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ORIGINAL COMMUNICATION

A Proposed Novel Function of the Psoas Minor Revealed Through Cadaver Dissection

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There is sparse information about the anatomy and function of the psoas minor, specifically the extent and frequency to which the muscle attaches into the iliac fascia that drapes over the iliopsoas. This information may help clarify the function of the psoas minor, especially regarding the possibility of controlling the position and mechanical stability of the underlying iliopsoas. This descriptive, semiquantitative cadaveric study sought to clarify the gross anatomic detail of the psoas minor, particularly the muscle's distal attachments. Thirty-two embalmed cadaver hips were examined. Hips that presented with a psoas minor underwent further anatomic measurements. The psoas minor was present in 65.6% of the 32 hips. All of the psoas minor tendons attached firmly into iliac fascia, while 90.5% also had a firm bony attachment to the pelvis. On average, the muscle belly occupied the proximal 37.5 ± 6.0% of the entire musculotendinous unit, while the muscle belly's average anatomical cross-sectional area was 52.5 ± 34.3 mm^2. The psoas minor's firm and consistent distal tendinous attachment into the iliac fascia may allow this muscle to partially control the position and mechanical stability of the underlying iliopsoas as it crosses the femoral head and adjacent regions. This hypothesized function may be clinically related to inflammation and pathology involving the iliopsoas tendon and adjacent tissues in the anterior region of the hip. Further study is now warranted to determine the clinical relevancy and biomechanical validity of this proposed function of the psoas minor. Clin. Anat. 28:243–252, 2015.

Key words: anatomic variance; hip pain; iliac fascia; iliopsoas; snapping iliopsoas

Additional Supporting Information may be found in the online version of this article.

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This cadaver study was conducted at Marquette University in Milwaukee, WI. Cadavers were obtained from a gross dissection course conducted through the College of Health Sciences at Marquette University.

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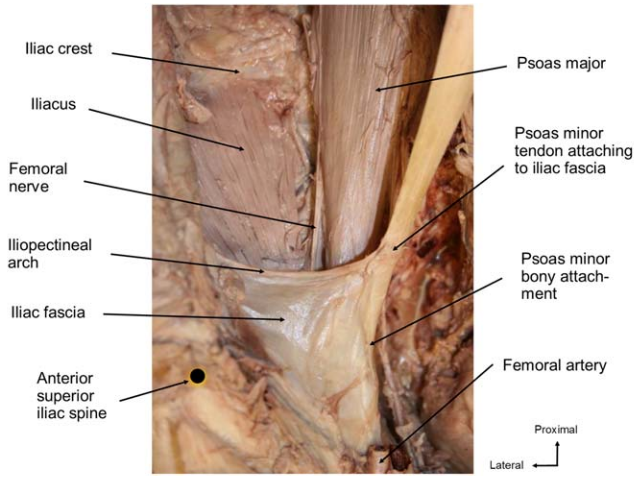

Fig. 1. Anterior view of the right psoas minor and iliopsoas muscles in an embalmed cadaver. Note that the tendon of the psoas minor has been manually reflected anteriorly and medially, away from its natural position anterior to the psoas major. The tendon of the psoas minor attaches distally into the pelvic bone as well as the broad iliac fascia. The femoral nerve is shown coursing immediately lateral to the psoas major. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

INTRODUCTION

Surprisingly little information exists on the anatomy and function of the psoas minor muscle in humans. Traditional anatomic sources cite that this bilateral muscle, frequently absent, attaches proximally to the lateral vertebral bodies of T12-L1 and intervening intervertebral discs (Standring, 2009; Drake et al., 2010; Moore et al., 2014). Accounts of the muscle's distal attachments are less clear, often complicated by inconsistent terminology or mixed descriptions. There seems to be a general consensus, however, that the muscle has a consistent distal tendinous attachment to the inner pelvic (iliopubic) brim, medial to the anterior edge of the acetabulum. Textbooks typically state that the psoas minor is a weak flexor of the trunk or lumbar spine (Oatis, 2008; Standring, 2009; Drake et al., 2010; Neumann, 2010b), however, this being its sole function seems unlikely compared to other much larger muscles capable of this action.

