van der Made, A.D., Wieldraaijer, T., Kerkhoffs, G., Kleipool, R.P., Engebretsen, L., van Dijk, C.N., Golanó, P. (2013). The hamstring muscle complex. *Knee Surgery, Sports Traumatology, Arthroscopy*. doi:10.1007/s00167-013-2744-0

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*Title Page

The hamstring muscle complex

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Keywords: hamstring muscles, biceps femoris, semitendinosus, semimembranosus, anatomy, injury mechanism

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Abstract

Purpose: The anatomical appearance of the hamstring muscle complex (HMC) was studied to provide hypotheses for the hamstring injury pattern and to provide reference values of origin dimensions, muscle length, tendon length, musculotendinous junction (MTJ) length as well as width and length of a tendinous inscription in the semitendinosus muscle known as the raphe.

Methods: Fifty-six hamstring muscle groups were dissected in prone position from 29 human cadaveric specimens with a median age of 71.5 years (range 45 to 98).

Results: Data pertaining to origin dimensions, muscle length, tendon length, MTJ length and length as well as width of the raphe were collected. Besides these data we also encountered interesting findings that might lead to a better understanding of the hamstring injury pattern. These include overlapping proximal and distal tendons of both the long head of the biceps femoris muscle (BFlh) and the semimembranosus muscle (SM), a twist in the proximal SM tendon and a tendinous inscription (raphe) in the semitendinosus muscle (ST) present in 96% of specimens.

Conclusion: No obvious hypothesis can be provided purely based on either muscle length, tendon length or MTJ length. However, it is possible that overlapping proximal and distal tendons as well as muscle architecture leading to a resultant force not in line with the tendon predispose to muscle injury, whereas the presence of a raphe might play a role in protecting the muscle against gross injury. Apart from these architectural characteristics that may contribute to a better understanding of the hamstring injury pattern, the provided reference values complement current knowledge on surgically relevant hamstring anatomy.

Level of evidence: Level IV

Introduction

Injuries of the hamstring muscle complex (HMC) are common in many sports such as soccer, American football, Australian rules football, athletics, and water skiing [5,21,23,24,26]. Both hamstring muscle strains and avulsions occur proximally rather than distally with the long head of the biceps femoris (BFlh) most frequently injured [15,20]. Even though there is no consensus on the topic, the semimembranosus (SM) is regarded as the second most injured hamstring muscle [15]. The most vulnerable part of the muscle-tendon-bone unit is the musculotendinous junction (MTJ) [4,9,15]. The MTJ is the region of the muscle that transmits the force generated by the muscle fibers to the tendon which subsequently transmits the force to the bone [10]. Although evidence regarding the exact localisation of hamstring injury is not in agreement (in the MTJ [9] vs. adjacent to the MTJ [10,12]), it is clear that this region plays a pivotal role in the hamstring injury pattern.

Although studies concerning the hamstring injury pattern exist, a clear understanding of this injury pattern is still lacking. In this study we aim to provide an explanation for the above mentioned hamstring injury pattern by studying the anatomical appearance of the hamstring muscle complex.

Several studies [11,15-17,25] mention the presence of a tendinous inscription, known as the raphe, dividing the m. semitendinosus (ST) in two distinct parts, causing the ST to be occasionally regarded as a digastric muscle. In this study the raphe is also covered because it is a part of hamstring anatomy and might play a role in the hamstring injury pattern.

Most hamstring strains or tears can be treated conservatively, but proximal hamstring avulsions can cause significant disability and may need surgery [6,8]. Surgery is indicated in active patients with an avulsion of the entire HMC or 1- or 2-tendon avulsion with a retraction of >2 cm [7]. Since there seems to be a recent trend towards a surgical approach for this injury, surgical anatomy of this region is important.

This work studies the anatomical appearance of the HMC and:

1. provides a hypothesis for the hamstring muscle injury pattern in which injury occurs mainly proximal with a particular high injury incidence of the biceps femoris.
2. provides reference values of origin dimensions, lengths of the m. biceps femoris (long head, BFlh), m. semitendinosus (ST) and m. semimembranosus (SM), lengths of their

tendons and subsequently the calculated lengths of their MTJ's as well as references values of length and width of the raphe in the ST.

Materials and Methods

Fifty-six hamstring muscle groups were dissected from twenty-nine human cadaveric specimens of the whole body donation program of the department of Anatomy, Embryology and Physiology of the Academic Medical Center, that were embalmed using an alcohol-based solution consisting of 32% ethanol, 0.33% phenol, 7.08% glycerol and 2.4% formaldehyde. They were subsequently conserved using 8.3% ethanol, 0.21% phenol and 16.7% glycerol.

No sample size calculation was performed prior to the measurements. The number of specimens dissected was the maximum of specimens that was available to us.

