

Comparing human skeletal muscle architectural parameters of cadavers with in vivo ultrasonographic measurements

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ABSTRACT

The purpose of this study was to document and compare the architectural parameters (fibre bundle length, angle of pennation) of human skeletal muscle in cadaveric specimens and live subjects. The medial (MG) and lateral (LG) gastrocnemius, and posterior (PS) and anterior (AS) soleus were examined bilaterally in 5 cadavers (mean age 72.6, range 65–83 y) and 9 live subjects (mean age 76.3, range 70–92 y). Data were obtained from direct measurement of cadaveric specimens and from ultrasonographic scans of the live subjects. In cadaveric muscle, fibre bundles were isolated; their length was measured in millimetres and pennation angles were recorded in degrees. In live muscle, similar measurements were taken from ultrasonographic scans of relaxed and contracted muscle. For the scans of relaxed muscle, subjects were positioned prone with the foot at a 90° angle to the leg, and for scans of contracted muscle, subjects were asked to sustain full plantarflexion during the scanning process. Fibre bundle length and angle of pennation were compared at matched locations in both groups. It was found that the relationship between cadaveric and in vivo values for fibre length and angle of pennation varied between muscle parts. The cadaveric architectural parameters did not tend to lie consistently towards either extreme of relaxation or contraction. Rather, within MG, PS and AS, cadaveric fibre bundle lengths lay between those for relaxed and contracted in vivo muscle. Similarly both the anterior and posterior cadaveric fibre angles of pennation lay between the in vivo values within LG and PS. In summary, architectural characteristics of cadaveric muscle differ from both relaxed and contracted in vivo muscle. Therefore, when developing models of skeletal muscle based on cadaveric studies, the architectural differences between live and cadaveric tissue should be taken into consideration.

Key words: Fibre length; pennation angle; gastrocnemius; soleus; ultrasound.

INTRODUCTION

Traditionally, studies which have examined the architectural and biomechanical properties of human skeletal muscle have used cadaveric tissue as the source from which the majority of data have been collected because of the difficulties associated with measuring in vivo muscle. Cadaveric tissue has been used to study sarcomere lengths (Cutts, 1988*b*) as well as some of the gross fibre architectural properties of human skeletal muscle (Wickiewicz et al. 1983; Friederich & Brand, 1990). These architectural para-

meters have then been used to develop and test biomechanical models of the muscles (Spoor et al. 1991; Legreneur et al. 1996). Cadaveric muscle studies are beneficial because structural features of the entire muscle can be directly observed (Oxorn et al. 1998) and measured, making it possible to develop a detailed 3-dimensional model of fibre architectural arrangement (Agur, 1999).

More recently, however, ultrasonography has been shown to be of use for studying in vivo skeletal muscle and therefore allow for direct measurement of the architectural parameters in living tissue (Rutherford

& Jones, 1992; Herbert & Gandevia, 1995; Fukunaga et al. 1997a; Kawakami et al. 1998; Maganaris et al. 1998; Narici, 1999). Ultrasonographic studies will provide a better understanding of the dynamic nature of skeletal muscle and could be used to elucidate the biomechanics of muscle contraction. Magnetic resonance imaging studies have also been used to study the architecture of cadaveric skeletal muscle (Scott et al. 1993), but this method has been less successful when studying skeletal muscle *in vivo* (Narici, 1999).

There is little information in the literature which documents the relationship between living and cadaveric skeletal muscle architectural parameters. It has been suggested that the architectural parameters of cadaveric muscle differ from those of living tissue (Rutherford & Jones, 1992; Fukunaga et al. 1997b). Cadaveric tissue is subject to standard embalming procedures. Cutts (1988a) has shown that these procedures will not shorten the 'contractile portion' of skeletal muscle if muscle is fixed while intact upon the skeleton. However, the effect of fixation on the internal fibre architecture of human skeletal muscle is not known. Cadaveric tissue also undergoes post-mortem changes, one of which is rigor mortis. It has been shown that this change can produce a slow contraction in skeletal muscle (Bendall, 1951; Davies, 1963). This process may therefore have some effect on the internal fibre architecture.

