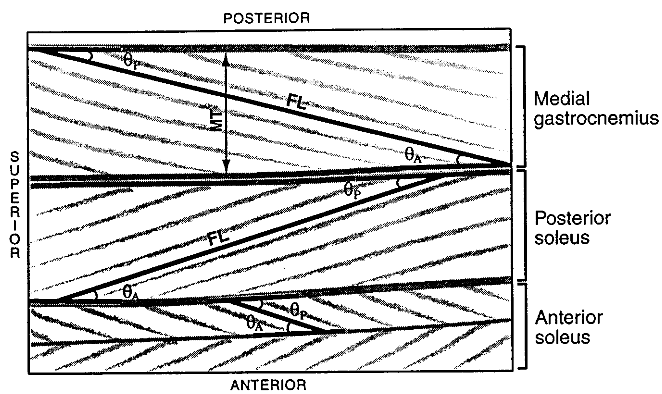

Fig. 5 Schematic illustration to show measurement of fiber bundle length (*FL*), muscle thickness (*MT*) and angles of pennation (θ_A) and (θ_P)

bundles attach (see Fig. 5). All variables were measured independently by two investigators.

Leg length was measured from the anterior superior iliac spine to the inferior end of the medial malleolus and correlated with gender and architectural variables.

For the male and female subject groups measures of central tendency were calculated for every architectural parameter at each scanning site. Percentage differences were recorded as: [(average male value − average female value)/average female value] × 100. Gender difference and the consistency of this difference across sites were statistically analyzed using multivariate analysis of variance (MANOVA; $P < 0.05$).

Results

As corresponding data from the left and right legs of the same subject were not significantly different ($P < 0.05$), all results in this paper reflect the averaged data of both legs. There was no correlation between leg length and any of the three architectural variables measured.

Fiber bundle length and muscle thickness measurements were found to be consistent to ±1 mm, and angles of pennation to ±1 degree when measurements were done independently by two individuals.

A consistent relationship in the difference between architectural parameters in males and females was found at the scanned sites of gastrocnemius and soleus.

Fiber bundle length

In the gastrocnemius and soleus muscles of males and females the difference between the overall fiber bundle length was statistically significant ($P < 0.05$). Females were found to have longer average muscle fiber bundle length in all parts of the muscles examined except in the proximal part of the medial head of gastrocnemius and lateral part of the posterior soleus, see Table 2. The largest percentage difference of fiber length between males and females was in the midline of the posterior soleus (proximal: 13% and distal: 9%) and in the proximal anterior soleus (12%), see Table 6. The lateral head of gastrocnemius had the smallest percentage difference in fiber length (1–2%). Fiber bundle length in the female varied more than in the male, as shown by the greater standard deviations in Table 2.

Table 2 Average fiber bundle length (*FL*) (standard deviation) in multiple sites of the male and female medial gastrocnemius (*MG*), lateral gastrocnemius (*LG*), posterior soleus (*PS*) and anterior soleus (*AS*)

Muscle	Scan location	FL (mm)	
		Female	Male
MG	A	50.7 (10.6)	50.8 (10.3)
	B	44.6 (9.3)	43.8 (7.6)
	C	48.9 (9.6)	45.2 (8.8)
LG	D	45.4 (9.7)	44.6 (8.2)
	E	45.2 (10.5)	44.6 (8.4)
PS	F	37.2 (13.2)	32.3 (7.7)
	G	31.7 (8.8)	29.0 (6.8)
	H	32.1 (9.4)	33.2 (8.4)
AS	I	31.7 (10.0)	28.0 (7.1)
	J	30.0 (9.7)	27.7 (9.7)

Angle of pennation

The angle of pennation measurements (θ_A and θ_P) in the gastrocnemius and soleus muscles of males and females were significantly different ($P < 0.05$). Males were found to have greater average angles of pennation (θ_A and θ_P) in all parts of the muscles examined except in the proximal part of the medial gastrocnemius where angle θ_A was found to be greater in females, see Tables 3 and 4. The largest percentage difference of angle of pennation between males and females was in the midline of the posterior soleus: proximal 27% (θ_A), 26% (θ_P); and distal 20% (θ_A), 19% (θ_P), see Table 6.

