

# Hamstring Muscles: Architecture and Innervation

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## Key Words

Architecture · Hamstring muscles · Innervation

## Abstract

Knowledge of the anatomical organization of the hamstring muscles is necessary to understand their functions, and to assist in the development of accurate clinical and biomechanical models. The hamstring muscles were examined by dissection in six embalmed human lower limbs with the purpose of clarifying their gross morphology. In addition to obtaining evidence for or against anatomical partitioning (as based on muscle architecture and pattern of innervation), data pertaining to architectural parameters such as fascicular length, volume, physiological cross-sectional area, and tendon length were collected. For each muscle, relatively consistent patterns of innervation were identified between specimens, and each was unique with respect to anatomical organization. On the basis of muscle architecture, three regions were identified within semimembranosus. However, this was not completely congruent with the pattern of innervation, as a primary nerve branch supplied only two regions, with the third region receiving a secondary branch. Semitendinosus comprised two distinct partitions arranged in series that were divided

by a tendinous inscription. A singular muscle nerve or a primary nerve branch innervated each partition. In the biceps femoris long head the two regions were supplied via a primary nerve branch which divided into two primary branches or split into a series of branches. Being the only muscle to cross a single joint, biceps femoris short head consisted of two distinct regions demarcated by fiber direction, with each innervated by a separate muscle nerve. Architecturally, each muscle differed with respect to parameters such as physiological cross-sectional area, fascicular length and volume, but generally all partitions within an individual muscle were similar in fascicular length. The long proximal and distal tendons of these muscles extended into the muscle bellies thereby forming elongated musculotendinous junctions.

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## Abbreviations used in this paper

PCSA	physiological cross-sectional area
MTJ	musculotendinous junction
SM	semimembranosus
ST	semitendinosus
BFlh	biceps femoris long head
BFsh	biceps femoris short head

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## Introduction

The collective term 'hamstrings' refers to four muscles located in the posterior compartment of the thigh – semimembranosus (SM), semitendinosus (ST), biceps femoris long head (BF<sub>lh</sub>) and biceps femoris short head (BF<sub>sh</sub>). These muscles are long, multiarticular, and susceptible to strain injury, which is often recurrent [Heiser et al., 1984; Upton et al., 1996; Bennell et al., 1998; Orchard and Seward, 2002; Slavotinek et al., 2002]. In order to develop models of relationships between structure and function in these muscles, or to propose injury prevention or treatment procedures, a detailed understanding of the anatomy of this group of muscles is required. While it would be an exaggeration to state that previous studies and anatomical textbooks treat the hamstrings as an undifferentiated mass, it is certainly not the case that a clear picture of the relationship within, among, or between the muscle fibers, tendons and nerves of these muscles exists.

A number of authors have proposed that anatomical partitioning is an important characteristic of muscles which can be used in describing and interpreting their structure and function [Segal et al., 1991; Segal, 1992; Johnson et al., 1994; Bakkum et al., 1996; Wolf and Kim, 1997; Wickham and Brown, 1998; Segal et al., 2002]. With respect to the hamstrings the only previous study to allude to partitioning is that of Prose et al. [1990], who reported that SM consists of three unipennate units. Seventeen embalmed human lower limbs were investigated but no detailed methods were supplied, lending difficulty to analyzing and interpreting the results. However, it was reported that each of the three units of SM had a specific distal insertion site, was innervated by an individual nerve, and performed a specific function at the knee joint. Other studies have in some part investigated the morphology [Markee et al., 1955; Garrett et al., 1989; Hayashi and Maruyama, 2001], innervation [Sunderland and Hughes, 1946; Markee et al., 1955; Seidel et al., 1996] or specific components of muscle architecture such as fascicle or fiber length, volume or physiological cross-sectional area (PCSA) [Barrett, 1962; Wickiewicz et al., 1983; Friederich and Brand, 1990; Chelboun et al., 2001], but a complete description of both architecture and innervation was not available for all the hamstring muscles. Therefore, the purpose of this study was to clarify the gross morphology of these muscles, specifically to (a) determine whether anatomical partitioning exists, on the basis of architecture and/or innervation; (b) describe the fascicular anatomy, and (c) detail the length and form of their tendons and musculotendinous junctions (MTJs).

## Materials and Methods

### Materials

*Cadaveric Material.* The morphology of the hamstring muscles was studied by dissection in six embalmed human cadaveric lower limbs complete with pelvis (3 female and 3 male, aged 68–88 years at death). Five of the cadavers were embalmed with an alcohol-based embalming fluid used by the Otago School of Medicine. This solution consists of 57.3% ethanol, 18.1% water, 15.1% glycerol, 7.8% phenol and 1.7% formalin. The remaining cadaver was embalmed in the Dodge Anatomical Mix, which is a formalin-based fixative.

*Other Materials.* Gross dissection of the hamstring muscles was aided by use of a 1.5 times magnification lens (Eschenbach). In addition to dissecting tools, a tape measure, volumetric measure (25 ± 0.5 ml) and metal ruler were also used. Observations, sketches and relevant data were noted in a logbook and analyzed to identify trends and variations that may exist. Photographs taken with a Nikon Coolpix 995 digital camera were used to aid analysis of the written data. Each step of the fascicular dissection was also photographed with images stored on a Macintosh computer for further examination.

### Methods

*Dissection.* The specimens were positioned in prone, and the skin incised in the midline and reflected. The underlying subcutaneous tissue and fascia were gently removed to expose the hamstring and the gluteus maximus muscles. Prior to removing gluteus maximus by blunt dissection, any association with the proximal fibers of BF<sub>sh</sub> was noted.

The hamstring muscles, once exposed, were investigated in order to determine their morphology. The criteria used for anatomical partitioning was that described by Segal et al. [2002], based on two characteristics: architecture and innervation. With respect to architecture, partitioning was defined by two parameters: (a) a region of muscle fibers in which fiber orientation differed from surrounding regions and (b) the presence of tendinous inscriptions. Pertaining to innervation, partitioning was defined as a group of muscle fibers innervated by an exclusive primary nerve branch [English and Letbetter, 1982]. Specific measurements were recorded and these are documented below (architectural parameters). The sciatic nerve was identified as it exited the greater sciatic foramen, and was cleared of surrounding tissue to reveal its course and branches in the posterior thigh, and the branching pattern of the nerves supplying the hamstring muscles were recorded.

The hamstring muscles were then dissected to establish their fascicular anatomy. A muscle fascicle was defined as a bundle of muscle fibers that had a distinctive, identifiable attachment [Johnson et al., 1994; Lieber and Friden, 2000] both proximally and distally, and which could be detached and stripped from the rest of the muscle without disrupting its integrity [Johnson et al., 1996]. Each fascicle was detached from its proximal insertion and gently stripped from above downwards, taking care not to stretch it in the process. The fascicle was removed from its distal tendon of insertion, and all tendinous attachments were cut away, leaving only muscle fibers. The proximal and distal attachment sites of each fascicle were measured relative to the ischial tuberosity.

As each fascicle was isolated, its length was measured (in centimeters, to the nearest millimeter) using a metal ruler. Each fascicle was then immersed in a volumetric cylinder containing warm wa-

ter, and the displacement of fluid was measured (to the nearest 0.5 mm) to determine its volume. These two measurements were used to calculate the PCSA of the fascicle, with the PCSA being equal to the volume divided by the length ( $\text{cm}^2$ ) [Bogduk et al., 1992; Johnson et al., 1994; Bogduk et al., 1998].

#### *Morphometric Data*

*Architectural Parameters.* In addition to muscle fiber orientation, other defining characteristics of architecture include muscle length, fascicular length and PCSA. All these parameters were considered in this study, and additional measurements were taken of the length of the proximal and distal tendons and MTJs using the methods and definitions outlined below. The angle of pennation may be included when calculating the PCSA of a muscle [Wickiewicz et al., 1983; Lieber, 1992; Lieber and Bodine-Fowler, 1993; Lieber and Friden, 2000]. Traditionally, this has been measured by determining the average angle of fibers on the superficial surface of the muscle, relative to the muscle's axis of force generation [Gans and Bock, 1965; Lieber and Bodine-Fowler, 1993; Lieber and Friden, 2000]. More recently, imaging techniques such as magnetic resonance imaging and ultrasound have been utilized to measure the *in vivo* pennation angle of selected lower limb muscles [Scott et al., 1993; Fukunaga et al., 1997; Maganaris et al., 1998; Chelboun et al., 2001; Reeves and Narici, 2003]. The pennation angle has been shown to vary considerably along the length of a muscle [Scott et al., 1993], and to alter with changes in contractile state or joint position [Fukunaga et al., 1997; Maganaris et al., 1998; Brinckmann et al., 2000; Chelboun et al., 2001; Reeves and Narici, 2003]. This architectural characteristic can therefore affect the mechanical properties of a muscle, but Gans and Bock [1965] suggest that variations in the pennation angle may not strongly alter function. Due to the complex architectural arrangement of the hamstring muscles, and the fact that the pennation angle is not always necessary in the development of clinical models, the angles of pennation were not measured.