It seems important to investigate the possibility that cadaveric muscle differs from living tissue because it is not yet known whether architectural models based on data from cadaveric sources accurately reflect the anatomical structure of living muscle. The present study was therefore undertaken to document and compare the architectural parameters of cadaveric with *in vivo* human skeletal muscle.

MATERIALS AND METHODS

Human gastrocnemius and soleus muscles were examined bilaterally from 5 cadavers and 9 live subjects. The mean age of the cadaver group was 72.6 (range 65–83)y while the mean age of the live subject, ultrasound group was 76.3 (range 70–92)y.

Two skeletal muscle architectural parameters, fibre bundle length and angle of pennation, were studied and then used to compare the 2 groups. Each parameter was measured at matched locations in both the cadaveric and ultrasound groups. For the cadaveric group, measurements were taken directly from the muscles following their excision from the body, while *in vivo* measurements were taken from ultrasonographic scans.

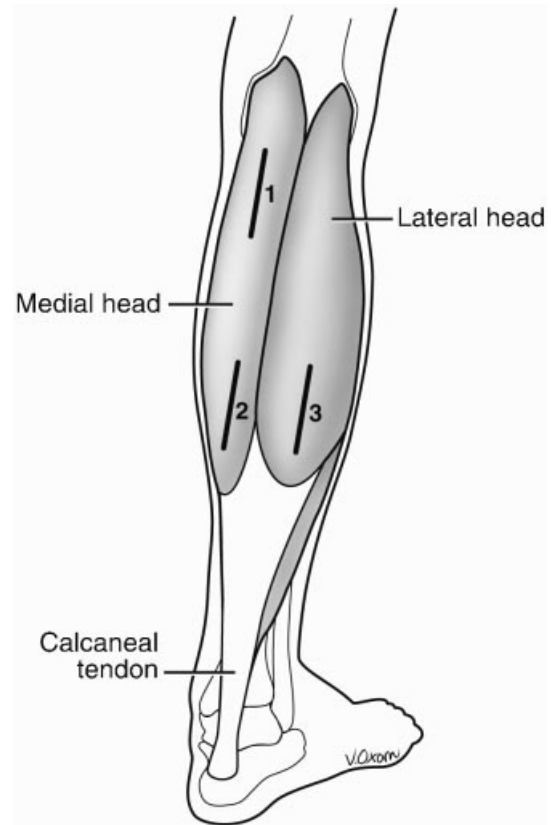


Fig. 1. Sites within the medial (MG) and lateral (LG) gastrocnemius from which fibre length and angle of pennation measurements were taken from cadaveric tissue and ultrasound scans of *in vivo* muscle, posterior view. 1, MG proximal fibres; 2, MG distal fibres; 3, LG distal fibres.

Cadaveric study

Ten gastrocnemius and 10 soleus muscles were excised bilaterally from 5 formalin embalmed cadavers with no indication of musculoskeletal disease. The medial (MG) and lateral (LG) gastrocnemius, posterior (PS) and anterior (AS) soleus muscles were cleaned in preparation for direct measurements of the architectural parameters.

Sagittal incisions were made in MG, LG and PS, and coronal (frontal) incisions were made in AS at the locations as shown in Figures 1 and 2. Fibre bundles were selectively teased apart at regular intervals along the length of the incision to determine their points of attachment along the anterior and posterior aponeuroses. Each end of a fibre bundle was then marked with a colour-coded pin. Fibre bundles of the bipennate AS were isolated along its anterior surface and the attachments of the fibre bundles were marked from the median septum to the anterior aponeurosis of PS.