After reflecting the skin and subcutaneous tissue of the entire lower limb, leaving the musculature exposed, both the gluteus maximus and medius muscle were subsequently split to both sides using a longitudinal incision to reveal the hamstring origin on the ischial tuberosity. After gently removing fascia and excess fat, the muscle morphology was studied, measured with standardized tape measures and recorded using a digital camera (Sony Cyber-shot DSC-W200). The standardized tape measure allows measurements to be presented in one decimal. Mean values and standard deviation were subsequently calculated using SPSS©.

The total length of each separate hamstring muscle was measured as follows: the BFlh was measured from the ischial tuberosity and the short head of the biceps femoris (BFsh) from its most proximal origin on the lateral femur to their common insertion on the head of the fibula. The ST was measured from its common origin with the BFlh on the ischial tuberosity to the pes anserinus on the medial surface of the proximal tibia. The SM was measured from the ischial tuberosity to its insertion on the posteromedial aspect of the proximal tibia.

The length of the proximal tendon of each separate muscle was described as following:

- Total tendon length: measured from ischial tuberosity to where the tendon was no longer visible as it continued into the muscle.
- Free tendon length: measured from the ischial tuberosity to where muscle fibers started to insert into the tendon.

This was also done for distal tendons, measured from their insertion instead of from the ischial tuberosity. MTJ's could be calculated by subtracting the length of the free tendon from the total tendon length.

Subsequently, the width and height of the BFlh/ST common origin and the SM origin on the ischial tuberosity and of the BFsh on the lateral femur were studied and recorded.

Next, the partitioning of the common origin (conjoint tendon) of the BFlh and ST into their separate muscles was studied by careful blunt separation while removing cohesive fascia, until common muscle fibers could no longer be separated in this way. The distance to the ischial tuberosity at which the common tendon divided into two separate tendons was measured. The same was done in defining the partitioning of the SM muscle from the ST/BFlh muscles near their origin on the ischial tuberosity. Also the distance between the ischial tuberosity and the point at which the muscles parted was measured.

The length of the raphe of the ST was studied by examining its nearest and furthest distance from the ischial tuberosity, alongside its maximum width.

Results

Seventeen of twenty-nine cadaver specimens were female, the other twelve were male. Median age was 71.5 years (range 45 to 98).

Hamstring muscles

Mean hamstring muscle length including standard deviation can be found in table 1.

Origin dimensions

The common origin of the BFlh/ST muscles was found on the posteromedial aspect of the ischial tuberosity and measured 2.6±0.4 cm medial-to-lateral and 1.8±0.2 cm anterior-to-posterior. In addition to the common origin, muscle fibers of the ST were often seen attaching directly onto the ischial tuberosity.

The origin of the SM was located anterior to the common BFlh/ST origin, with anterolateral positioned variations. A SM origin purely located lateral of the common BFlh/ST origin was found in only two hamstrings, belonging to the same specimen. The SM origin measured a mean 1.3±0.3 cm medial-to-lateral and 1.1±0.5 cm anterior-to-posterior. Proceeding distally, the tendon attaching to this origin twists from anterolateral of the common BFlh/ST tendon to posteromedial where it ends as a wide tendon sheet before proceeding in the SM.

The BFsh has a long origin in the proximal-to-distal direction. Mean distances of the start and end of this origin measured as distance to ischial tuberosity were 12.8±3.4 and 28.1±4.1 respectively, so mean length of this BFsh origin was calculated to be 15.3 cm (figure 1a & 1b).

Tendon and MTJ lengths

Mean lengths of free tendon, total tendon and MTJ are given in table 2. Note that the distal tendon of the biceps femoris is a common tendon of the long and short head.

When proximal and distal total tendon lengths of a muscle are displayed as in figure 2, it becomes clear that proximal and distal tendons (and thus also the MTJ) of the biceps femoris (long head) and semimembranosus overlap. This means that the middle sections of these muscles have attachments to both the proximal and distal tendon (figure 2). This is not the case for the ST.

Raphe

A raphe, or tendinous inscription, was present in the ST in all but two ST muscles that belonged to the same specimen (54/56 = 96%). This raphe runs in a proximal-to-distal direction and measured a mean 9.0 cm in length with a maximum width of 3.0 cm medial-to-lateral. The length of this raphe comprises 20.3% of ST muscle length (figure 3, 4a & 4b).

Muscle partitioning

The BFlh and the ST have a common origin and a common tendon originating from the ischial tuberosity which ultimately divides into two separate tendons at a mean distance of 9.1±2.3 cm from the ischial tuberosity (figure 3, 4a & 4b).

The most proximal part of the SM tendon is conjoint with the BFlh/ST common tendon and gets separated at a mean distance of 2.7±1.0 cm from the ischial tuberosity (figure 3, 4a & 4b).

Discussion

The most important findings of the present study were architectural characteristics of the hamstring muscle complex that may very well play a role in the hamstring injury pattern. On top of that, reference values of a relatively large number of specimens were provided.