*Muscle Length.* To determine the length of each muscle, excluding its tendons of attachment, the distance between the most proximal muscle fiber and the most distal muscle fiber was measured using a tape measure (in centimeters to the nearest millimeter). The portion of the tendon which extends into the muscle belly was included in this measurement.

The length of each muscle, including its tendons of insertion, was also measured. The proximal insertion site of ST, BF<sub>l</sub>h and SM was taken from the prominent tubercle on the lateral aspect of the medial portion of the ischial tuberosity. Although SM attached on the lateral portion of the ischial tuberosity, it passed close to the above point, which was a good marker of its insertion proximally. The anatomy of the distal insertion sites of the hamstring muscles was not the focus of the present study, as they have previously been described in detail [Warren and Marshall, 1979; Terry and LaPrade, 1996; Kin et al., 1997; Mochizuki et al., 2004]. It was decided to mark the site of distal insertion of all the hamstring muscles along a line traversing between the inferior margin of the fibular head and the point on the tibia where the medial condyle begins to flare laterally. Because BF<sub>sh</sub> had no proximal tendon, only the distal tendon was included in the measurement, together with the length of the muscle.

*Fascicle Length.* The length of every fascicle in each hamstring muscle was measured. The mean fascicular length (in centimeters, to the nearest millimeter) for each anatomical partition was calcu-

lated by summing the length of the fascicles in the compartment and dividing by the total number of fascicles. The mean fascicular length of each muscle was established by adding together the mean fascicular lengths of its partitions and dividing this by the number of partitions. The mean fascicular lengths for each muscle were added together and divided by six (the number of specimens) to determine the representative fascicular length for the muscle.

*Fascicle Volume.* The volume of each fascicle (milliliter) was determined by measuring fluid displacement using a volumetric cylinder. The mean fascicular volumes for each partition and muscle and the representative value (all muscles) were calculated in the same way as described for fascicular length.

*Physiological Cross-Sectional Area.* As previously documented, the PCSA ( $\text{cm}^2$ ) of each fascicle was calculated by dividing the volume of each fascicle by its length. The total PCSA of each anatomical partition or muscle was determined by adding together the total PCSAs of all its fascicles. The mean PCSA for each partition was determined by summing the PCSAs of all the fascicles comprising the partition, and dividing this by the number of fascicles in the partition. The representative mean size (PCSA) of each fascicle in a muscle was determined by summing the PCSA of all the fascicles comprising the muscle, and dividing this by the number of fascicles. Once a mean fascicular PCSA value had been established for each muscle, these were added together and divided by six (the number of specimens) to gain a mean value representative of all muscles. The range of the data was also calculated and expressed in conjunction with the mean data.

*Tendon Length.* It was evident that most of the tendons of the hamstring muscles could be separated into two components: the portion of the tendon which had no muscle fibers inserting into it, and the portion which extended into the muscle belly giving rise to muscle fibers. The lengths of the proximal and distal tendon of each muscle were calculated (in centimeters) to include both of these components, whilst recognizing that BF<sub>sh</sub> does not have a proximal tendon due to its insertion directly into the femur and lateral intermuscular septum.

The proximal insertion sites of the proximal tendons of SM, ST and BF<sub>l</sub>h were measured from the prominent tubercle on the lateral aspect of the medial portion of the ischial tuberosity. The length of each of the proximal tendons was calculated by measuring the distance between the insertion site proximally, and the point at which the most distal muscle fibers arose from the proximal tendon. The length of the distal tendon was determined by measuring the distance between the point at which the most proximal muscle fibers inserted into the distal tendon of the muscle and the site of distal insertion.

*Musculotendinous Junctions.* A MTJ was defined as the portion of a tendon (either proximal or distal) into which muscle fibers inserted [Garrett and Best, 2000]. It is important to distinguish these MTJs, which span a relatively large distance, from the MTJ at a cellular level, which measures only a few microns. The length of a proximal MTJ was determined by calculating the distance (in centimeters) between the most proximal and the most distal fibers which arose from the proximal tendon (and aponeurosis) of the muscle. These data were obtained during the fascicular dissection. Similarly, the length of the distal MTJ was calculated by measuring the distance between the point of insertion of the most proximal and most distal muscle fibers on the distal tendon (and aponeurosis) of the muscle. The length of each MTJ was also expressed as a proportion of muscle length. This was calculated by dividing the length

**Table 1.** Length of the proximal tendons and MTJs

	Length, cm			Length as a proportion of muscle length, %	
	muscle <sup>a</sup>	proximal tendon	proximal MTJ	proximal tendon	proximal MTJ
SM	43.8	31.9	20.8	72.7	47.1
ST	43.8	12.9	11.7	29.4	26.7
BFlh	43.8	27.1	20.6	61.9	46.8
BFsh	29.1	–	–	–	–

<sup>a</sup> Muscle length is measured from the ischial tuberosity to the determined distal insertion sites.

**Table 2.** Length of the distal tendons and MTJs

	Length, cm			Length as a proportion of muscle length, %	
	muscle <sup>a</sup>	distal tendon	distal MTJ	distal tendon	distal MTJ
SM	43.8	26.1	19.3	59.4	44.0
ST	43.8	25.0	13.9	56.8	31.6
BFlh	43.8	27.5	18.3	62.6	41.4
BFsh	29.1	11.2	10.7	45.6	36.5

<sup>a</sup> Muscle length is measured from the ischial tuberosity to the determined distal insertion sites.

of the muscle (inclusive of tendons of insertion) by the length of the respective MTJ. This value was then converted into a percentage.

**Innervation.** The site at which the sciatic nerve separated into its two divisions, the tibial and common peroneal nerves, was recorded relative to the prominent tubercle on the lateral aspect of the medial portion of the ischial tuberosity. As previously indicated, the pattern of innervation of each muscle was sketched in a logbook, and photographed. Specifically, the origin and number of primary nerve branches supplying each muscle were determined. Measurements were taken at the points where the nerve or its branches entered the muscle. The numbers of terminal branches supplying each partition and muscle were also documented.

## Results

### *Semimembranosus*

**Proximal Tendon and MTJ.** The proximal tendon of SM passed laterally and deep compared to those of ST and BFlh, to insert into the lateral part of the upper half of the ischial tuberosity. From its insertion the tendon rapidly widened becoming broad, expansive and aponeurotic, being thick and rounded at its lateral border and flattening into a thin membrane medially. It was not simply positioned in one plane, but gradually curved posteriorly when viewed from lateral to medial. Accordingly, part of the medial portion of the tendon was positioned in an anterior-posterior direction or in the sagittal plane. SM possessed the longest proximal tendon of all of the hamstring muscles, with the lateral portion of the tendon extending the furthest distally, on the posterior aspect of the muscle. The proximal tendon measured 31.9 cm on average, therefore occupying 72.7% of the length of the muscle (table 1). The proximal MTJ, formed by muscle fascicles inserting into the proximal tendon, had a mean