Muscle thickness

In the gastrocnemius and soleus muscles of males and females the difference between muscle thickness was

Table 3 Average angle of pennation, θ_A (standard deviation) in multiple sites of the male and female medial gastrocnemius (*MG*), lateral gastrocnemius (*LG*), posterior soleus (*PS*) and anterior soleus (*AS*)

Muscle	Scan location	θ_A (degrees)	
		Female	Male
MG	A	19.2 (3)	18.7 (3)
	B	21.6 (3)	22.8 (2)
	C	18.1 (3)	19.1 (2)
LG	D	15.8 (2)	16.4 (2)
	E	14.7 (2)	15.5 (3)
PS	F	19.0 (3)	24.1 (4)
	G	21.1 (3)	25.4 (3)
	H	19.0 (2)	24.0 (3)
AS	I	15.7 (2)	17.0 (2)
	J	16.9 (2)	18.2 (2)

Table 4 Average angle of pennation, θ_P (standard deviation) in multiple sites of the male and female medial gastrocnemius (*MG*), lateral gastrocnemius (*LG*), posterior soleus (*PS*) and anterior soleus (*AS*)

Muscle	Scan location	θ_P (degrees)	
		Female	Male
MG	A	14.5 (3.6)	15.8 (3.8)
	B	17.2 (4.9)	19.0 (4.5)
	C	12.7 (2.6)	14.0 (3.2)
LG	D	11.7 (2.6)	12.6 (2.8)
	E	11.2 (2.5)	12.3 (3.6)
PS	F	17.6 (6.5)	22.2 (7.1)
	G	20.5 (5.8)	24.4 (6.5)
	H	18.0 (6.2)	20.6 (5.9)
AS	I	13.8 (4.0)	16.3 (4.0)
	J	15.1 (4.0)	17.8 (6.1)

statistically significant ($P < 0.05$). Males were found to have greater average muscle thickness in all parts of the muscles examined except in the distal part of the anterior soleus and distal part of the medial gastrocnemius, see Table 5. The greatest percentage difference of muscle thickness between males and females was in the proximal part of the posterior soleus (midline: 13% and lateral: 26%), see Table 6. The smallest percentage difference was in the anterior soleus.

No measurements are presented in this paper to support the non-parallel positions of the anterior and posterior aponeurosis, but this was frequently observed.

Discussion

The results obtained from this study (Tables 2, 3, 4, 5) are presented as means of measurements at ten sites from soleus and gastrocnemius muscle from both legs of 19 males and 16 females. These sonographic data are based on a larger population than in past studies (Table 1).

Much of the previous data are from cadavers. More recent data have come from other investigators using sonography (Narici et al. 1996; Kawakami et al. 1998; Maganaris et al. 1998).

When compared to values obtained in this study, correspondence to reported values for fiber length varies depending on the muscle part in question (Table 1). In general, reported fiber lengths in the medial gastrocnemius and soleus are somewhat shorter, while in the lateral gastrocnemius they are considerably longer than those obtained in this study. The sonographically obtained angles of pennation closely resemble angles reported by other investigators, except for the lateral gastrocnemius. Muscle thickness is not represented in some of the previous studies. Values reported by Alexander and Vernon (1975) are similar to those obtained in this study. Maganaris et al. (1998) reported the soleus muscle thickness (posterior part judging by the scans) of six healthy male volunteers to be 15 mm. The age of the volunteers is not mentioned, but the group probably did not include any elderly people, whereas several were included in this study with similar distribution of age for both males and females. A trend for the thickness of the medial gastrocnemius to be greater than that of either the lateral gastrocnemius or the soleus is apparent in the data of Maganaris et al. (1998) (MG 17 mm, LG 15 mm, soleus 15 mm) and this study (Table 5).