These architectural characteristics lead to new hypotheses concerning the hamstring injury pattern. Note that these hypotheses are not solid explanations for the injury pattern, but serve to inspire new research.

Injury pattern

According to Askling et al. [1,2], a distinction can be made between two injury mechanisms leading to injury of a different muscle at a different site. Hamstring injuries sustained during high-speed running usually affect the BFlh at a mean distance of 6.7 cm distal to the ischial tuberosity [1]. According to our data this is located at the MTJ. The most prevalent secondary injury was located in the ST [1]. Hamstring injuries sustained during stretching with a combination of extensive hip flexion and knee extension are usually located in the SM at a mean distance of 2.3 cm distal to the ischial tuberosity [2]. Taking our data in account, this injury occurs at the free tendon of the SM.

For both of these hamstring injury patterns, no obvious hypothesis can be provided purely based on either muscle length, tendon length (both free tendon and total tendon) or MTJ length. Measuring these data as a proportion of total muscle length also did not contribute to this cause. However, there are some interesting findings to report from this study regarding the hamstring injury pattern.

As discussed above, the most frequently injured muscles are the BFlh during high-speed running and the SM during extensive stretching. Our data show that the proximal and distal tendons of both the BFlh and the SM overlap (figure 2). This muscle architecture might very well be a predisposing factor to injury and should be considered in future (biomechanical) studies.

The proximal SM tendon proceeds distally with a twist before ending as a wide tendon sheet. This has been confirmed by Woodley/Mercer [25]. It could very well be that this twist causes a resultant force that is not in line with the direction of the tendon, making the muscle vulnerable to injury at this point. Future studies should aim to study the dynamic interaction of the muscle-tendon-bone complex. It is conceivable that not only individual muscle characteristics, but also dynamic interaction between proximal tendons predisposes to muscle injury (e.g. tendons twisted around each other may create a lever arm during contraction).

The tendinous inscription found in the ST ('raphe') is also a potential factor of influence in the injury pattern. It seems that the raphe could play a role in protecting the ST against gross injury considering the low frequency of injury [1,2,15] in this muscle and the unique appearance of the raphe, but future studies are required to elucidate the role of the raphe in the injury pattern.

<u>Measurements</u>

The anatomy of the hamstring muscle complex has been studied and measured by several other authors [3,11,13,14,16-18,22,25].

Data on total muscle length corresponds well with data of other studies [13,14,16,25], with some exceptions that are likely attributable to different measuring methods.

Four other studies [3,13,14,25] measured tendon lengths and show great variety of data between studies. Like total muscle length, this is also probably due to different measuring methods.

The common BFlh/ST tendon divides into two separate tendons at a mean distance of 9.1±2.3 cm from the ischial tuberosity. These findings correspond well with those of Miller et al. [18] and Garrett et al. [11] who found this division at a mean distance of 9.9±1.5 and approximately 10 cm from the ischial tuberosity.

The most proximal part of the SM tendon is conjoint with the BFlh/ST common tendon and gets separated at a mean distance of 2.7±1.0 cm from the ischial tuberosity. Garrett et al. [11] described this division more distally, at approximately 5 cm from the ischial tuberosity. Possible explanations for these different findings could be the technique of blunt separation of cohesive fascia, and the extent to which these were removed.

The anterolateral positioned origin of the SM as reported by Woodley/Mercer [25] and Sato et al. [22] has been confirmed by this study. However, origin dimensions of the common BFlh/ST as described by Miller et al. [18] did not correspond with our findings. Aside from the origin dimensions, we also found the BFlh/ST and SM origins to be positioned differently. Miller et al. described the SM origin as located purely lateral of the common BFlh/ST origin, which we only found in 2 of the 56 hamstring complexes, belonging to the same specimen.

Several studies mention the existence of a tendinous inscription in the ST [11,15-17,25]. This inscription, or raphe, architecturally divides the ST into two muscle bellies, making it a digastric muscle. It was found in 96% of our specimens (54/56). Woodley/Mercer [25] described this 'raphe' as a complex 3D-structure dividing the ST into two regions. They described it as a V-shaped tendinous inscription with a medial and lateral arm spanning a mean 2.8 and 6.7 cm respectively. We did not confirm the V-shape, possibly due to the fact that we only approached it posteriorly.

Despite differences in certain findings we feel confident about the acquired results, due to the fact that we had a considerable number of specimens to study. This study has reported architectural characteristics of the hamstring muscle complex that lead to a series of hypotheses that aim at a better understanding of the hamstring injury pattern. Apart from these characteristics, reference values complement current knowledge on surgically relevant hamstring anatomy. Furthermore, the different outcome in dimensions of the common ST/BF origin and SM origin provides discussion that could result in a revision of the origin of the proximal hamstring tendons, thereby having consequences for surgical reattachment in case of a complete proximal hamstring avulsion.

There were limitations in this study that deserve mentioning. Woodley/Mercer [25] described the raphe as a complex 3D-structure. This is the case for the entire anatomy of the hamstring muscle complex. However, our measurements were performed with the specimens in prone position because they were simultaneously used for educational purposes.