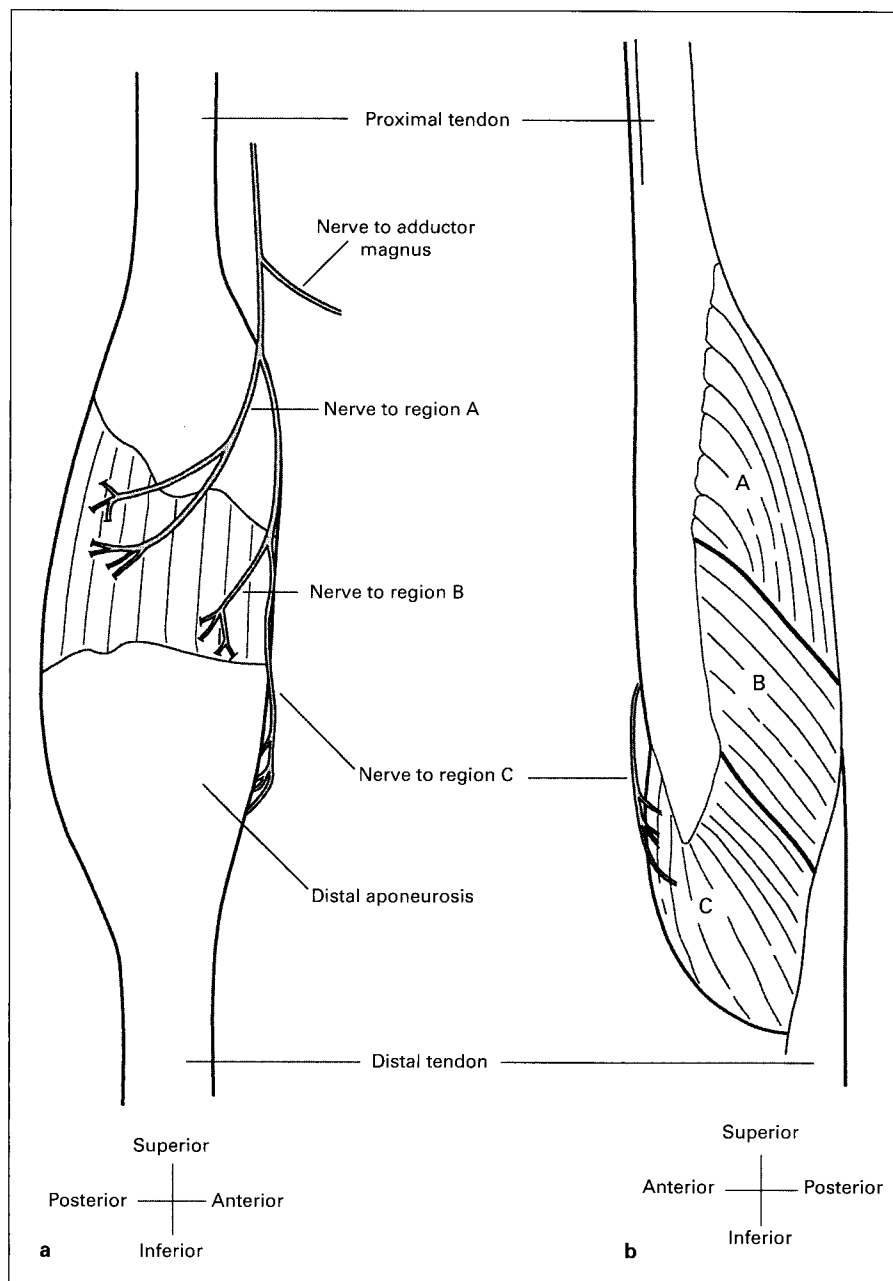
length of 20.8 cm, which was similar in length to that of BFlh, extending 47.1% of the length of the muscle (table 1).

**Distal Tendon and MTJ.** The tendon of SM at its distal end was thicker and shorter relative to that of ST. However, it widened proximally, forming a large, broad aponeurosis (fig. 1a), which gave the distal tendon a mean length of 26.1 cm, spanning 59.4% of the length of the muscle. Distally, muscle fascicles inserted into the lateral aspect of the tendon, with the distal MTJ extending 44.0% of the length of the muscle (table 2).

**Fascicle Direction.** SM had a bulky muscle belly, with the first muscle fascicles commencing at a mean distance of 11.1 cm (range 8.6–14.5 cm) from the ischial tuberosity. On the basis of fascicular orientation, three distinct regions were identified (fig. 1; regions A–C). The most superior fascicles arose from the thin medial surface of the proximal tendon (fig. 1b, region A) which was positioned in the medial plane. These fascicles passed inferiorly to attach to the lateral surface of the distal tendon (fig. 1b).

Fascicles comprising region B arose from the medial and lateral surfaces of the proximal tendon, travelling inferiorly and posteriorly to insert into the lateral aspect of the distal tendon (fig. 1). The distal region was thick and bipennate in arrangement (fig. 1b; region C). Proximally, these fascicles arose from the thick lateral edge of the tendon, coursing inferiorly to insert into the broad expansive distal tendon.

**Pattern of Innervation.** In five specimens, SM was innervated by one muscle nerve branch that arose from either the sciatic or tibial nerves. In two specimens, the nerve to SM shared a common trunk with the nerve supplying the inferior compartment of ST. The nerve to SM



**Fig. 1.** Right semimembranosus. **a** Lateral view. **b** Medial view.

divided into three primary branches with the first branch always supplying the posteromedial portion of adductor magnus, and the ensuing two primary branches innervating SM (fig. 1a).

One primary branch of the nerve to SM regularly supplied region A, and the other regularly supplied region C. The branch to region A entered the muscle on its lateral aspect, close to the superficial surface of the muscle (fig. 1a). The point at which the nerve entered the muscle

proximally was 14.6–21.2 cm distal to the ischial tuberosity. The branch to the fascicles in region C split into numerous secondary and tertiary branches, which ran inferiorly along the ventral surface of the muscle (fig. 1b). This branch entered the muscle most proximally 22.5 cm distal to the ischial tuberosity in one specimen, with the most distal terminal branch being 34.5 cm distal to the tuberosity in another.

Variation existed with regard to innervation of the B fascicles, as they were supplied by a secondary branch from either one of the two primary branches. If the secondary branch to region B split from the nerve innervating region A (two specimens), it also entered the lateral surface of the deeper half of the muscle (18.3–23.3 cm distal to the ischial tuberosity). However, if the branch to region B originated from that supplying the C fascicles (four specimens), it pierced the ventral aspect of the muscle, often at the junction of the two regions (20.7–31.5 cm distal to the ischial tuberosity).

In one specimen, two muscle nerve branches supplied SM. These arose from the sciatic nerve within 2 mm of each other, with one branching to supply regions A and B, and the other coursing distally to supply region C. A branch from the nerve supplying regions A and B innervated the posteromedial portion of adductor magnus.

#### *Semitendinosus*

*Proximal Insertions and MTJ.* The proximal fascicles of ST arose from three distinct locations: the posteromedial aspect of the medial portion of the upper half of the ischial tuberosity, the medial border of the proximal tendon of BFlh, and a proximal aponeurosis located anteriorly, which appeared to be a medial extension of the proximal tendon of BFlh.

Firstly, muscle fascicles arising from the ischial tuberosity inserted into thick connective tissue that encased the medial three quarters of the medial portion of the tuberosity. The tendon of BFlh occupied the other quarter of this area of the tuberosity. The second insertion site, which gave rise to the largest number of fascicles, was a portion of the medial border of the proximal tendon of BFlh (fig. 2a). Variation was seen in the number of fascicles, and hence the length that fascicles of ST extended down the medial border of the tendon of BFlh (fascicles spanned a mean distance of 8.4 cm, range 5.9–11.5 cm). The third site of attachment was an aponeurosis, which appeared to be continuous with the tendon of BFlh anteriorly. It extended medially to cover the proximal anterior aspect of ST, being continuous with the thick connective tissue of the ischial tuberosity proximally, and extending no further distally than 16.5 cm (range 5.3–16.5 cm) from the ischial tuberosity. In addition to attachment into the tendon of BFlh, fascicles contributing to the ventral part of the superior region of ST also arose from this site.

The length of the proximal tendon was determined by calculating the distance between the ischial tuberosity proximally, and the most distal muscle fascicles arising

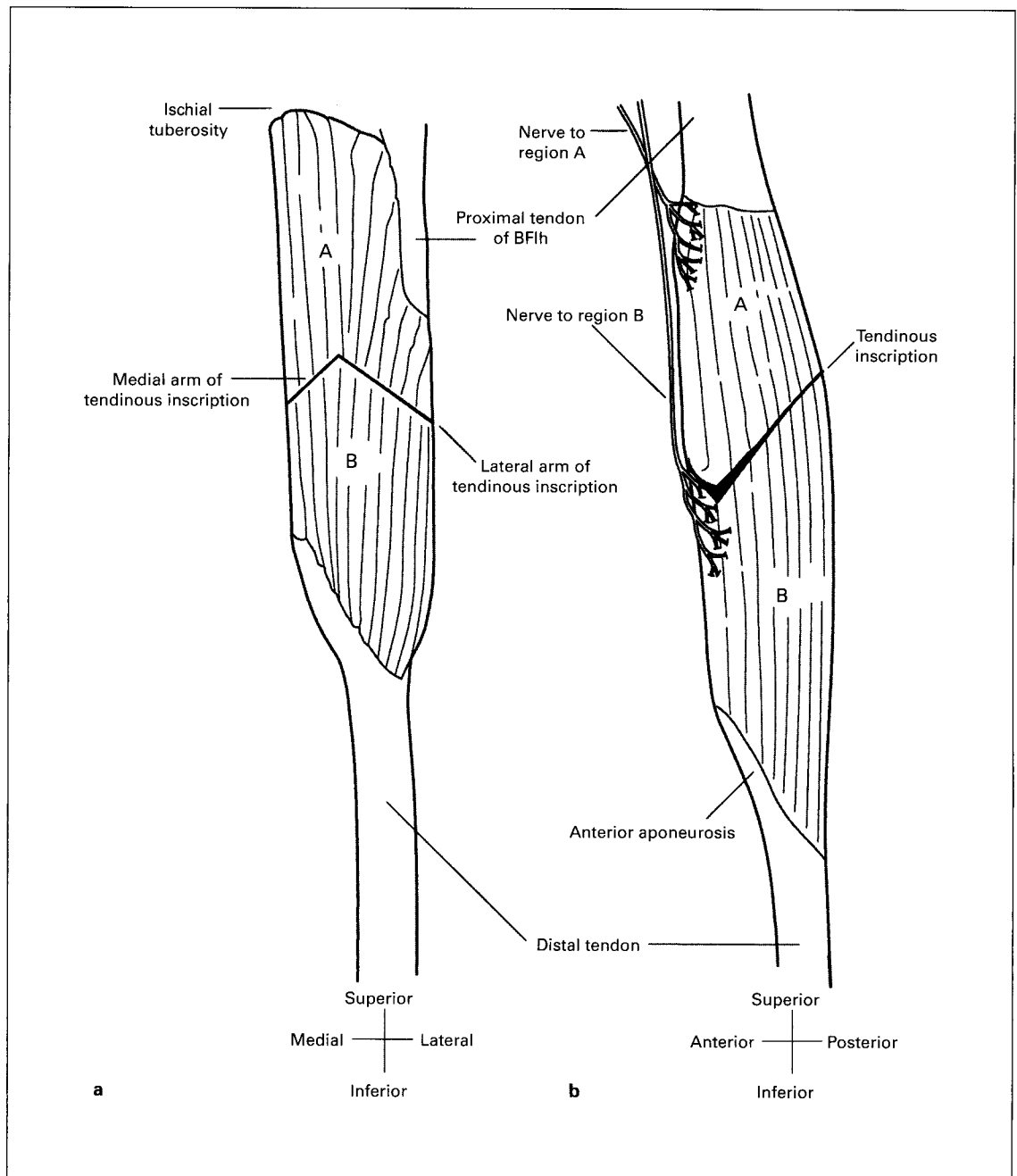
from either the proximal tendon of BFlh or the anterior aponeurosis. In general the proximal tendon was relatively short, having a mean length of 12.9 cm (range 8.5–17.7 cm), therefore occupying 29.4% of the length of the muscle (table 1).