The lateral gastrocnemius measurements reported in previous studies are very interesting. Differences with observed fiber lengths and angles of pennation in Table 1 may be attributable to the small sample sizes in previous studies and to different and unreported sites measured in lateral gastrocnemius by different investigators. The authors have consistently found longer muscle fibers in the anterior part of the lateral gastrocnemius in cadaver studies (unpublished). These anterior-most fibers were not measured in the ultrasonographic protocol of this study but would have been readily accessible to those doing cadaver studies. This does not explain how the fiber lengths reported by ultrasound studies (Kawakami et al. 1998; Maganaris et al. 1998) both exceed what is reported here. A variable that could contribute is age (Hooper 1981) but then why would it be a factor for the lateral gastrocnemius more than the other components of the triceps surae?

It is important to recognize that many of the studies summarized in Table 1 were performed on cadaveric subjects of unspecified but generally advanced age. Cutts (1988) reported shrinkage of muscle fibers on fixation. Fukunaga et al. (1997) reported that "the use of cadaver data in the study of architecture and modelling [can] result in inaccurate and in some cases erroneous

Table 5 Average muscle thickness (MT) (standard deviation) in multiple sites of the male and female medial gastrocnemius (MG), lateral gastrocnemius (LG), posterior soleus (PS) and anterior soleus (AS)

Muscle	Scan location	MT (mm)	
		Female	Male
MG	A	13.8 (3.4)	14.7 (2.8)
	B	14.3 (2.9)	15.3 (2.3)
	C	12.7 (2.5)	12.5 (2.0)
LG	D	10.5 (2.1)	11.0 (1.8)
	E	9.8 (1.9)	10.6 (2.5)
PS	F	10.7 (3.0)	12.1 (3.6)
	G	10.8 (3.3)	11.7 (2.8)
	H	9.4 (2.2)	11.8 (2.8)
AS	I	7.8 (2.4)	8.0 (2.3)
	J	8.2 (2.3)	8.0 (2.2)

Table 6 Percentage difference between the architectural parameters of male and female medial gastrocnemius (*MG*), lateral gastrocnemius (*LG*), posterior soleus (*PS*) and anterior soleus (*AS*). Fiber bundle length (*FL*), muscle thickness (*MT*) and angles of pennation (θ_A) and (θ_P) are considered. A positive % difference indicates the male data > female, a negative % difference indicates male data < female

Muscle	No. legs		Scan location	% difference			
	Female	Male		*FL*	θ_A	θ_P	MT
MG	32	38	A	0	−3	+9	+7
	32	38	B	−2	+6	+10	+7
	31	38	C	−7	+6	+10	−2
LG	31	37	D	−2	+4	+8	+5
	25	37	E	−1	+5	+10	+8
PS	27	37	F	−13	+27	+26	+13
	28	35	G	−9	+20	+19	+8
	24	33	H	+3	+26	+14	+26
AS	26	27	I	−12	+8	+18	+3
	27	31	J	−8	+8	+18	−2

results". However, ultrasound of live subjects can be assumed to be an accurate means of measuring architectural parameters based on the observation that ultrasound measures taken from cadaveric muscle correspond to manual measurements taken directly from the muscle (Narici et al. 1996).

Differences in muscle architecture in males and females

The results demonstrate that overall the muscle architectural parameters of fiber bundle length, angles of pennation and thickness are significantly different in males and females. As there was no correlation between leg length and the architectural parameters, and there was a consistent relationship between male and female measurements from different muscle sites, the results appear to reflect true gender-based differences in muscle architectural properties.

The relationship between gender-based differences in muscle architecture and in performance merits investigation. Factors to consider include greater endurance in females than males in performing isometric and dynamic contractions at low to medium proportions of their maximum voluntary force of contraction (Maughan et al. 1986; Miller et al. 1993), and larger muscles and greater absolute strength in males than females even when corrections are made for age, body mass and proportion of lean body mass (Maughan et al. 1983; Kanehisa et al. 1994). Ichinose et al. (1998) reported data from highly trained athletes indicating that "the sex difference in force generation capability of the triceps brachii muscle could in the main be attributed to the difference in CSA [cross-sectional area] rather than in the architectural characteristics".