Also, median age of the specimens was relatively high (71.5 years). This could play a role since ageing is known to be of influence on muscle architecture (e.g. shortening of muscle fascicles) [19].

In short, these factors may have contributed to differences in certain measurements between our study and the ones discussed.

Conclusion

No definite hypothesis for the hamstring injury pattern can be provided purely based on either muscle length, tendon length (both free tendon and total tendon) or MTJ length. It is possible that overlapping proximal and distal tendons as well as muscle architecture leading to a resultant force not in line with the tendon predispose to muscle injury, whereas the presence of a raphe might play a role in protecting the muscle against gross injury. Future studies are required to confirm or reject these hypotheses.

Besides studies regarding individual muscle characteristics, future studies should also focus on dynamic interaction between bone-tendon-muscle complexes of the hamstrings.

Conflict of interest

The authors declare that they have no conflict of interest.

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Tables

	Mean length (cm)
Biceps femoris (long head)	42.0±3.4
Biceps femoris (short head)	29.8±3.9
Semitendinosus	44.3±3.9
Semimembranosus	38.7±3.5

Table 1. Mean lengths of hamstring muscles.

	Muscle	Free tendon length in cm (length as a proportion of muscle length)	Total tendon length in cm (length as a proportion of muscle length)	MTJ length in cm (length as a proportion of muscle length)
Proximal	BFlh	5.0±3.4 (12%)	19.6±4.1 (47%)	14.6 (35%)
	ST	0.2±0.7 (0.4%)	12.4±3.6 (28%)	12.2 (28%)
	SM	9.4±2.6 (24%)	24.3±3.9 (63%)	14.9 (39%)
Distal	BF	9.1±3.0 (22%)	26.2±2.9 (62%)	17.1 (41%)
	ST	13.2±2.9 (30%)	24.9±3.7 (56%)	11.7 (26%)
	SM	5.5±1.9 (14%)	22.0±3.3 (57%)	16.5 (43%)

Table 2. Mean lengths of free tendon, total tendon and MTJ per muscle including length as a proportion of muscle length. (BF = Biceps femoris, BFlh = long head of the biceps femoris, ST = Semitendinosus & SM = Semimembranosus)

Figures

Fig. 1 a Posterior view of the right coxal bone showing the ischial tuberosity which can be divided into two regions. 1. Upper region. 2. Lower region. 3. Vertical ridge, which divides the upper region in two facets. 4. Lateral facet, for insertion of the tendon of the semimembranosus muscle. 5. Medial facet, for insertion of the conjoint tendon of the long head of biceps femoris and semitendinosus muscle. 6. Sciatic spine. 7. Greater sciatic notch. 8. Lesser sciatic notch. 9. Acetabulum. **b** Osteoarticular dissection showing the insertions in the ischial tuberosity. 10. Sacrospinous ligament. 11. Sacrotuberous ligament. 12. Adductor longus ischial origin

Fig. 2 Muscle and tendon lengths of the hamstring muscle complex. Total tendon length was measured from the muscle origin to where the tendon was no longer visible as it continued into the muscle. Free tendon length was measured from the muscle origin to where the muscle fibers started to insert into the tendon
(BF = Biceps femoris, ST = Semitendinosus & SM = Semimembranosus)

Fig. 3 Anatomical dissection showing the muscular characteristics of the semitendinosus muscle. 1. Semitendinosus muscle. 2. Raphe. 3. Length of the raphe (mean 9.0 cm). 4. Width of the raphe (3.0 cm maximum). 5. Semitendinosus tendon. 6. Long head of biceps femoris muscle. 7. Short head of biceps femoris muscle. 8. Biceps femoris tendon. 9. Ischial tuberosity. 10. Conjoint tendon (Long head of biceps femoris and semitendinosus muscles)

Fig. 4 Dissection of the hamstring tendons. **a** Normal topographic anatomy. **b** The semitendinosus and long head of biceps femoris muscles have been rejected laterally to observe its relationship with the ischial origin of the semimembranosus muscle. 1. Semitendinosus muscle. 2. Raphe of semitendinosus muscle. 3. Semimembranosus muscle. 4. Long head of biceps femoris muscle. 5. Ischial tuberosity. 6. Sacrotuberous ligament. 7. Great trochanter. 8 Sciatic nerve. 9. Gluteus maximus (cut and rejected)