A total of 12–14 measurements were taken from each MG, 3 from each LG, 5 from each PS, and 6–10

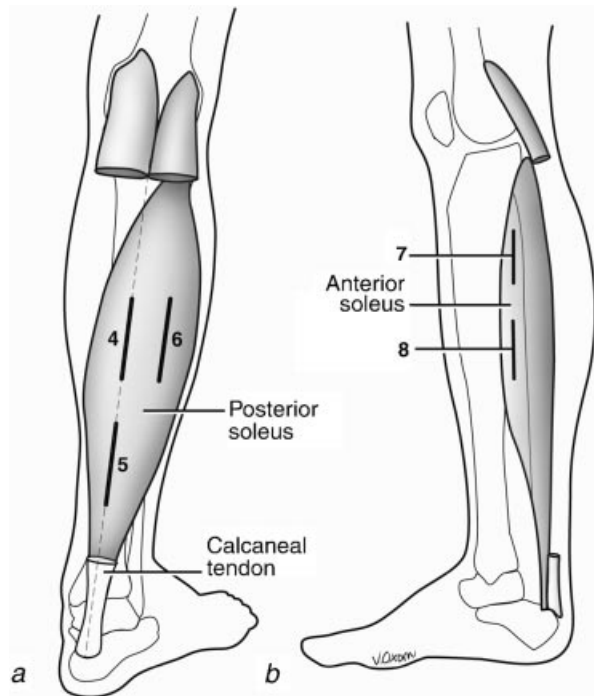


Fig. 2. Sites within the posterior soleus (a) and anterior soleus (b) from which fibre length and angle of pennation measurements were taken in both cadaveric tissue and from ultrasound scans of in vivo muscle. (a) Posterior soleus, posterior view. (b) Anterior soleus, medial view. 4, PS proximal midline fibres; 5, PS distal midline fibres; 6, PS proximal lateral fibres; 7, AS proximal fibres; 8, AS middle fibres

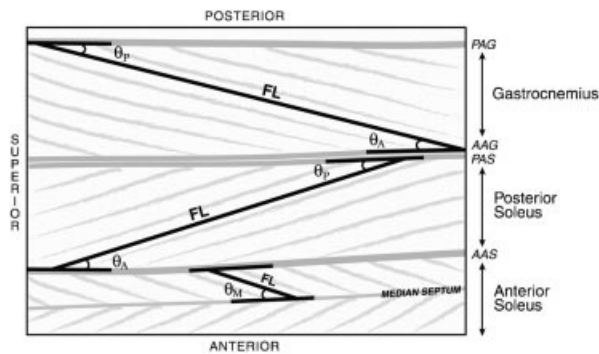


Fig. 3. Schematic representation of muscle fibre architectural measurements. FL, fibre length; θ_A , anterior angle of pennation, θ_P , posterior angle of pennation, θ_M , medial angle of pennation, PAG, posterior aponeurosis of gastrocnemius; AAG, anterior aponeurosis of gastrocnemius; PAS, posterior aponeurosis of soleus; AAS, anterior aponeurosis of soleus.

measurements from each AS. Fibre bundle lengths were determined by measuring the distance (mm) between the pins using dividers and a scaled ruler. For MG, LG, and PS an anterior and posterior angle of pennation for each fibre was measured relative to the anterior and posterior aponeuroses using a protractor (Fig. 3). For AS one angle of pennation (medial angle) was measured relative to the median septum.

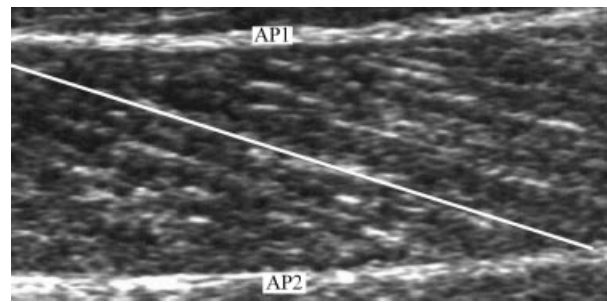


Fig. 4. Ultrasound scan of MG. White line, representative muscle fibre bundle; AP1, posterior aponeurosis; AP2, anterior aponeurosis.

Ultrasonographic study

Elite athletes and individuals with a history of musculoskeletal disease were excluded. Informed written consent was obtained from each subject as outlined in the protocol approved by the University of Toronto Human Subjects Review Committee.