To learn more about the anatomy of this relatively obscure muscle, particularly its distal attachments, we performed a pilot dissection on a single human male cadaver. The dissection revealed that the psoas minor had a prominent distal attachment into pelvic bone, as traditionally described, but also into an equally prominent attachment into an aponeurotic envelope, or sleeve. According to classic anatomic descriptions (Standring, 2009; Moore et al., 2014), this fascial sleeve is a component of the iliac fascia, which lies directly over the distal, pretendinous portion of the iliopsoas muscle and the femoral nerve (Fig. 1). Some sources depict the sharp superior edge of the iliac fascia as the iliopectineal arch (Agur and Dalley, 2013; Moore et al., 2014). To our knowledge, however, traditional anatomic sources give only sparse or no attention to the interconnections between the iliac fascia and the tendon of the psoas minor (Standring, 2009; Gosling et al., 2009; Drake et al., 2010; Agur and Dalley, 2013; McKinley et al., 2014; Moore et al., 2014). Furthermore, no anatomical textbooks or published journal articles could be found that specifically address the structure or possible functional significance of these interconnections.

Whether the psoas minor tendon firmly blends with the iliac fascia in all cadavers that possess a psoas minor is not known. If this is indeed a universal finding, it is possible that an overlooked function of the psoas minor is to control the tension in the iliac fascia. Such control may assist with the mechanical stability of the underlying iliopsoas as it approaches and crosses over the femoral head and associated capsule region, the iliopectineal eminence, and the lateral part of the superior pubic ramus. This may have important clinical implications. Several clinical pathologies or conditions are thought to be associated with excessive stress (i.e., force divided by contact area) at this part of the iliopsoas, including iliopsoas "snapping hip" syndrome (Lewis, 2010; Philippon et al., 2014), iliopsoas impingement (Dora et al., 2007), iliopsoas bursitis, or tendonitis (Nunley et al., 2010), and possibly acetabular labral pathology (Philippon et al., 2014). The underlying pathomechanics of these potentially painful conditions are not understood. Various treatment approaches for these syndromes include arthroscopic iliopsoas tendon release (Dobbs et al., 2002; Flanum et al., 2007; Philippon et al., 2014), iliopsoas bursa injection (Blankenbaker et al., 2006), and various forms of physical therapy (Travell and Simons, 1992; Johnston et al., 1999; Philippon et al., 2011).

Greater anatomic detail of the distal part of the iliopsoas and surrounding fascia may help clinicians better understand and treat the aforementioned musculoskeletal pathologies. One potentially relevant but lacking detail is the extent and frequency to which the psoas minor tendon attaches into the iliac fascia. This cadaveric study is performed to shed light on this issue. The primary purpose of this investigation is to describe the gross anatomic detail of the psoas minor, with specific attention to the muscle's distal attachments. A secondary purpose is to describe the iliac fascia that drapes over the distal iliopsoas, specifically its anatomic and spatial relationship to the distal, pretendinous part of the iliopsoas muscle. This information may help clarify the functional role of the psoas minor. Furthermore, findings from this work may justify additional study on a possible pathomechanical relationship between the psoas minor, iliac fascia, and adjacent regions of the iliopsoas muscle.

MATERIALS AND METHODS

Cadavers

Thirty-two embalmed hip specimens from 16 cadavers (7 female and 9 male), were available for this study. The mean ± SD age was 78.6 ± 12.4

years, height was 173.6 ± 14.6 cm and mass at time of death was 64.4 ± 17.6 kg. Cause of death was unknown to the investigators. Cadavers were available as part of a gross anatomy course offered by the university's College of Health Sciences. Although the thorax, anterior abdominal wall, and viscera were previously dissected, the posterior abdominal wall, inguinal region, and lower extremities were not disrupted. Cadavers were randomly chosen for dissection; specimens were excluded if signs of pathology were visually apparent in the abdominopelvic region (i.e., large tumor, hematoma), or in the hip and proximal thigh (i.e., contractures, arthroplasty, amputation, marked asymmetric atrophy). Approval to examine the deidentified specimens was obtained from the College in accordance with the guidelines set forth by the United States Department of Health & Human Services Office for Human Research Protections.