The proximal MTJ of ST was formed along both the anterior aponeurosis and the proximal tendon of BFlh. Mirroring the length of the proximal tendon, this MTJ was relatively short, having a mean length of 11.7 cm, extending 26.7% of the total muscle length (table 1).

*Distal Tendon and MTJ.* The distal tendon passed along the medial aspect of the knee joint, and was long and thin, having a mean length of 25.0 cm (range 22.1–30.0 cm) (table 2). When considered in isolation (the portion of tendon without any muscle fascicles inserting into it), the distal tendon of ST was the longest tendon of the hamstring muscles, measuring on average 11 cm (range 9.0–13.1 cm). The tendon expanded proximally to form a small aponeurosis on the anterior aspect of the muscle (fig. 2b), with the distal MTJ measuring on average 13.9 cm, and occupying 31.6% of the length of the muscle (table 2). In four specimens, the distal tendon of ST was cradled in a trough formed by the superficial, distal fascicles of SM. The distal tendon of ST in the remaining two specimens was either in contact with, or just separate from the superficial border of the distal tendon of SM.

*Fascicle Direction.* The muscle belly of ST was long, thin and straplike, being deeper than it was wide. Fascicles originating proximally from both the ischial tuberosity and the anterior aponeurosis ran vertically downwards, while those from the tendon of BFlh were oriented medially and inferiorly (fig. 2a). The vast majority of these fascicles inserted distally into a tendinous inscription (described below), however, in all but one of the specimens, one or two fascicles bridged the inscription, inserting into the distal tendon of ST.

Particular to ST was the presence of a tendinous inscription that divided the muscle into superior (A) and inferior (B) regions (fig. 2). The inscription was visible on the surface of the muscle, and was well defined in three of the specimens, but not immediately evident in the other three. The inscription was observed as a thin, white line on the surface of the muscle, extending almost continuously around its circumference. On the posterior surface of the muscle, it presented as an inverted 'V' shape, with arms extending obliquely and inferiorly from the apex of the 'V' (fig. 2a). In five specimens, the medial arm (mean length 2.82 cm) was considerably shorter than the lateral arm (mean length 6.7 cm). On the lateral surface of ST the inscription expanded, to form a broad tendi-



**Fig. 2.** Semitendinosus. **a** Posterior view (right). **b** Lateral view (left).

nous sheath (fig. 2b) with a mean length of 6.0 cm (range 4.2–9.5 cm). A thin extension of this sheath curved anteriorly, terminating on the narrow ventral surface of the muscle. The inscription was not seen on the medial surface of ST past the point where the medial arm finished. Posteriorly, the inscription commenced at a mean dis-

tance of 11.0 cm (range 9.5–14.4 cm) from the ischial tuberosity.

During dissection it became obvious that the tendinous inscription was a complex three-dimensional tendinous structure. Although not part of this study, it was apparent that histological studies would be required to

detail the elaborate network of layered tendinous tissue that was present. Fascicles from region A passed distally from their proximal insertions to terminate at the tendinous inscription, inserting in a staggered, layered manner. The proximal insertion sites of the fascicles of the inferior B region were also from the inscription (usually from its ventral surface), with the fascicles arranged in a similar layered fashion to those of region A. Because the inscription formed the shape of an inverted 'V', the fascicles of region B originated from both the lateral and medial aspects of the 'V', and passed inferiorly and inwards to insert into the distal tendon of ST (fig. 2a).

*Pattern of Innervation.* Two muscle nerves supplied ST in four of the specimens, with one nerve innervating the superior A region, and the other the inferior B region. In two of these specimens, the nerve to the inferior fascicles shared a common trunk with the nerve to SM. The single muscle nerve that innervated ST in two of the specimens divided into two, with one primary branch supplying the superior region and the other, the inferior. All the nerves to ST terminated in multiple branches (fig. 2a).

Terminal branches of the nerve supplying the superior fascicles entered the muscle relatively proximally on its deep surface in four specimens (between 4.2 and 12.2 cm from the ischial tuberosity). Branches of the nerve innervating the inferior fascicles entered the muscle distal to the tendinous inscription, between 7.5 and 19.0 cm from the ischial tuberosity (fig. 2b).

#### *Biceps Femoris Long Head*

*Proximal Insertion and MTJ.* The BF<sub>lh</sub> muscle inserted into the medial portion of the upper half of the ischial tuberosity via a thick, round tendon. As previously described, the proximal tendon of BF<sub>lh</sub> occupied the lateral one quarter of the upper medial portion of the ischial tuberosity, with proximal fascicles of ST inserting into the medial three quarters of this area of the tuberosity (fig. 2a). In addition, some connections with the sacrotuberous ligament were observed proximally.

The proximal tendon of BF<sub>lh</sub> was relatively long, with a mean length of 27.1 cm (range 23.4–30.2 cm), extending to occupy 61.9% of the length of the muscle (table 1). It narrowed distally to form a small, cord-like tendon complete with aponeurotic expansion on the medial aspect of the muscle (fig. 3a). The first muscle fascicles of BF<sub>lh</sub> arose from the lateral aspect of the tendon (fig. 3), over a length of 20.6 cm, thereby forming the proximal MTJ which comprised 46.8% of the length of the muscle (table 1). As reported earlier in this paper, some fascicles of ST also arose from the medial aspect of the proximal tendon of BF<sub>lh</sub>.

*Distal Tendon and MTJ.* The distal tendon of BF<sub>lh</sub> was the longest distal tendon of all the hamstring muscles, taking the form of a broad, fan-shaped aponeurosis (fig. 3b). The aponeurosis covered the entire lateral aspect of the inferior portion of the muscle belly of BF<sub>lh</sub>, and to a lesser extent that of BF<sub>sh</sub>. The length of the distal tendon of BF<sub>lh</sub> was variable (range 24.1–33.9 cm), measuring on average 27.5 cm and extending 62.6% of the length of the muscle. Consequently the distal MTJ of BF<sub>lh</sub> was long, occupying 41.4% of the length of the muscle (table 2).