Medial gastrocnemius (MG), lateral gastrocnemius (LG), posterior soleus (PS), and anterior soleus (AS) were scanned in the same locations from which the cadaveric measurements were taken (Figs 1, 2). A Toshiba SSH-140A real time ultrasound scanner with 5 MHz or 7.5 MHz linear array transducer was used for the study (Leekam et al. 1999; Chow et al. 2000). Information was processed with the Agfa Impax System (Pax System). The MG, LG and PS were scanned in the sagittal plane and the AS in the coronal plane. All muscles were scanned to show, optimally, the plane of fibre orientation (Fig. 4).

Scans were taken while each subject lay prone on a bed with their foot hanging from the end at a 90° angle to the leg. To obtain the scans for contraction the subject was asked to plantarflex their ankle maximally and to maintain this position without resistance while the scan was taken.

Using the scanned image, the anterior and posterior aponeuroses of MG, LG and PS were defined and for AS the median septum and anterior aponeurosis of PS were identified as illustrated in Figure 3. These connective tissue sheaths were marked with thin (1/32") Letraline tape. One clear fibre bundle was then selected from within each muscle part and marked along its length between aponeurotic attachment sites. The bundle lengths were measured with a scaled ruler, and for MG, LG and PS both the posterior and anterior angles were measured, using a protractor, against the posterior and anterior aponeuroses. For AS a single angle of pennation was measured relative to the median septum. Both the markings and measurements were independently

checked twice and the measurements were found to be accurate to within 1–2 mm.

Statistics

Data from ultrasonographic scans (MG, LG, PS and AS) were matched with corresponding data from cadaveric specimens. Multivariate analysis of variance was carried out to identify the presence of variation in muscle architectural parameters between cadaveric and live muscle. Analysis was carried out on the entire gastrocnemius and soleus muscles and on their individual muscle parts (MG, LG, PS and AS). Results indicating significant variation ($P < 0.05$) were further analysed using the Tukey’s post hoc comparison test. Ultrasonographic values are given as simple means ± standard deviation. Reported cadaveric measurements, calculated to give each muscle part equal weight irrespective of the number of measurements taken at a given location, are reported as means ± standard deviation.

RESULTS

Mean fibre bundle lengths of MG, LG, PS and AS, measured from relaxed and contracted in vivo muscle and from cadaveric muscle, are shown in Table 1. Also summarised is the percentage by which the fibre length of cadaveric muscle differed from relaxed in vivo muscle.

A comparison of cadaveric fibre lengths with the in vivo measurements shows that in all muscle parts, except for LG, the cadaveric fibre length lay between that of the relaxed and contracted value from the living tissue. Within MG the cadaver fibre length was significantly ($P < 0.05$) shorter than the relaxed fibre length. In LG, PS and AS, however, the cadaveric

Table 1. Fibre bundle length (mm)

Muscles	In vivo relaxed	In vivo contracted	Cadaveric	Difference (%)
MG	43.6 ± 8.6 ^a	27.7 ± 5.6 ^b	34.4 ± 6.9 ^b	–21.1
LG	41.6 ± 7.4 ^a	30.0 ± 6.1 ^a	43.1 ± 9.6 ^a	+3.6
PS	29.7 ± 11.1 ^a	20.4 ± 6.1 ^b	25.0 ± 4.1 ^{ab}	–15.8
AS	26.9 ± 7.7 ^a	20.8 ± 8.6 ^a	26.8 ± 5.8 ^a	–0.4

Percentage difference calculated by comparing cadaveric with relaxed in vivo values. Number of observations per muscle part in vivo/cadaveric): MG(10/135), LG (10/30), PS(10/46), AS(10/79). The superscript letters are used to indicate the presence or absence of statistical significance (multivariate analysis of variance) between in vivo relaxed, in vivo contracted and cadaveric fibre length for MG, LG, PS, and AS. If the superscript letters in a row differ, then the result is statistically significant. If the letter is repeated, there is no statistical significance.