Dissection and Preparation

The abdominal cavity of each cadaver had been previously dissected to a depth exposing the posterior abdominal wall. The first step was to identify the presence of a psoas minor. When present, this muscle and the iliacus, quadratus lumborum, psoas major, iliac fascia, and pelvic contents were clearly exposed. The inguinal ligament was removed to expose both the iliopsoas (as it crossed the lateral part of the superior pubic ramus toward the lesser trochanter) and the inferior extent of the iliac fascia. In situ photographs and dissection videos of the aforementioned structures were made. Prior to excising the psoas minor and associated iliac fascia, several anatomic measurements were taken to describe the location of the iliac fascia, relative to the psoas minor and pelvis, and the distal attachments of the psoas minor. These measurements, reported online in Supporting Information Appendix A and in the Results section, will be used to generate a pictorial summary of this anatomy. All distances were measured to the nearest millimeter using a tape measure and verified by the two investigators.

In Situ Measurements

To identify the exact location that the tendon of the psoas minor fused with the iliac fascia (i.e., the tendon–fascial junction), an *XY* coordinate system was developed with its origin at the anterior-superior iliac spine (ASIS). *X* was defined as a horizontal line directed medially toward the contralateral ASIS; *Y* was defined as an orthogonal vertical line relative to *X*, directed in the cranial direction. The corresponding *X* and *Y* data points (i.e., indicating linear distances from the ipsilateral ASIS) identified the location of the tendon–fascial junction of each cadaver hip specimen. The specific location of the distal attachment of the psoas minor's tendon was determined by measuring the shortest distance between the midpoint of its tendinous attachment to the pelvis and the ipsilateral pubic tubercle. Additionally, the width of the psoas minor tendon was measured at its distal bony attachment.

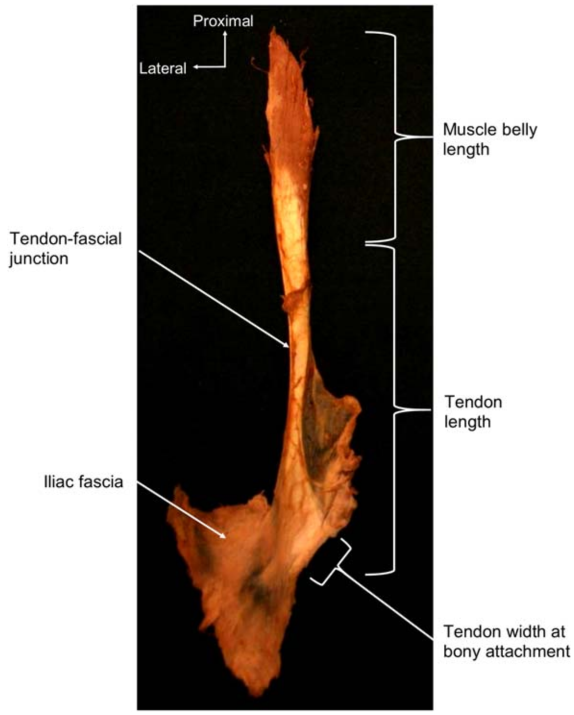

Fig. 2. A representative sample of an excised psoas minor–iliac fascia complex (anterior view). The complex was removed from the right side of the body. Note that the iliac fascia extends lateral and medial to the tendon of the psoas minor. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Excision of psoas minor–iliac fascia complex

The entire psoas minor (i.e., its muscle belly and its tendon) and attached iliac fascia is referred as the psoas minor–iliac fascia complex in this study. This complex was excised from the cadaver in preparation for measurements of the anatomic data describing the psoas minor (i.e., mass, muscle belly volume, and so forth [described ahead]). First, the muscle belly was carefully cut away from its proximal vertebral attachments. Next, the tendon and attached iliac fascia were released medially along the inner pelvic brim, from the sacroiliac joint region inferiorly toward the pubis. The excision of the complex was completed by cutting the iliac fascia along a line from near the pubic tubercle to the ipsilateral ASIS. A representative sample of the entire excised psoas minor–iliac fascia complex is shown in Figure 2.