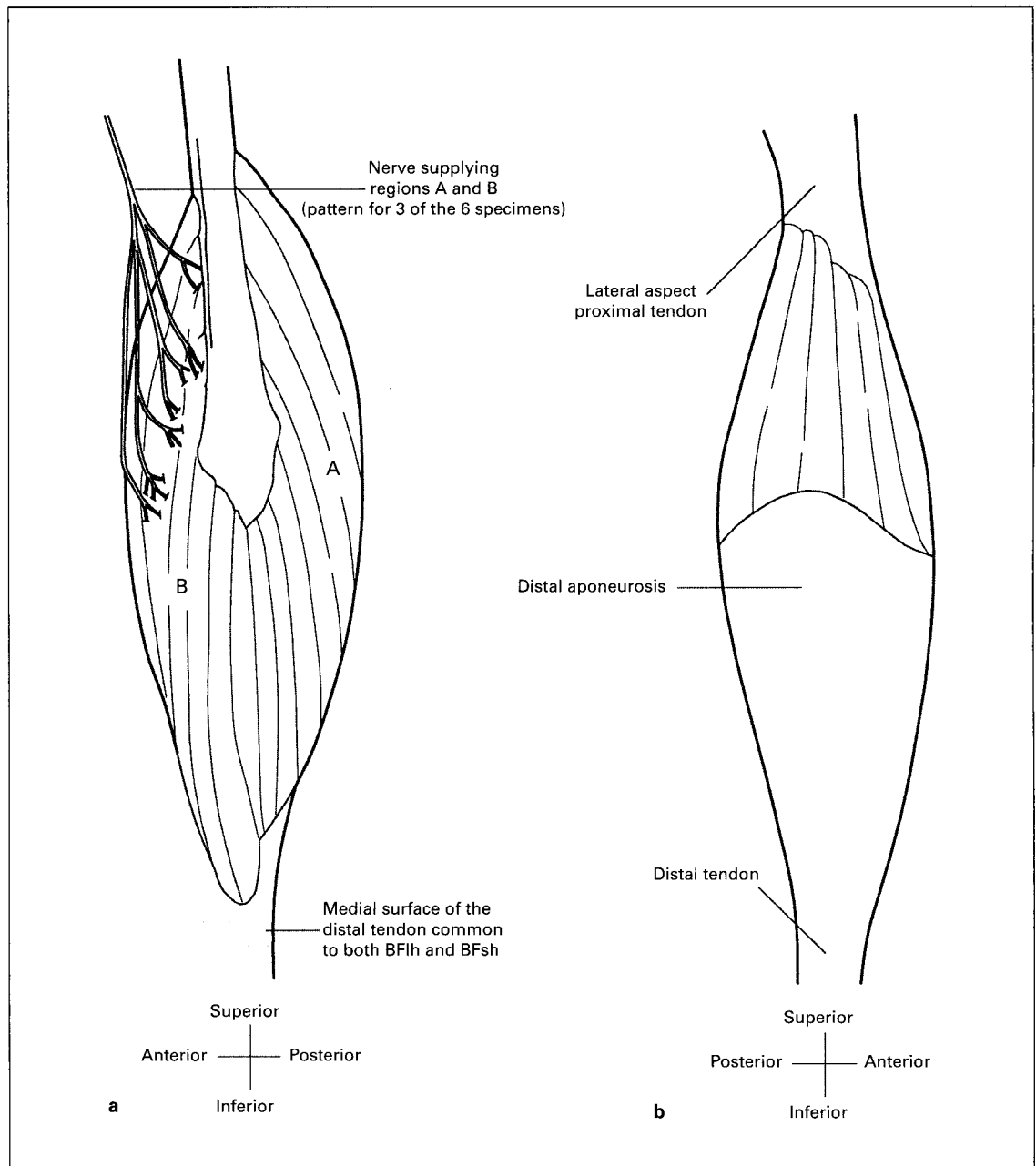
The ventral portion of the distal tendon of BF<sub>lh</sub> also formed the distal insertion site for fascicles of BF<sub>sh</sub>. From their origin, the fascicles comprising BF<sub>sh</sub> were directed inferiorly and posteriorly, passing at a different angle to those of BF<sub>lh</sub>. Consequently, fascicles from both muscles inserted into the medial surface of the distal tendon of BF<sub>lh</sub>, meeting at an angle of approximately 45°.

*Fascicle Direction.* The bulky belly of BF<sub>lh</sub> descended inferiorly and slightly laterally in its course. Based on attachment sites and fascicular direction, BF<sub>lh</sub> was bipennate in appearance, and contained two distinct regions (fig. 3a). Region A was superficial, slightly larger in size and occupied the area lateral to the proximal tendon. Fascicles arose from the lateral aspect of the proximal tendon, with the majority directed slightly laterally as they passed inferiorly. Distally, the fascicles inserted into the superficial part of the medial aspect of the distal tendon and aponeurosis of BF<sub>lh</sub> (fig. 3).

Region B was located deep to region A and the most superior muscle fascicles commenced further distally, originating from the medial aspect of the proximal tendon (fig. 3a). These fascicles passed inferiorly running obliquely posteriorly and laterally, to insert into the medial surface of the distal tendon and aponeurosis of BF<sub>lh</sub>, adjacent to the distal fibers of BF<sub>sh</sub>. Fascicles from both BF<sub>sh</sub> and BF<sub>lh</sub> inserted simultaneously into the distal tendon of BF<sub>lh</sub>, commencing at a mean distance of 27.7 cm from the ischial tuberosity. Fascicles inserted alongside each other over a mean distance of 7.1 cm, and distal to this point fascicles of BF<sub>sh</sub> continued on average a further 5.3 cm.

*Pattern of Innervation.* In all specimens BF<sub>lh</sub> was supplied by one muscle nerve. On visual inspection, this nerve branch originated from the sciatic nerve in four specimens and from the tibial nerve in two. A pattern emerged with regard to where the nerves branched from the sciatic or tibial nerves. In five specimens, this was proximal to the ischial tuberosity (range 2.8–4.0 cm), while only one branched distal to the ischial tuberosity (3.6 cm). In three specimens, the nerve divided into two



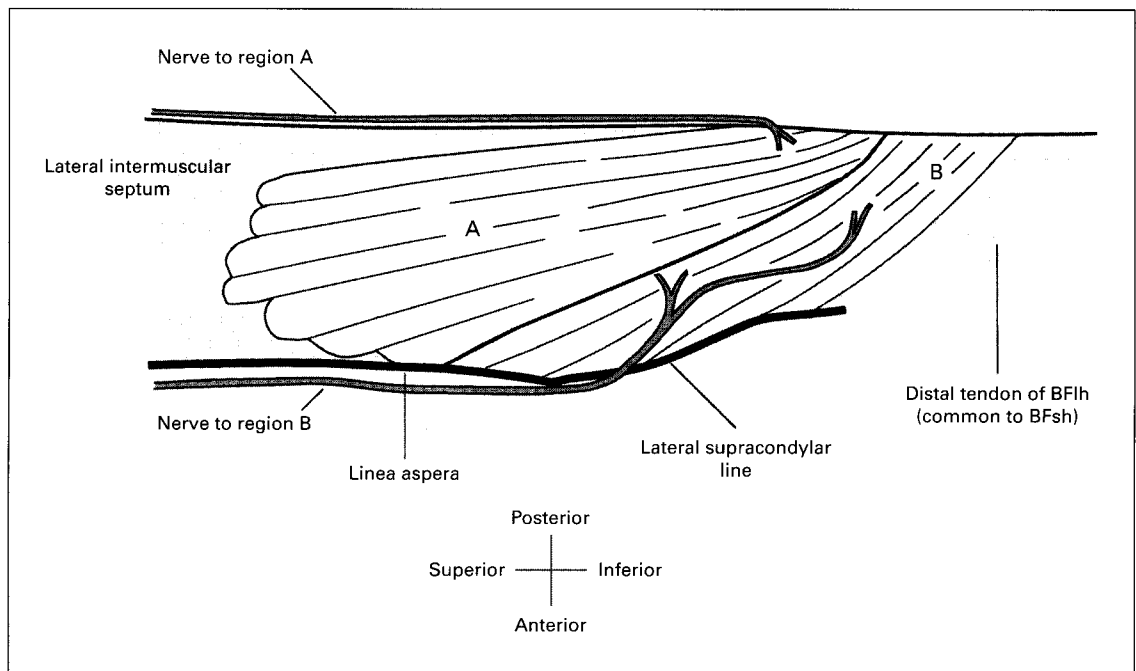


**Fig. 3.** Right biceps femoris long head. **a** Medial view. **b** Lateral view.

primary branches relatively proximally, with a branch supplying each region of the muscle. In the remaining three specimens, the nerve lay on the deep aspect of the muscle and gave off a series of branches (at least five), supplying both regions A and B as it traveled distally (fig. 3a). Multiple terminal branches were observed in all nerve branches supplying BF<sub>lh</sub>.

#### *Biceps Femoris Short Head*

**Proximal Insertions.** In all specimens, fascicles of the BF<sub>sh</sub> muscle arose below the level of the distal insertion site of the gluteus maximus muscle, commencing at a mean distance of 14.9 cm (range 12.7–16.2 cm) from the ischial tuberosity. The fascicles of BF<sub>sh</sub> arose directly from three locations: (a) the length of the linea aspera of



**Fig. 4.** Right biceps femoris short head (medial view).

the femur, (b) the upper two thirds of the lateral supracondylar line, and (c) the lateral intermuscular septum (separating BFsh from the vastus lateralis muscle) (fig. 4). With no intervening proximal tendon, fascicles that gained insertion from these three sites spanned a mean length of 15.7 cm (range 14.5–17.8 cm).