Table 2. Anterior angle of pennation (°)

Muscles	In vivo relaxed	In vivo contracted	Cadaveric	Difference (%)
MG	18.6 ± 3.6 ^a	30.3 ± 8.5 ^b	32.5 ± 4.7 ^b	+74.7
LG	16.4 ± 2.6 ^a	24.7 ± 4.9 ^a	21.0 ± 2.5 ^a	+28.0
PS	23.7 ± 6.3 ^a	35.5 ± 9.7 ^b	30.3 ± 7.3 ^{ab}	+27.8
AS	16.5 ± 5.4 ^a	25.5 ± 7.6 ^b	46.1 ± 11.0 ^c	+179.4

Percentage difference calculated by comparing cadaveric with relaxed in vivo values. Number of observations per muscle part (in vivo/cadaveric): MG(10/135), LG(10/30), PS(10/46), AS(10/80). The superscript letters are used to indicate the presence or absence of statistical significance (multivariate analysis of variance) between in vivo relaxed, in vivo contracted and cadaveric anterior angle of pennation for MG, LG, PS and AS.

Table 3. Posterior angle of pennation (°)

Muscles	In vivo relaxed	In vivo contracted	Cadaveric	Difference (%)
MG	14.4 ± 3.6 ^a	28.7 ± 9.0 ^b	31.6 ± 5.9 ^b	+119.4
LG	12.1 ± 3.4 ^a	21.4 ± 6.5 ^a	16.8 ± 3.0 ^a	+38.8
PS	22.2 ± 7.2 ^a	34.2 ± 10.3 ^b	25.2 ± 4.6 ^{ab}	+13.5
AS	14.4 ± 5.3 ^a	23.6 ± 7.0 ^b	NM	—

Percentage difference calculated by comparing cadaveric with relaxed in vivo values. Number of observations per muscle part (in vivo/cadaveric): MG(10/135), LG(10/30), PS(10/46). The superscript letters are used to indicate the presence or absence of statistical significance (multivariate analysis of variance) between in vivo relaxed, in vivo contracted and cadaveric anterior angle of pennation for MG, LG, PS and AS. NM, not measured.

values were not significantly different from either the relaxed or contracted values. Within in vivo MG and PS, contracted fibre lengths were shown to be significantly ($P < 0.05$) shorter than relaxed fibre lengths.

Mean anterior angles of pennation of MG, LG, PS, and AS measured from relaxed and contracted in vivo muscle and from the cadaveric tissue are shown in Table 2 while the corresponding posterior angles are shown in Table 3. Also summarised in Tables 2 and 3 is the percentage by which the angles of pennation of cadaveric muscle differed from relaxed in vivo muscle.

In the ultrasound subjects both the anterior and posterior angles of pennation in contracted muscle within MG, PS, and AS were significantly greater than each of the anterior and posterior angles in relaxed muscle ($P < 0.05$). In the cadaver, the anterior and posterior angles of pennation within LG and PS lay between each of the relaxed and contracted in vivo values. However, the anterior and posterior cadaveric angles of MG and the medial angle of AS were greater than both the relaxed and contracted values. In MG the anterior and posterior cadaveric angles were

significantly ($P < 0.05$) greater than the relaxed angles and in AS the medial cadaveric angle was significantly ($P < 0.05$) greater than the medial relaxed angle. Within LG and PS the cadaveric values did not differ significantly from the *in vivo* values for either angles.

DISCUSSION

The data in Table 1 indicate that the relationship between cadaveric and *in vivo* fibre bundle length varies between muscle parts. The data in Tables 2 and 3 also show that variation exists between muscle parts when comparing cadaveric and *in vivo* fibre pennation angles. This variation can best be seen when comparing the percentage differences between the cadaveric and relaxed living muscle. The cadaveric values do not tend to lie consistently towards either extreme of relaxation or contraction. Rather, cadaveric fibre bundles within MG, PS, and AS, had lengths which lay between the values for relaxed and contracted *in vivo* fibre bundle lengths. Similarly, both the anterior and posterior cadaveric pennation angles within PS and LG were found to lie between relaxed and contracted values. These results suggest that cadaveric skeletal muscle exists architecturally in a state of partial contraction somewhere between fully relaxed and contracted living skeletal muscle. It is also interesting to note, however, that significant differences were identified within MG between the cadaveric and relaxed *in vivo* tissues for all 3 architectural parameters measured. From this it is possible to conclude that MG cadaveric muscle more closely resembles that of contracted living muscle than it does relaxed muscle.