Anatomic Measurements of Excised Psoas Minor

To properly describe the psoas minor, the iliac fascia was completely cut away from the muscle's tendon. The muscle belly and tendon were separated at the musculotendinous junction, defined as the point which the most distal muscle fibers completely transitioned to tendon (Ward et al., 2009; as noted in

TABLE 1. Descriptive Data of 32 Dissected Hip Specimens[a]

Cadaver (R = right; L = left)	Gender	Age (years)	Height (cm)	Mass (kg)	Psoas minor presence
1R	Male	90	–	–	Yes
1L	Male	90	–	–	Yes
2R	Male	80	188.0	63.5	Yes
2L	Male	80	188.0	63.5	Yes
3R	Female	81	154.9	40.8	Yes
3L	Female	81	154.9	40.8	Yes
4R	Female	61	162.6	40.8	No
4L	Female	61	162.6	40.8	No
5R	Female	64	–	–	Yes
5L	Female	64	–	–	Yes
6R	Male	73	195.6	90.7	No
6L	Male	73	195.6	90.7	No
7R	Female	100	162.6	66.5	No
7L	Female	100	162.6	66.5	No
8R	Male	69	182.9	72.6	No
8L	Male	69	182.9	72.6	Yes
9R	Female	83	–	–	Yes
9L	Female	83	–	–	Yes
10R	Male	74	–	–	No
10L	Male	74	–	–	No
11R	Male	77	182.9	75.8	Yes
11L	Male	77	182.9	75.8	Yes
12R	Female	93	–	–	Yes
12L	Female	93	–	–	Yes
13R	Male	58	177.8	–	Yes
13L	Male	58	177.8	–	Yes
14R	Female	74	–	–	Yes
14L	Female	74	–	–	Yes
15R	Female	99	154.9	–	No
15L	Female	99	154.9	–	No
16R	Male	82	–	–	Yes
16L	Male	82	–	–	Yes
Mean(SD)		78.6 (12.4)	173.6 (14.6)	64.4 (17.6)	

[a]Data not available indicated by –.

Figure 2, this intersection was typically oblique). The lengths of the muscle belly and separated tendon were measured, including a calculation of the percentage of the muscle belly relative to the entire musculotendinous unit. The mass of the muscle belly was measured to the nearest tenth of a gram, and verified by both investigators (Portable Advanced, Model CT600-S. OHAUS Corp. Florham Park, NJ). Muscle belly volume was measured to the nearest milliliter using a water displacement method (An et al., 1981). The anatomical cross-sectional area (CSA) was calculated by dividing muscle belly volume by its length, similar to a technique used by An et al. (1981). Visual observation indicated that the muscle fibers of the psoas minor appeared parallel with the tendon, therefore, pennation angle was assumed to be essentially 0° (Lieber, 2009).

Creation of Pictorial Summary

To create a pictorial summary of the psoas minor–iliac fascia complex, each complex was graphically transposed on to an image of a human pelvis (displayed in next section). This graphic transposition required that the data describing the location of the iliac fascia, as it draped over the distal iliopsoas (included online in Supporting Information Appendix A), and the distal attachments of the psoas minor be scaled to the anatomical dimensions of the image of our model human pelvis. The common scaling factor was based on the distance between the ipsilateral pubic tubercle and the ASIS. Data points normalized to this scale were used to carefully recreate the complex with the aid of in situ photographs and dissection videos.

Descriptive Statistics

Simple descriptive statistics were used to quantify the presence or absence, distal attachments, and anatomic measurements of the psoas minor complex. Not all descriptive data on cadavers (i.e., height, mass, and so forth) were available to the investigators. Also, in a few cases, cadaver material was damaged during removal which prohibited measurement. These exceptions are indicated in the tables ahead.