**Distal Tendon and MTJ.** As previously described, the distal tendon of BFsh was visually indistinguishable from that of BFh (fig. 3a, 4). The distal MTJ of BFsh (formed by fascicles inserting into the distal tendon of BFh) spanned 10.7 cm (range 9.2–12.8 cm), therefore occupying 36.5% of the total length of the muscle (table 2).

**Fascicle Direction.** The muscle belly of BFsh was relatively thin, but broad and long. As defined by attachment sites, fascicle orientation and nerve supply, BFsh comprised two anatomical regions (fig. 4). In two specimens the presence of a layer of connective tissue lying between the two regions further enhanced this division. The majority of fascicles comprising region A arose from the medial wall of the lateral intermuscular septum, and passed longitudinally and inferiorly to insert into the distal tendon of BFh. A few fascicles in this region also arose from the linea aspera, and ran inferiorly and posteriorly in their course. Fascicles constituting region B typically originated deep to those of region A, arising from both the ventral

aspect of the medial wall of the lateral intermuscular septum and from the linea aspera. In comparison with the fascicles in region A, these were orientated at an acute angle, passing posteriorly, inferiorly and slightly laterally towards their distal insertion site (fig. 4).

**Pattern of Innervation.** BFsh was innervated by two muscle nerve branches in five specimens, and by three in the remaining specimen. In all but one specimen, the first of these nerve branches originated from the sciatic nerve. Depending on where the sciatic nerve split, the second and third muscle nerves branched either from the lateral aspect of the sciatic or common peroneal nerves, which in the majority of cases occurred distal to the ischial tuberosity. With a total of thirteen muscle nerves supplying BFsh in six specimens, only four branched directly from the common peroneal nerve.

In all specimens, the first muscle nerve supplied region A. This nerve was embedded in connective tissue and tracked along the dorsal surface of the muscle, entering it approximately 20.0 cm distal to the ischial tuberosity. The nerve to region B traversed along the ventral aspect of the muscle, entering it anywhere between 22.2 and 34.2 cm distal to the ischial tuberosity (fig. 4). In three specimens this nerve divided, with one primary branch piercing the ventral part of the muscle, and the other pass-

**Table 3.** Morphometric data of the hamstring muscles

Muscle	Region	Fascicle number		Mean fascicular length, cm		Mean fascicular volume, ml		Mean fascicular PCSA, cm <sup>2</sup>		Total compartmental PCSA, cm <sup>2</sup>	
		mean	range	mean	range	mean	range	mean	range	mean	range
SM	A	9	6-14	5.2	3.6-6.1	2.9	1.4-4.2	0.54	0.34-0.69	4.29	1.87-5.48
	B	8	4-14	4.9	3.4-6.1	2.9	1.8-4.3	0.60	0.45-0.71	4.43	1.36-8.41
	C	11	7-14	4.9	3.1-6.2	2.9	1.9-3.9	0.61	0.37-0.77	7.03	2.60-9.63
	Whole muscle	28		5.0		2.9		0.58		15.75	5.83-23.52
ST	A	13	6-23	7.9	7.4-8.9	3.0	1.8-5.5	0.38	0.23-0.74	4.25	2.27-7.10
	B	12	7-18	8.0	5.2-9.5	2.6	1.6-4.7	0.33	0.22-0.51	3.63	2.19-6.26
	Bridging fascicles	2	1-3	14.4	13.0-18.3	1.4	0.5-2.5	0.09	0.05-0.19	0.20	0.05-0.56
	Whole muscle	27		9.0		2.7		0.27		8.08	4.67-13.40
BFlh	A	13	8-23	7.0	5.2-10.0	3.4	1.7-5.2	0.49	0.28-0.75	5.82	2.51-7.96
	B	9	3-17	6.9	4.6-10.7	3.3	1.7-4.0	0.49	0.31-0.67	4.24	0.99-6.78
	Whole muscle	22		7.0		3.4		0.49		10.06	3.50-12.31
BFsh	A	6	4-11	13.2	12.1-14.6	4.2	1.7-6.7	0.31	0.15-0.52	1.69	1.06-2.45
	B	6	3-11	11.5	10.2-13.1	3.0	1.4-3.9	0.26	0.14-0.35	1.29	0.82-1.81
	Whole muscle	12		12.4		3.6		0.29		2.98	2.12-4.26

ing dorsally before entering the muscle (fig. 4). In contrast to the rest of the hamstring muscles, the nerves supplying BFsh had very few terminal branches.

#### Morphometry

*Semimembranosus.* The mean muscle length of SM, excluding its tendons, was 26.4 cm (range 22.0-32.6 cm), in comparison to the total mean length of the muscle (inclusive of tendons) which measured 43.8 cm. On average, SM comprised 28 fascicles (range 14-37), having a mean fascicular length of 5.0 cm. At 15.75 cm<sup>2</sup>, SM had the largest mean total PCSA of all of the hamstring muscles, but variation was evident among specimens. With respect to regional PCSA, region C was the largest, comprising 45% of the mean PCSA of the whole muscle. The other two regions were relatively equal in PCSA, with 27% of the cross-sectional area attributable to region A, and 28% to region B (table 3).

*Semitendinosus.* The mean muscle length of ST (exclusive of tendons) was the longest of all the hamstring muscles at 31.6 cm (range 28.4-37.3 cm). On average ST consisted of 27 fascicles (range 13-43), and had a mean fascicular length of 9.0 cm. Incorporated into calculations of the mean fascicular length were the long fascicles bridging the tendinous inscription, that were both few in number and small in PCSA. Although there was variability between specimens with regard to fascicular morphom-

etry, the mean fascicular lengths and PCSAs of the two anatomical regions were similar. Of the total mean PCSA of the muscle (8.08 cm<sup>2</sup>), the distribution was such that region A contributed to 53% and region B to 45%, with the remaining 2% made up by the bridging fascicles (table 3).

*Biceps Femoris Long Head.* The mean muscle length of BFlh (exclusive of tendons) was 28.1 cm (range 23.6-35.5 cm), measuring 43.8 cm inclusive of tendons. On average BFlh comprised 22 fascicles (range 11-40), with a mean fascicular length of 7.0 cm. Like that of ST, when considered individually the mean fascicular lengths of each of the regions of BFlh were very similar. The total mean PCSA was 10.06 cm<sup>2</sup>, with the fascicles of region A accounting for 58% of the PCSA, compared to those of region B which accounted for 42% (table 3).

*Biceps Femoris Short Head.* Exclusive of tendons BFsh had a mean length of 25.8 cm (range 24.4-28.6 cm), and inclusive of its distal tendon it measured 29.1 cm (range 26.7-32.8 cm). On average BFsh comprised 12 fascicles (range 7-19), having the longest mean fascicular length of all the hamstring muscles (12.4 cm). However, it was the smallest in area (2.98 cm<sup>2</sup>), with region A constituting 57% of the total mean PCSA, and region B 43% (table 3).

## Discussion

To assist in the development of accurate models of muscle function, knowledge of anatomical organization is important. Human muscles are not simply homogeneous structures extending from points of origin to points of insertion, but can be arranged on the basis of architecture and/or patterns of innervation into distinct partitions or compartments [Segal et al., 1991; Segal, 1992; Johnson et al., 1994; Bakkum et al., 1996; Wolf and Kim, 1997; Wickham and Brown, 1998; Segal et al., 2002]. The premise of an anatomical partition is that a particular region within the musculotendinous unit differs from surrounding regions by at least one architectural characteristic, and that the region is innervated by a distinct primary muscle nerve [Segal et al., 1991; Segal et al., 2002].

Muscle architecture is stated to be a primary determinant of muscle function [Lieber and Friden, 2000] and can be defined as 'the arrangement of muscle fibers relative to the axis of force generation' [Lieber, 1992]. Lieber and Friden [2000] suggest that understanding the structure-function relationship of a muscle will, amongst other things, clarify the physiological basis of movement and force production, provide guidelines for electrode placement during EMG studies, and explain the mechanical basis of muscle injury during normal movement. Parameters requiring consideration when determining architecture may include muscle fiber orientation, the presence of tendinous inscriptions [Segal et al., 1991; Segal et al., 2002], muscle length, fiber length and PCSA [Lieber, 1992; Lieber and Friden, 2000], and fascicular length and PCSA [Bogduk et al., 1992; Johnson et al., 1994; Bogduk et al., 1998].