Figure 1a

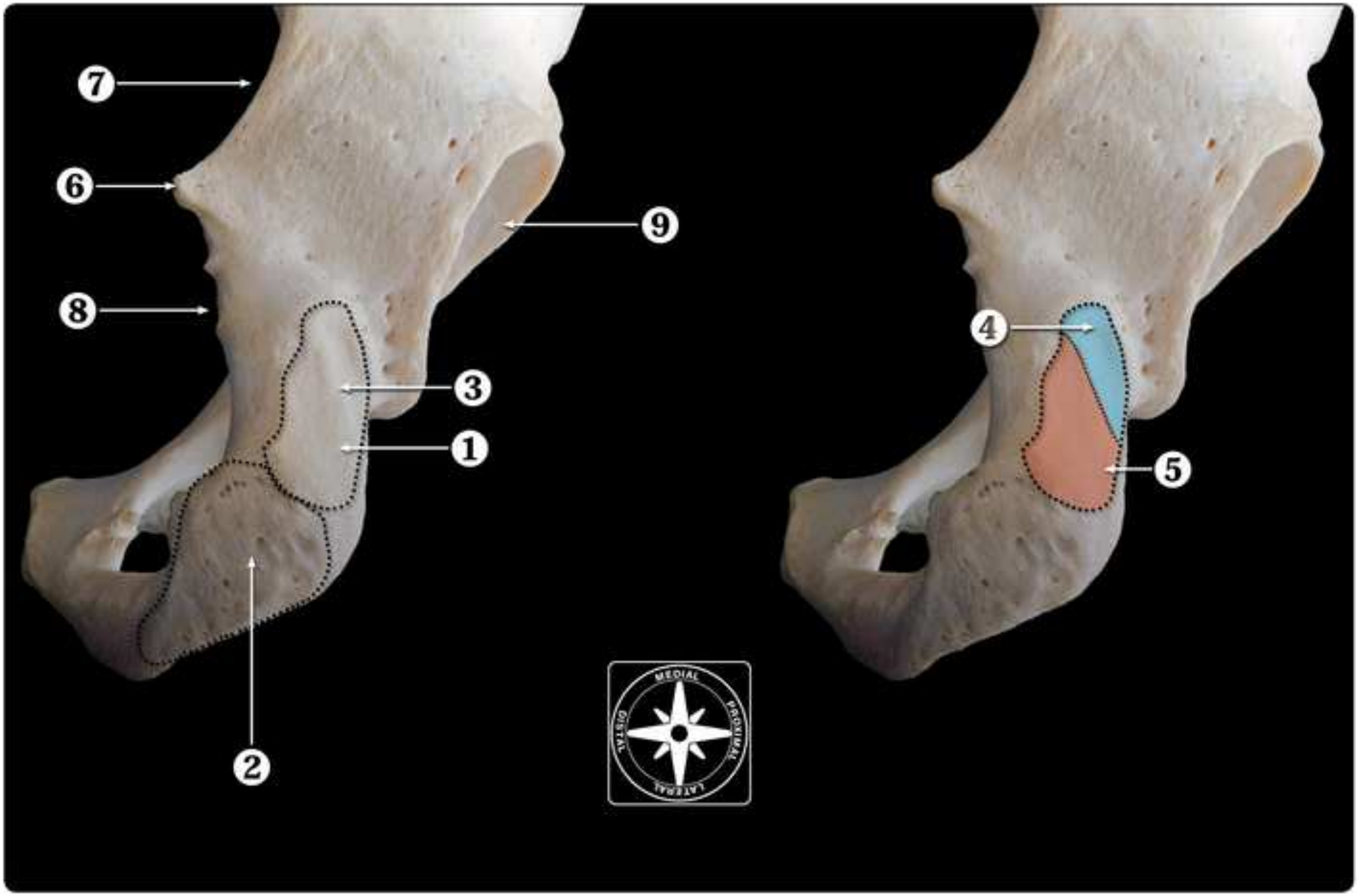


Figure 1b