RESULTS

Presence of Psoas Minor

The descriptive data of all 32 hips are presented in Table 1. Of the 32 hips studied, 21 (65.6%) presented

TABLE 2. Data on the Psoas Minor Distal Attachments in 21 Cadaver Hip Specimens

	Bony attachment		Tendon–fascial junction (relative to ASIS)	
Cadaver (R=right; L=left)	Distance from tendon midpoint to pubic tubercle (mm)	Tendon width at bony attachment (mm)	*X*-axis (mm)	*Y*-axis (mm)
1R	82	25	67	32
1L	65	29	65	61
2R	85	35	81	35
2L	85	33	83	31
3R	65	19	64	32
3L	68	20	65	30
5R	75	65	69	18
5L	90	45	71	13
8L	70	22	83	21
9R	92	22	[a]	[a]
9L	69	21	61	23
11R	70	[b]	64	7
11L	68	[b]	66	19
12R	60	25	61	17
12L	68	21	68	6
13R	70	38	76	51
13L	60	30	60	48
14R	70	18	53	64
14L	68	20	75	25
16R	80	31	80	28
16L	90	33	85	35
Mean(SD)	73.8 (9.9)	29.1 (11.4)	69.9 (9.0)	29.8 (16.1)

Descriptions: *X*-axis, a horizontal line originating at the ipsilateral anterior-superior iliac spine (ASIS) and directed in the medial direction; *Y*-axis, a vertical line originating at the ipsilateral ASIS and directed in the cranial direction.
[a]Specimen damaged during removal.
[b]No bony attachment, fascial attachment only.

with a fully intact psoas minor. Furthermore, the psoas minor was present bilaterally in 10 cadavers and unilaterally in one male cadaver. Of the 21 hips that presented with a psoas minor, 19 (90.5%) attached distally to bone and fascia. The remaining two, which were from the same cadaver, displayed only a distal attachment to the iliac fascia.

Distal Attachments of Psoas Minor–Iliac Fascia Complex

As stated above, 19 of the 21 psoas minor muscles had a distal attachment into pelvic bone. The midpoint of the tendinous attachment was along the inner pelvic brim, located on average 73.8 ± 9.9 mm proximal to the ipsilateral pubic tubercle. The average width of the tendon at its attachment was 29.1 ± 11.4 mm (Table 2).

In all cases, the tendon of the psoas minor firmly blended into the iliac fascia. The point of this tendon–fascial junction was located on average 69.9 ± 9.0 mm medial and 29.8 ± 16.1 mm superior to the ipsilateral ASIS. This location places the average tendon–fascial junction immediately lateral to the ipsilateral sacroiliac joint. The fascial and bony attachments of the tendon of the psoas minor are also reported in Table 2 and are depicted (in red) in the pictorial summary in Figure 3. Furthermore, Figure 3 shows the location of the iliac fascia (in black dotted lines) relative to the pelvis, as well as the photographically assisted estimated location of the underlying iliopsoas muscle.

The location of the iliac fascia was consistently similar across all hip specimens (Fig. 3). Although not formally measured, its thickness varied considerably across cadavers. The arched superior border of the iliac fascia (i.e., the iliopectineal arch) presented with its concavity facing superiorly. During the excision of the psoas minor–iliac fascia complex, we found that the superior-medial aspect of the iliac fascia was adhered to bone overlying the sacroiliac joint in 11 hips (52.4%). Inferiorly, the fascia continued to attach along the inner pelvic brim where it was continuous with the tendinous bony attachment of the psoas minor. The iliac fascia continued inferiorly toward the superior pubic ramus, and posterior-medially to blend with the fascia covering the superior part of the obturator internus muscle. The inferior border of the iliac fascia was continuous with the proximal fascia lata of the thigh; it also attached to bone laterally near the ASIS, and bone medially near the proximal portion of the superior pubic ramus.