Many diverse factors have been reported to be linked to observed gender-based differences in muscle performance. Larger muscle fibers in males (Sale et al. 1987; Miller et al. 1993) and differences in activity level or in adrenergic response during muscular exertion (Gratas-Delamarche et al. 1994) may contribute to differences in muscle performance between males and females. On the other hand, attempts to determine whether performance differences are due to differences in fiber number (Shantz et al. 1983; Sale et al. 1987; Alway et al. 1989; Miller et al. 1993) or muscle fiber composition (Maughan and Nimmo 1984; Sale et al. 1987; Miller et al. 1993) have produced conflicting results. Postulations that differences in motor unit activation ability or motor unit number between males and females influences gender-based performance have been discounted (Young et al. 1985; Miller et al. 1993).

Architectural differences in this study

The average values of the architectural parameters can be used to depict the following: with certain exceptions, muscle in the gastrocnemius and soleus of females has longer fibers, smaller angles of pennation and is not as thick as male muscle. Conversely, muscle in the gastrocnemius and soleus of males has shorter fibers, larger angles of pennation and greater thickness. Where results were statistically significant, larger angles of pennation and greater muscle thickness in males than in females were observed also by Ichinose et al. (1998) in the triceps brachii of highly trained athletes.

Based on the formula for physiological cross-sectional area, the above-described differences in muscle architectural properties between males and females have significant implications with respect to force and velocity. Current explanations of the relationship between muscle architecture and function rest on the assumption that, due to practical reasons such as mobility, there is a finite maximum mass or volume that is structurally possible for all muscles (Wickiewicz et al. 1983). Larger pennation angles have been argued to permit a greater degree of fiber packing (Gans and Gaunt 1991; Rutherford and Jones 1992), the net result of which is a larger overall force on a tendon for the same muscle volume. In turn, thicker muscle with otherwise similar properties would result in a larger force vector on the same tendon. In contrast, longer muscle fibers have more sarcomeres arranged in series, permitting greater muscle excursion and contraction velocity (Wickiewicz et al. 1983; Lieber 1993; Burkholder et al. 1994). Burkholder et al. (1994) in a study of mouse hindlimbs reported that "decreased fiber length is correlated with (although not causal of) increased muscle force". This said, the observed larger pennation angles, thicker muscle and (less likely) shorter fibers recorded in the gastrocnemius and soleus muscles of males would each contribute to greater force generation in males than in females. In line with this, males with significantly larger angles of pennation and greater muscle thickness than females were also reported to have significantly greater isokinetic forces at constant velocities of both 60°/s and 180°/s than females (Ichinose et al. 1998).

Past analyses have used cross-sectional area calculations based on muscle thickness (Ichinose et al. 1998); others have used physiological cross-sectional area incorporating angle of pennation and fiber length (Wickiewicz et al. 1983). Nishio et al. (1992) recognized that normalizing muscle force to physiological cross-sectional area was problematic in some situations and suggested alternative methods of normalization. Narici et al. (1996) showed that physiological cross-sectional area could be said to change by 34.8% (calculated by the formula) in the medial gastrocnemius muscle from the relaxed to the contracted state. Fukunaga et al. (1996) presented data that "suggest that factors other than PCSA [physiological cross-sectional area] contribute to the force output potential of plantar flexors and dorsiflexors in humans".

The dichotomy in muscle architectural properties between males and females is most prominent in the posterior soleus. In the three sites sampled in posterior soleus, males were observed to have up to 26% thicker muscle, up to 27% larger angles of pennation and up to 13% shorter fiber lengths on average than females. This observation suggests that, of the muscle parts studied, potential force generation for males differs most from that for females in the posterior soleus, the antigravity muscle. From Table 6, it is also evident that the parameter most different between males and females is the angle of pennation.

It is interesting to note that muscle fiber bundle length varied more in females than in males based on the standard deviation, Table 1. This difference might be attributed to the slightly smaller sample size of females (Table 6); however, male–female differences of variance in data were not observed for angles of pennation and muscle thickness. Hence it appears that fiber bundle length in females may show more variance than that in males.

In summary, it is evident that there are distinct gender-based differences in the muscle architecture of normal human soleus and gastrocnemius muscles. These differences have interesting ramifications with respect to muscle performance.

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