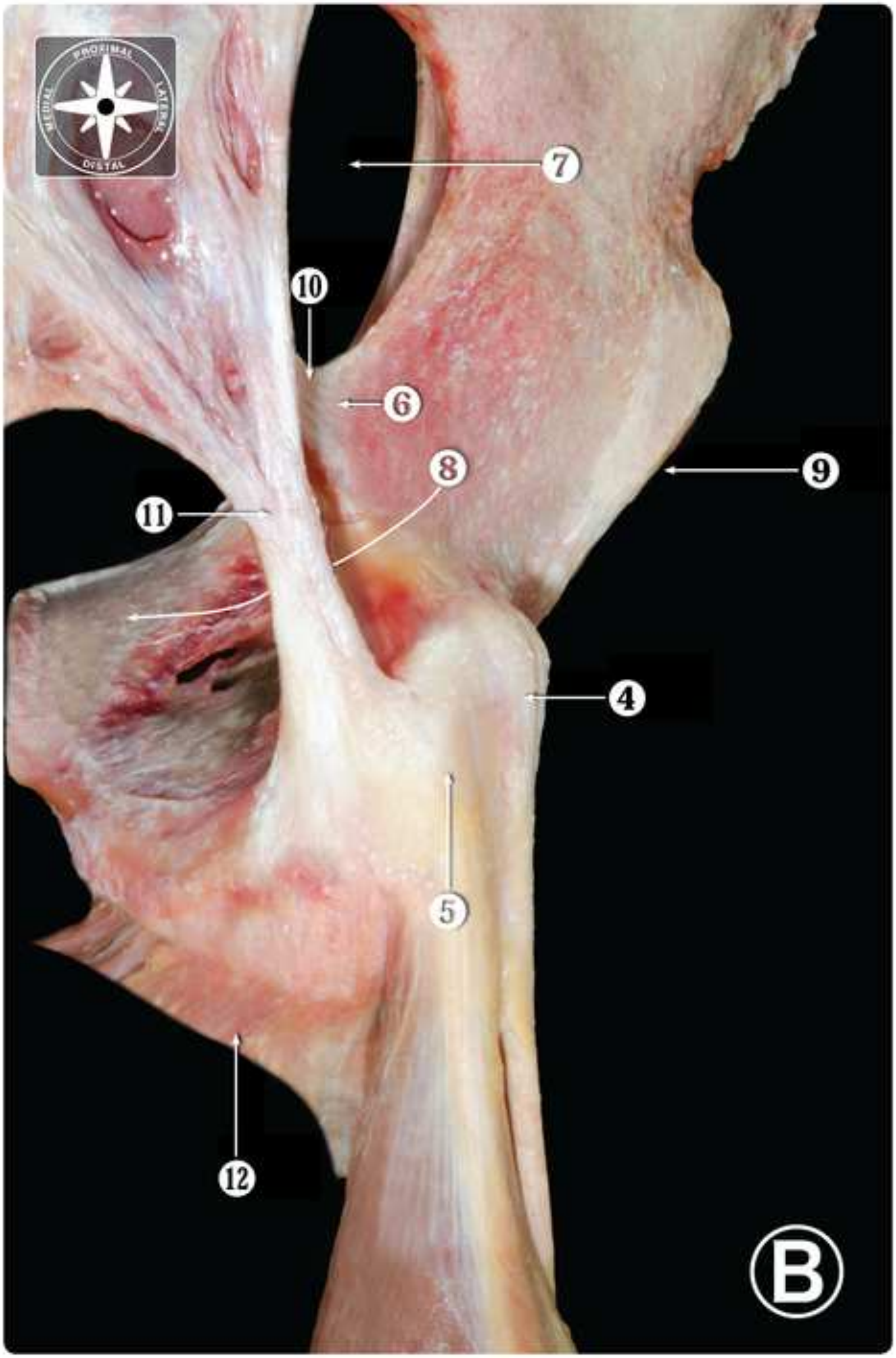
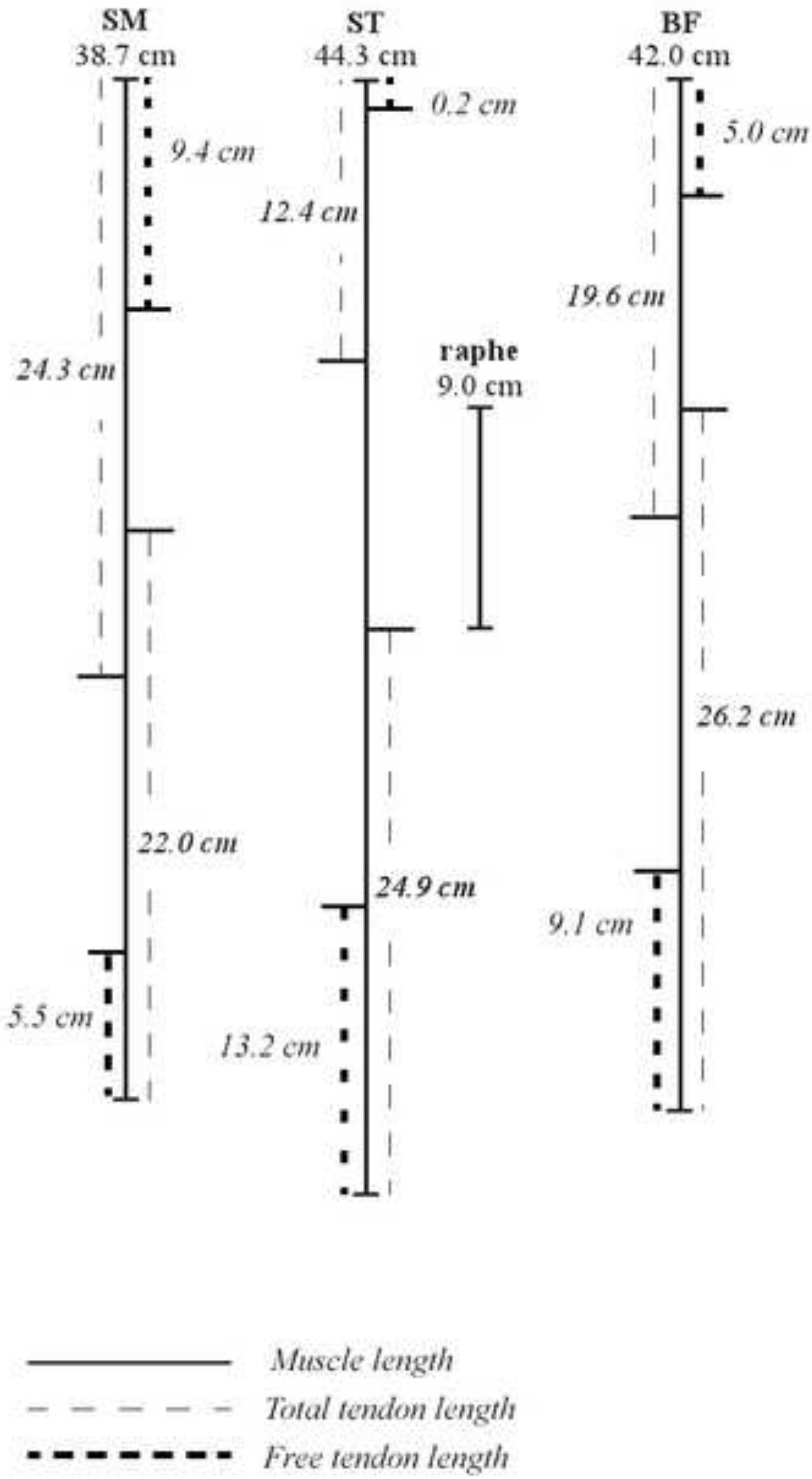