Psoas Minor Anatomic Measurements

The individual data on the anatomic measurements of the excised psoas minor of all 21 cadaver hips are presented in Table 3. The average length of the psoas

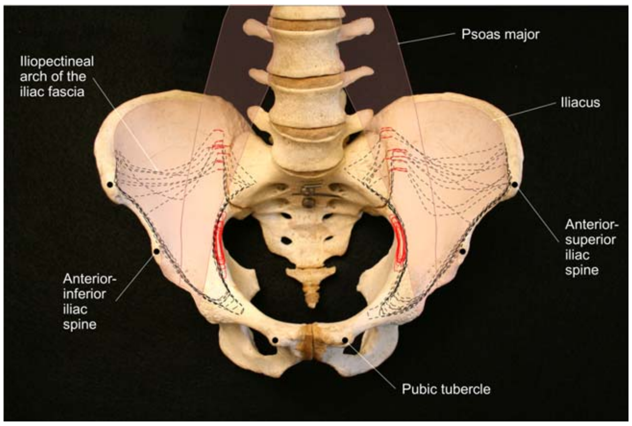

Fig. 3. Pictorial summary of the distal attachments of the psoas minor–iliac fascia complex in 21 (10 right and 11 left) hips. The dashed black lines represent the location of the iliac fascia. The red lines show the location of the attachments of the psoas minor tendon into the iliac fascia and pelvic bone. Note that the tendon–fascial junctions are located just lateral to the sacroiliac joint. Furthermore, the bony attachments are clustered near the proximal end of the pectineal line, medial to the iliopubic eminence. For perspective, the estimated location of the psoas major and iliacus muscles, which lie deep to the iliac fascia, are depicted through the use of a translucent outline. All drawings were scaled to the above skeletal model. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

minor muscle belly was 89.3 ± 15.1 mm and its average tendon length was 149.2 ± 22.8 mm. On average, the muscle belly occupied the proximal 37.5 ± 6.0% of the entire musculotendinous unit. Average muscle belly mass was 4.5 ± 2.6 g., while its volume was 4.5 ± 2.6 mL. The average CSA of the psoas minor was 52.5 ± 34.3 mm^2.

DISCUSSION

In this study, the psoas minor was present in 65.6% of cadaver hip specimens. British Gray's Anatomy (Standring, 2009) reports a 60% presence (40% absence) of the psoas minor, while a study published in 1934 (Seib, 1934) on 1,000 cadaver hips reported a 38.6% presence of this muscle. We cannot account for these differences, although variations in sample sizes and ethnicity may play a role (Hanson et al., 1999).

We were unable to locate studies that allowed us to critically and meaningfully compare the accuracy of our anatomic measurements on the psoas minor (CSA, volume, and so forth; Table 3). Each psoas minor muscle observed in our study presented with a similar morphology consisting of a slender proximal muscle belly connected to relatively long distal tendon. On close visual inspection, the muscle fibers appeared fusiform in architecture, running parallel with the tendon. Although variable, the average CSA of the psoas minor muscle belly measured in this study was 52.5 mm^2. This is a relatively small CSA compared with reports on other muscles in the hip

TABLE 3. Anatomic Measurements of the Excised Psoas Minor in 21 Cadaver Hip Specimens

Cadaver (R=right; L=left)	Muscle belly length (mm)	Tendon length (mm)	Muscle belly length % of MTU	Mass of muscle belly (g)	Volume of muscle belly (mL)	Cross-sectional area of muscle belly (mm^2)
1R	70	145	32.6	2.3	2.5	35.7
1L	95	170	35.8	4.3	5.0	52.6
2R	85	141	37.6	3.5	3.5	41.2
2L	103	128	44.6	4.4	4.5	43.7
3R	88	130	40.4	2.6	2.5	28.4
3L	69	132	34.3	2.8	2.7	39.1
5R	102	193	34.6	5.4	5.1	50.0
5L	102	190	34.9	4.7	5.0	49.0
8L	98	160	38.0	4.4	4.0	40.8
9R	58	165	26.0	2.9	3.0	51.7
9L	100	159	38.6	3.4	3.2	32.0
11R	96	160	37.5	1.8	1.9	19.8
11L	105	105	50.0	3.5	3.2	30.5
12R	93	122	43.3	1.9	2.0	21.5
12L	85	150	36.2	1.9	2.0	23.5
13R	70	156	31.0	9.2	9.1	130.0
13L	84	168	33.3	11.5	11.5	136.9
14R	110	110	50.0	3.8	3.7	33.6
14L	110	150	42.3	4.7	4.5	40.9
16R	85	150	36.2	6.4	9.0	105.9
16L	68	150	31.2	8.9	6.5	95.6
Mean (SD)	89.3 (15.1)	149.2 (22.8)	37.5 (6.0)	4.5 (2.6)	4.5 (2.6)	52.5 (34.3)