With respect to muscle architecture, muscle fiber length (number of sarcomeres in series) is proportional to maximal muscle excursion (or velocity of shortening), and PCSA proportional to maximal muscle force generation [Gans and Bock, 1965; Lieber, 1992]. Muscle fiber length may be determined by microdissection of individual fibers from muscle bundles [Loeb et al., 1987] or by use of glycogen depletion methods [Richmond et al., 1985; English and Weeks, 1987]. A difficulty inherent in microdissection techniques is the ability to isolate individual muscle fibers due to their fragility [Barrett, 1962; Loeb et al., 1987; Friederich and Brand, 1990]. Therefore, with microdissection techniques it is rare that the length of a solitary muscle fiber is measured, but instead typically between 5 and 50 fibers are used to estimate fiber length [Lieber, 2000]. This point holds true for previous

studies investigating fiber length of the hamstring muscles, in which small bundles of muscle fibers were sampled in order to calculate muscle fiber length [Barrett, 1962; Wickiewicz et al., 1983; Friederich and Brand, 1990].

This study investigates the macroanatomy of the hamstring muscles in their entirety and therefore does not employ microdissection techniques. Instead, previously documented gross anatomical methods [Bogduk et al., 1992; Johnson et al., 1994; Bogduk et al., 1998] are utilized by measuring fascicle length together with fascicle volume in order to calculate representative PCSAs of the muscles and their respective partitions. Anatomical data, including accurate representative PCSAs, are required to calculate the force output of a muscle or of a distinct portion of a muscle [Bogduk et al., 1992; Willan et al., 2002]. Once the architectural arrangement and pattern of innervation for a muscle have been established, physiological studies can be conducted to establish if the anatomical partitioning is of functional significance [Segal et al., 1991].

Several limitations of this study are acknowledged. A factor that could potentially affect fascicular dimension is the shrinkage of muscle fibers, which can occur during or after the embalming process. Reported mean values of shrinkage are variable, ranging from 2.22 to 12% [Cutts, 1988; Friederich and Brand, 1990]. With respect to age, the specimens used were elderly and therefore architectural parameters such as fascicular length and volume may be smaller than those of younger, healthier individuals. However, limitations aside, the cardinal underlying findings regarding the architecture should be similar regardless of age [Bogduk et al., 1992; Bogduk et al., 1998].

### *Semimembranosus*

Based on fascicular orientation and areas of insertion, it appears grossly that SM comprises three partitions. However, based on both architecture and pattern of innervation, only the superior A and the inferior C regions (which both received a primary nerve branch) conform to the definition of an anatomical partition as described by Segal et al. [2002]. Classification of region B was difficult, because although fascicular orientation differed from surrounding regions, suggesting partitioning on the basis of architecture, it was supplied by a secondary nerve branch (which divided from a primary branch supplying either one of the other two partitions). Therefore, region B may be a constituent of either region A or region C, or alternatively it may be a discrete anatomical partition,

given that it is possible that secondary or even tertiary branches can innervate subdivisions of whole muscles [Letbetter, 1974; English and Weeks, 1987]. This incongruency needs addressing in the future, possibly by using intramuscular electromyography which would assist in delineating these partitions. Functionally, electromyography would also aid in determining whether the described partitions activate simultaneously, or have different activation patterns during movement and gait.

The three partitions of SM are homogenous with regard to fascicular length and fascicular PCSA. Markee et al. [1955] previously described the fibers of SM as either unipennate or bipennate in arrangement. This is expanded upon in the present study with the finding that two partitions of SM are unipennate (regions A and B), while the remaining region is bipennate (region C). As observed with SM, the fascicles of a pennate muscle are arranged in parallel, and attach at an oblique angle to the long axis of the muscle [Gans and de Vree, 1987; Levangie and Norkin, 2001]. One potential disadvantage of this type of fascicular arrangement is decreased force production secondary to the angulation. However, a larger number of fascicles can potentially attach to the tendon if the insertion sites are spread along its length, thereby increasing PCSA and offsetting the reduction in force [Gans and Bock, 1965; Gans and de Vree, 1987]. It is also suggested that fibers of pennate muscles can be more easily arranged to comfortably fit into a specified or anatomical space [Gans and de Vree, 1987; Brinckmann et al., 2000]. Organization of SM and ST within the posterior thigh certainly enables both muscles to fit within the restrictions of the fascia lata, although proximally and distally, this is largely due to the arrangement of the tendons rather than the muscle bellies.

According to Lieber [1992] and Lieber and Friden [2000], fiber length and PCSA are the two most important parameters of muscle architecture. Fiber length is stated to be proportional to maximum muscle excursion (or velocity), and PCSA proportional to maximum muscle force. It is recognized that fascicular length is not the equivalent of fiber length, however it is interesting that the mean fascicular lengths of all the hamstring muscles determined in this study fell within the range of fiber lengths reported in previous studies [Markee et al., 1955; Barrett, 1962; Wickiewicz et al., 1983; Friederich and Brand, 1990]. Based on the data of Wickiewicz et al. [1983] and Friederich and Brand [1990] it is proposed, that due to their relatively long fiber length and intermediate PCSA, the hamstring muscles are designed for relatively long excursions [Lieber, 1992; Lieber and Bodine-

Fowler, 1993; Lieber and Friden, 2000]. By examining each muscle individually, this study shows that within the hamstring group each muscle differs with regard to fascicular length and muscular PCSA. SM has a relatively short fascicular length (mean 5.0 cm) but a relatively large PCSA (mean 15.74 cm<sup>2</sup>). In effect, the large PCSA of SM coupled with a short fascicular length could imply that, of the hamstring muscles, SM is designed more for force production rather than excursion.

The concept that human tendons may span long distances and extend into the muscle belly, thereby forming elongated MTJs, has previously been described in other muscles [Segal et al., 1991; Segal, 1992; Segal et al., 2002]. With the exception of Garrett et al. [1989], this notion as it pertains to the hamstring muscles is not otherwise acknowledged in anatomical texts [Romanes, 1964; Hollinshead, 1969; Basmajian, 1982; Woodburne and Burkel, 1988; Agur and Lee, 1999] or recognized in the clinical literature. In the case of SM, the proximal and the distal tendons (extending 72 and 52% of the length of the muscle) overlap to some extent within the belly of the muscle. With regard to the hamstring muscles, the importance of this architectural arrangement is paramount when considering both muscle function as well as possible injury sites, given that hamstring strain injuries often occur at, or involve a MTJ [De Smet and Best, 2000; Slavotinek et al., 2002; Koulouris and Connell, 2003].

#### *Semitendinosus*

Meeting all criteria for anatomical partitioning, ST was found to comprise two distinct regions of muscle fascicles arranged in series. Unique to ST was the presence of a tendinous inscription within the muscle belly that divided it into two partitions, with each partition receiving innervation from one muscle nerve, or from a primary branch of the nerve. This pattern of innervation is in agreement with previous reports which state that one nerve supplying ST enters the muscle above the level of the tendinous inscription, while the other enters below the inscription [Markee et al., 1955; Romanes, 1964; Hollinshead, 1969; Woodburne and Burkel, 1988; Rab et al., 1997].

This study presents a detailed gross description of the tendinous inscription of ST in humans, which manifests superficially on the posterior surface of the muscle as an inverted 'V' shape. Reports in the literature do not often mention this inscription, and when they do, no details regarding its structure are provided [Romanes, 1964; Hollinshead, 1969; Williams et al., 1995]. The tendinous inscription commences approximately a third of the way

down the muscle belly, but the fascicles comprising each region are relatively equal in length. This finding is in agreement with that of Wickiewicz et al. [1983], but differs from two other reports that suggest the fibers on either side of the inscription are of different lengths [Markee et al., 1955; Barrett, 1962]. Analysis and comparison of these results is difficult as both Barrett [1962] and Markee et al. [1955] fail to provide descriptions of their respective methodologies.

The equal fascicular lengths either side of the inscription can be explained by the organization of the fascicles within ST. As previously detailed, the fascicles of the superior A region do not originate from a single point, but arise from three distinct areas, being staggered in arrangement. Similarly, the tendinous inscription is not symmetrical in form, with fascicles inserting into what is a complex network of layered tendinous tissue dividing the muscle belly. Fascicles from region B that arise from the tendinous inscription pass to insert into the distal tendon, spreading along approximately half the length of the tendon as they do so. It is due to this staggered, parallel arrangement that the fascicles in both regions are similar in length. Because of its complex nature, the tendinous inscription of ST requires further detailed investigation in order to understand its microarchitecture and functional significance.