Figure 2



SM
38.7 cm
9.4 cm
24.3 cm
22.0 cm
5.5 cm
ST
44.3 cm
0.2 cm
12.4 cm
24.9 cm
13.2 cm
raphe
9.0 cm
BF
42.0 cm
5.0 cm
19.6 cm
26.2 cm
9.1 cm
Muscle length
Total tendon length
Free tendon length

Figure 3

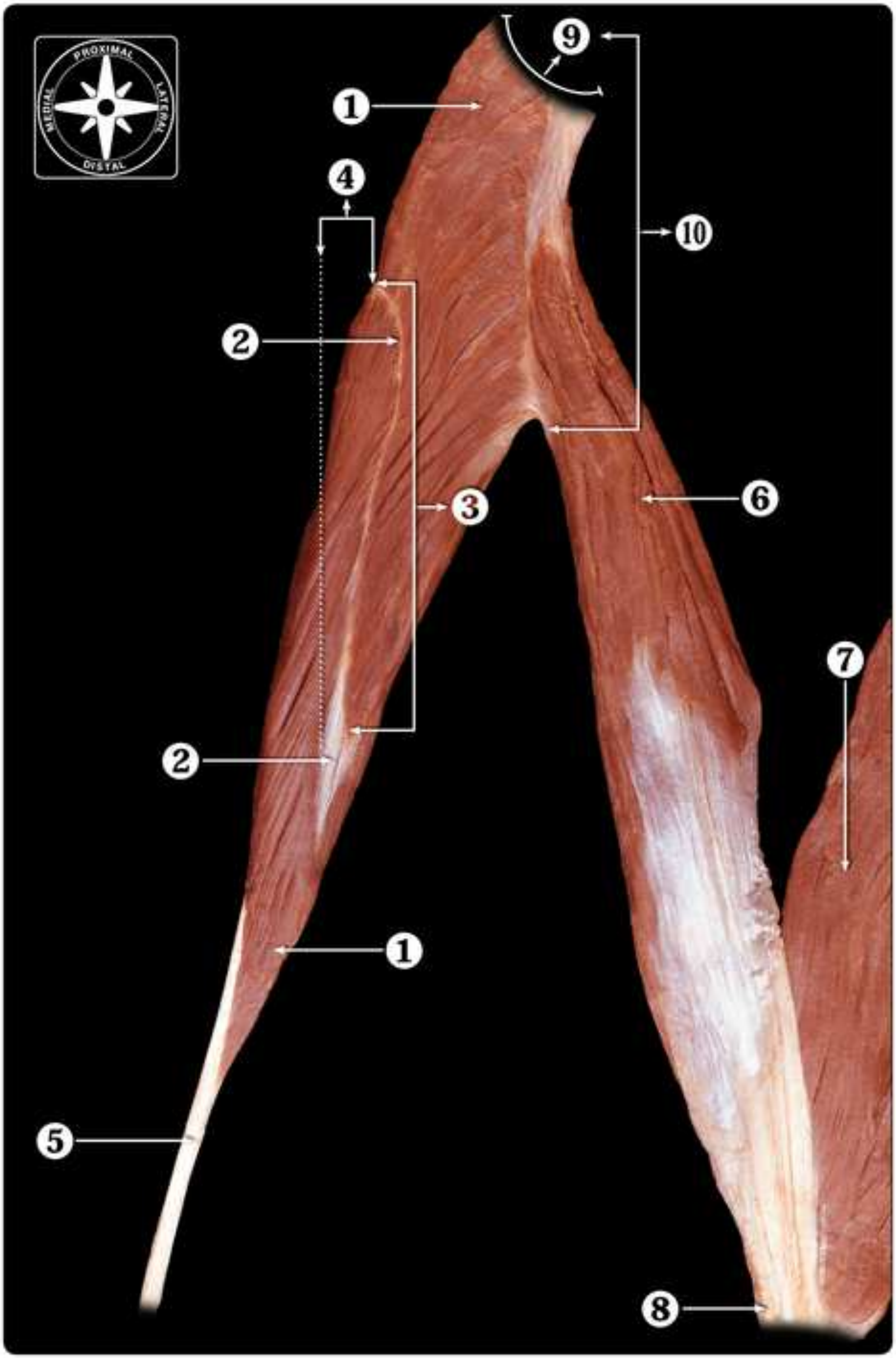


Figure 4a

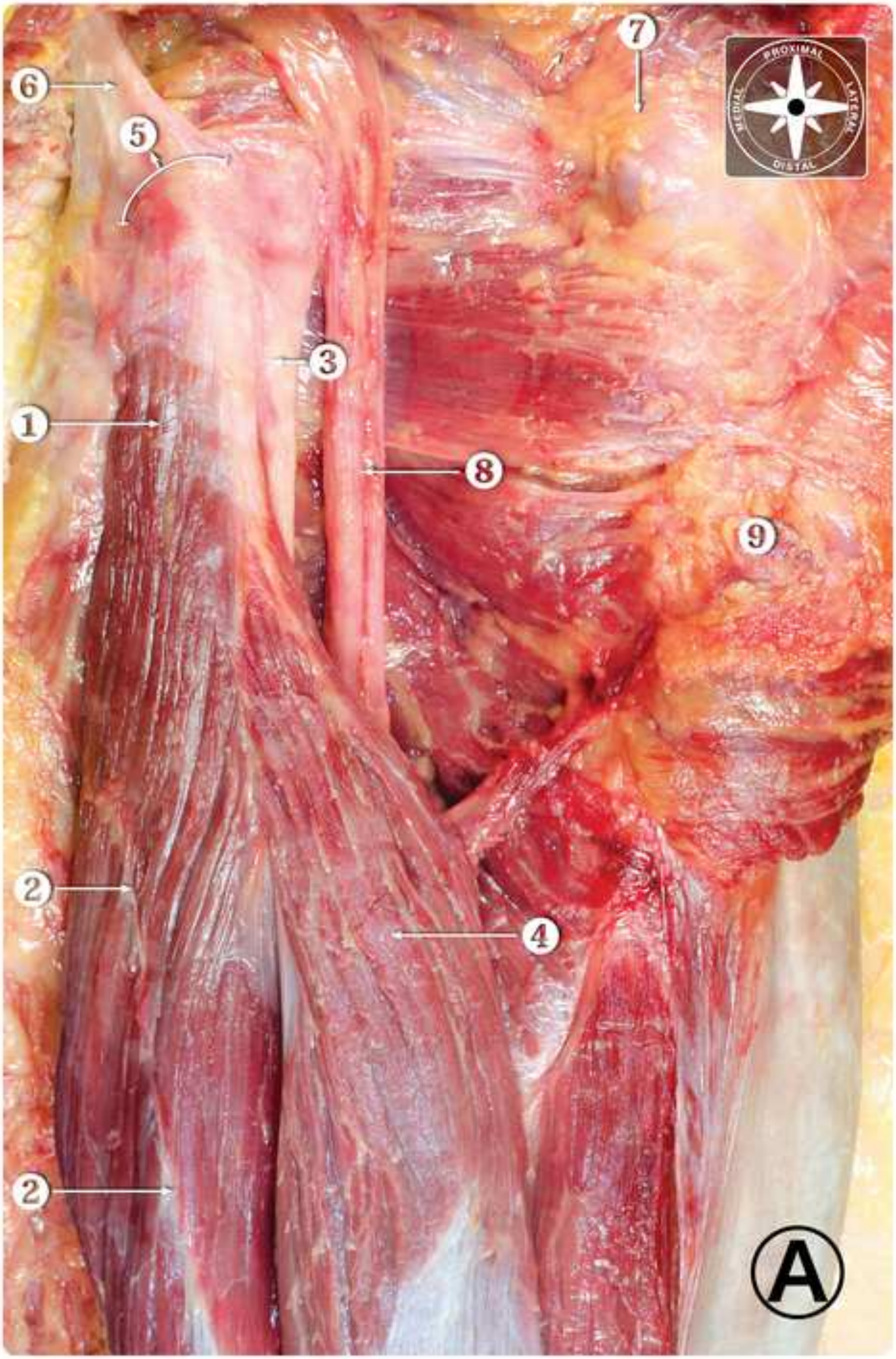


Figure 4b