There are several possible reasons which may explain the observed results. Postmortem skeletal muscle undergoes rigor mortis, a process that has been shown to cause a slow contraction in muscle fibres (Bendall, 1951; Davies, 1963). However, Bendall (1973) explained that this contraction is minimal in comparison with a living contraction, yielding only a small fraction of the total work which can be performed by the living tissue. Indeed, when examining animal muscle, only a fraction of the fibres actively contract during rigor mortis while the remaining fibres contract passively (Hooper & Hegarty, 1973). It is therefore possible that when cadavers are embalmed, their skeletal muscle becomes fixed in this state of partial muscle contraction found during rigor mortis.

The embalming procedure may also have some effect on skeletal muscle tissue directly. Cutts (1988a) has studied the effects of shrinkage on skeletal muscle

as a result of cadaveric fixation and found that a significant loss in muscle length occurs when muscles are fixed in isolation from the skeleton but not when fixed *in situ* on the skeleton. Most cadavers are subject to standard embalming procedures before the internal tissues are examined, as was the case in the present study. This therefore eliminates the possibility that whole muscle shrinkage may occur as a result of fixation. However, it is still possible that formalin fixation may alter the architectural parameters within the muscle itself without altering gross muscle length. Using ox muscle, Locker (1959) showed that formalin fixation does not alter sarcomere length within rigor muscles. Hooper & Hegarty (1973), however, found that it does cause an increase in the percentage of passively contracted fibres in muscles previously excised from the skeleton. They therefore speculated that formalin fixation may increase the irritability potential of muscle or may cause shortening of surrounding connective tissue. It seems possible that such changes could also occur within muscle intact upon the skeleton leading to an alteration in fibre bundle length and angle of pennation.

The results obtained from measuring fibre pennation angles within AS were quite different from the results obtained in other muscle parts. The cadaveric value does not lie near the values measured from *in vivo* muscles. The AS is the deepest structure to be imaged and it could only be scanned from its medial aspect. Slight changes in the positioning of the angle of the probe, especially in the proximal part, may lead to an alteration in the fibre pennation angle. This is one of the limitations of using ultrasonography for studying muscle *in vivo*. This would have been easier to assess if ultrasound studies had also been done on the cadaver legs. Unfortunately, this was not done. Pilot work using ultrasound on fixed cadaver legs has not provided consistently useful images.

Other possible reasons why cadaveric muscle architectural parameters differ from those of living muscle include method of storage and long term changes in the tissue. The position at which full cadavers, cadaveric parts or individual muscles are stored may place consistent physical strain on a muscle or muscle part and this could lead to deformation of the tissue. In addition, long-term degradation of muscle tissue may slowly, throughout the course of storage, alter the architecture within skeletal muscle.

Ideally, the complexities of skeletal muscle architecture could be better recorded and modelled using 3D data (Ng-Thow-Hing et al. 1998). MRI (Roberts, 1995; Thorpe et al. 1998) and 3D ultrasound (Rankin et al. 1993; Fenster & Downey, 2000) studies may well

provide such internal structural data in the living, in the future.

CONCLUSIONS

When the fibre bundle length, as well as anterior and posterior angles of pennation were used to compare cadaveric with relaxed and contracted skeletal muscle, variability in the relationship between cadaveric and in vivo tissue was shown to exist between muscle parts. However, within three of the 4 muscle parts (MG, PS and AS), cadaveric fibre bundle lengths lay between the lengths of the relaxed and contracted in vivo tissue, and in 2 of the muscle parts (LG and PS) both anterior and posterior angles of pennation lay between the relaxed and contracted in vivo tissue. These results suggest that cadaveric muscle exists architecturally in a state of partial contraction. MG is the exception. In this muscle part, all three architectural parameters within cadaveric tissue differ significantly from relaxed muscle and so it more closely approximates muscle in a contracted state. Consideration must be given to these differences when developing architectural models of skeletal muscle based upon data obtained solely from cadaveric tissue.

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