A very small number of fascicles (two on average), with a mean length of 14.4 cm, were found to bridge the tendinous inscription in five of the six specimens. It has been shown that muscle fibers comprising a fascicle may extend the whole length of the fascicle, or terminate within it [Barrett, 1962; Eldred et al., 1993; Heron and Richmond, 1993; Hijikata and Ishikawa, 1997; Young et al., 2000]. Short muscle fibers terminating intrafascicularly are thus positioned in series, an arrangement which is proposed to maintain the mechanical stability of long muscle fascicles by ensuring synchronous contraction along the fascicles [Loeb et al., 1987]. Although previous studies have not located intrafascicularly terminating fibers within the hamstring muscles [Barrett, 1962; Paul, 2001], they have been found within other long muscles such as sartorius and gracilis [Barrett, 1962; Heron and Richmond, 1993], as well as the external oblique muscle [Bardeen, 1903]. The evidence presented by Heron and Richmond [1993] suggests that the fibers of both gracilis and sartorius run only about one quarter to one fifth the length of the muscle. Given the long fascicular lengths of the bridging fascicles of ST, as well as those of BFsh, it is possible that intrafascicularly terminating fibers exist, and the small sample sizes in the studies by Barrett [1962]

and Paul [2001] may offer a possible explanation as to why none were found. Further investigation is required into the existence of intrafascicularly terminating fibers within the hamstring muscles, as their presence would influence factors such as neural activation and the force-developing capabilities of the muscles or muscle regions [Heron and Richmond, 1993].

Studies investigating the morphology and actions of ST have been undertaken in animals [Bodine et al., 1982; English and Weeks, 1987; Loeb et al., 1987], but the effect this architectural organization has on function is not fully understood in humans. Following electromyography studies of the hamstring muscles in cats, Bodine et al. [1982] found that the two compartments of ST can activate separately, when the isolated nerve branches innervating the muscle were electrically stimulated. However, it has also been reported that both compartments are closely coordinated with regard to activity during locomotion [Bodine et al., 1982; English and Weeks, 1987]. Verification is required regarding the proposition by Levangie and Norkin [2001] that in humans ST may have some specificity of action at both the hip and knee joints, secondary to the presence of the tendinous inscription. A better understanding of the distinct morphology of ST means that more specific electromyography studies can be undertaken to determine the activity of the two anatomical partitions during movement.

#### *Biceps Femoris Long Head*

Biceps femoris consists of two separate components, the BFlh and BFsh muscles. Although both muscles may have common actions at the knee joint, they differ with regard to proximal attachment sites and morphology. Some authors consider that proximally BFlh and ST arise from a common origin [Williams et al., 1995; Romanes, 1964; Hollinshead, 1969; Last, 1978; ], but it was clear in this study that BFlh inserts independently into the lateral one quarter of the medial portion of the ischial tuberosity.

With respect to architecture BFlh consisted of two regions, but variability was evident with regard to partitioning by way of innervation. In agreement with many previous reports [Sunderland and Hughes, 1946; Markee et al., 1955; Romanes, 1964; Hollinshead, 1969; Palastanga et al., 1989; Shanahan et al., 1993; Williams et al., 1995; Seidel et al., 1996; Rab et al., 1997; Agur and Lee, 1999; Moore and Dalley, 1999] innervation was via a single muscle nerve. This nerve divided into two primary branches in half the specimens, concurring with the findings of Markee et al. [1955] and Shanahan et al. [1993]

respectively, and in the remaining half gave off a series of branches as it traveled distally. Previous reports suggest that in some instances BFlh may be innervated by two or three primary nerves [Sunderland and Hughes, 1946; Seidel et al., 1996], but this was not confirmed in this study. However, the relatively small number of specimens examined in comparison to the twenty specimens investigated by Sunderland and Hughes [1946], and the thirty used by Seidel et al. [1996] may offer a possible explanation for the differing observations.

Because BFlh crosses two joints it could be assumed, as proposed by Lieber [1992] and Lieber and Friden [2000], that it is designed as such to allow for long excursions. Architecturally, BFlh fits the suggested parameters, in that its fascicles are relatively long and its PCSA is intermediate in size, compared with other muscles of the lower extremity. The mean fascicular length of BFlh was 7.0 cm, which was representative of both regions of the muscle. This value is less than the fiber length reported in four previous studies [Barrett, 1962; Wickiewicz et al., 1983; Friederich and Brand, 1990; Chelboun et al., 2001], although it is close to the 7.26 cm reported by Friederich and Brand [1990]. Similarly the total PCSA of the muscle is smaller, as is the muscle length (exclusive of tendons, taking into consideration that some authors include the length of the proximal tendon in their calculations). The variability evident in the literature highlights difficulties encountered comparing data from studies that differ with respect to design and sample size.

The distal tendon of BFlh extended 27.5 cm or 62.6% the length of the muscle, which is similar to the findings of Garrett et al. [1989], who stated the distal tendon and MTJ of BFlh occupy 66% the length of the muscle. Similar to SM, the long distal and proximal tendons and MTJs of BFlh overlapped within the muscle belly, a trait that again requires consideration when developing clinical and biomechanical models of the muscle.

A unique feature of the distal tendon of BFlh is that it also receives fascicles from BFsh. There is little disagreement regarding this in the literature, however, no previous reports specifically document the site at which the fascicles of BFsh commence distally on the tendon of BFlh, or the area of the tendon that they occupy. The fibers of both muscles are arranged in such a way that they insert into the distal tendon of BFlh at an angle of approximately 45° to each other, which may have functional implications. If the fibers of each muscle can be activated separately, they would generate different angles of pull, resulting in a total vector force that is a summation of the force vectors of each region [Segal et al., 2002].

#### *Biceps femoris Short Head*

At least two anatomical partitions exist within the muscle of BFsh, as defined by characteristics of both architecture and innervation. In the majority of specimens, the two distinct regions demarcated by fascicular direction were each innervated by a single muscle nerve. However, in half the specimens, the nerve to region B split into two primary branches, which may indicate the presence of a further partition. The location of penetration of the most distal primary branch suggests the possibility that those fascicles arising from the lateral supracondylar line may in some cases form an additional partition or subpartition.

Little prior evidence exists that BFsh is innervated by more than one muscle nerve as textbooks generally imply innervation by a single nerve, as do two research papers addressing this topic [Markee et al., 1955; Hayashi and Maruyama, 2001]. Sunderland and Hughes [1946] are the only authors to report nerve supply from more than one nerve, with two muscle nerves noted in 30% of the specimens investigated. The described pattern of innervation was relatively uniform, with one nerve arising from the common peroneal nerve, and the other branching from the sciatic nerve. In this study all specimens received at least two muscle nerves, and variability was evident in patterns of branching. This variability may be explained by observed differences between specimens in the point at which the sciatic nerve divided into its common peroneal and tibial components.

With respect to insertion sites, it is noted that the lateral intermuscular septum is often omitted as one of the proximal insertion sites of BFsh in anatomical textbooks [Last, 1978; Basmajian, 1982; Jenkins, 1998; Agur and Lee, 1999; Moore and Dalley, 1999]. This is difficult to understand given the significant contribution that fascicles arising from this site give to the muscle (forming most of region A). The association of BFsh with the lateral intermuscular septum has previously been specified in one dissection report. Hayashi and Maruyama [2001] found that fibers of BFsh arose from the distal three quarters of the posterior aspect of the lateral intermuscular septum. This contrasts with the findings of the present study, as fascicles of BFsh occupied a small portion of the length of the lateral intermuscular septum (12.6 cm), mostly arising from the middle, rather than the distal section. The methods used by Hayashi and Maruyama [2001] to determine the sites of attachment of BFsh along the lateral intermuscular septum were not described in detail, and therefore comparison of results is difficult.

BFsh crosses only one joint, but was found to have the longest fascicular length of all the hamstring muscles, concurring with previous reports of fiber length [Barrett, 1962; Wickiewicz et al., 1983; Friederich and Brand, 1990]. Further research is required to determine if fibers within the fascicles run the whole length of the fascicle, or if they are arranged in series, terminating intrafascicularly. The PCSA of BFsh was small, particularly in comparison with the other hamstring muscles, therefore the magnitude of forces exerted by this muscle are likely to be small.

Due to its location, it has been suggested that as well as contributing to knee joint flexion, together with BFlh, BFsh laterally rotates the tibia on the femur when the knee joint is flexed [Paterson, 1917; Kaplan, 1962; Hollinshead, 1969; Last, 1978; Palastanga et al., 1989; Williams et al., 1995; Cutter and Kevorkian, 1999; Moore and Dalley, 1999]. Electromyography studies could be performed to determine if the architectural partitions and innervation patterns of BFsh observed in this study relate to the proposed functions of the muscle. This may lead to a better understanding of the role that BFsh has in

movements at the knee joint, and also how it functions in relation to BFlh, particularly as both muscles receive different nerve supplies.

## Conclusions

The morphology of each individual muscle within the hamstring complex is different, as each is unique with respect to architectural characteristics. All of the hamstring muscles demonstrated anatomical partitioning defined by architecture and/or pattern of innervation. However, of the four muscles investigated, ST was the only muscle for which each partition could be defined on the basis of both architecture and innervation. In addition, this division into partitions was augmented by the presence of a tendinous inscription. When considering architectural parameters such as fascicular length, volume and PCSA, variation was evident between specimens, and this requires consideration to ensure accuracy when designing clinical and biomechanical models.

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