Descriptions: Muscle belly length, distance from the cranial origin to the musculotendinous junction; Tendon length, distance from the musculotendinous junction to the distal attachment to the pelvis. Muscle belly length % of MTU, the percentage of the musculotendinous unit (MTU) length that represents the muscle belly.

region, such as the iliopsoas (831.8 mm^2), pectineus (246.4 mm^2), or the piriformis (321.3 mm^2) (Ito et al., 2003). Interestingly, the average CSA of the psoas minor compares relatively well against two other muscles with similar musculotendinous morphologic characteristics: palmaris longus (90 mm^2, 69.0 mm^2; An et al., 1981; Lieber, 2009, respectively) and plantaris (59.7 mm^2; Ito et al., 2003).

The most important objective of this study was to characterize the distal attachments of the psoas minor in our sample of 32 hips. As stated in the Results section, all psoas minor muscles attached firmly to the iliac fascia. Nineteen of the twenty-one muscles attached distally to bone and to iliac fascia. Two muscles (from the same cadaver) attached to iliac fascia only and had no bony distal attachments. To our knowledge, this finding has not been published, and therefore, could not be compared.

Based on our observations, forces produced by the psoas minor muscle tissue could theoretically be transferred distally to pelvic bone and iliac fascia. The magnitude of these forces in living individuals are unknown, but are likely small and roughly proportional to the muscle's CSA. A muscle's maximal force generation can be estimated by multiplying its CSA by a conversion factor, often referred to as a muscle's "specific tension" (Lieber, 2009). Although a wide range of conversion factors have been reported (Brand et al., 1981; Enoka, 2008; Lieber, 2009; Hunter and Brown, 2010), we used a midrange value of 40 N/cm^2 to estimate that a psoas minor (with an average CSA of 52.5 mm^2) could generate a maximal force of approximately 21 N (almost 5 lbs.) Although this is only a rough estimate, it does provide some context to consider the magnitude of functional demands naturally placed on this muscle. Current research methods typically used to assess the in vivo action of a muscle (e.g., electromyography, or ultrasound) have not been published for the psoas minor; apparently these methods are not practical or feasible to study the activation of this deep and poorly accessible muscle. Any action assigned to the psoas minor is speculative, based primarily on its anatomic connections and an estimate of its maximal force potential. Furthermore, there are no known injury or disease mechanisms that preferentially restrict or dennervate just this muscle's function. Therefore, unlike muscles such as the opponens pollicis or quadriceps femoris, clinicians are not able to ascertain clues on the muscle's function by observing a patient attempting to move when the muscle is known to be paralyzed.

Distal Attachments of the Psoas Minor to Bone: Possible Anatomic and Functional Association

Our data showed a consistent location of distal attachment of the tendon of the psoas minor to the pelvis. This attachment was near or along the proximal end of the pectineal line, medial and slightly superior to the iliopubic eminence. Comparing these distal attachments with the literature is slightly convoluted by inconsistent terminology. For example, the terms iliopubic eminence and iliopectineal eminence describe the same bony feature, a notable rounded and raised area medial to the anterior edge of the acetabulum, marking the junction between the ilium and pubis. Pectineal line and pectin pubis are also used interchangeably to describe a sharp ridge along the superior edge of the superior pubic ramus. When overlooking these inconsistent terms, agreement exists in the location of the distal bony attachment of the psoas minor in this study with that cited in traditional anatomy texts (Standring, 2009; Drake et al., 2010; Moore et al., 2014).

By observing the location of the psoas minor's bony (pelvic) distal attachment, it is reasonable to assume that the muscle's line of force is aligned slightly anterior to the medial–lateral axis of rotation at the hip (Neumann, 2010a). This being the case, a contracting psoas minor could theoretically produce a posterior tilt of the pelvis—a motion that rotates a point on the superior pubic ramus upward, thereby causing the iliac crest regions of the pelvis to rotate posteriorly. Furthermore, the psoas minor's line of force would also be aligned anterior to the medial–lateral axis of rotation through the L5-S1 junction. Similar to the psoas major (Santaguida and McGill, 1995), the psoas minor would, therefore, be in position to flex the lower lumbar spine relative to the sacrum.

Both of the psoas minor's typically agreed actions of posterior pelvic tilt and flexion of the lower lumbar spine are reasonable from a biomechanical perspective. However, the muscle's limited assumed moment arm length for these actions and likely small force potential raises the question as to the functional impact of this muscle's relative contribution to these actions. Nevertheless these are the primary actions typically assigned to this muscle in traditional anatomy and kinesiology textbooks (Oatis, 2008; Standring, 2009; Drake et al., 2010; Neumann, 2010b).

Distal Attachments of the Psoas Minor to Iliac Fascia: Proposed Anatomic and Functional Association

As stated earlier, only scant reference exists regarding the extent or frequency to which the psoas minor attaches distally into the iliac fascia. Data from this study, however, provides considerable clarity to this topic. We showed that all 21 psoas minor tendons attached firmly into the iliac fascia. The tendon–fascial junction was located, on average, just lateral to the anterior side of the sacroiliac joint (Fig. 3). Furthermore, the tendon of the psoas minor formed a vertical "backbone" primarily throughout the medial side of the iliac fascia, just medial to the psoas major (Figs. 1 and 3). In all cases, the tendon was completely fused with the substance of the iliac fascia; this fusion continued between the tendon–fascial junction and the tendon's bony pelvic attachment (see sample presented in Fig. 2). No precise pattern was consistently observed in the path of the embedded tendon within the fascia. In most cases, however, the tendon remained more or less as a single, thickened band; less frequently, the tendon bifurcated within the fascia, one lateral slip remaining within the substance of the fascia, and a second medial slip coursing to its bony attachment (see example in dissection in Video online). This study suggests that future editions of anatomy texts give equal weight to both the muscle's bony and fascial distal attachments. It was interesting that all cadavers in this study that lacked a psoas minor still had a well-developed, although thinner, iliac fascia that covered the distal part of the iliopsoas.

As described in the Results section (and apparent in the Video online), the iliac fascia attached to pelvic bone medially and laterally, but was free superiorly and inferiorly. One of the most characteristic features of the iliac fascia was its iliopectineal arch, running between the iliac crest laterally and the psoas minor's tendon–fascial junction medially (Figs. 1 and 3). From this arch, the iliac fascia formed an aponeurotic envelope, or vertical sleeve, which flowed distally and deep (and partially adhering) to the overlying inguinal ligament. This funnel-shaped sleeve created a retroinguinal space between the posterior side of the iliac fascia and the deeper pelvic bone. The iliopsoas and femoral nerve passed together within this space, while the femoral vessels passed superficial to this space (Fig. 1). The anterior side of the iliopsoas (and femoral nerve) made soft contact with the back side of the iliac fascia. The posterior side of the iliopsoas, however, made firm contact with pelvic bone between the anterior-inferior-iliac spine and the lateral part of the superior pubic ramus.

To our knowledge, there is no published work that offers a functional rationale for the psoas minor's firm and consistent distal attachment into the iliac fascia. Based on our measurements, however, it is conceivable that by actively adjusting the tension in the iliac fascia, the psoas minor could stabilize the position of the underlying iliopsoas as it crosses over the femoral head and lateral part of the superior pubic ramus. This proposed tensioning action of the psoas minor may have useful biomechanical functions that relate to the iliopsoas. Although unstudied and speculative at this point, it is possible that the myogenic tension in the iliac fascia may prevent the iliopsoas from forcefully "bowstringing" away from the lateral part of the superior pubic ramus, especially when the iliopsoas is strongly contracting with the hip in a high flexion angle. Other than the inguinal ligament, which is considerably farther anterior to the iliopsoas tendon, the iliac fascia appears to be the only tissue adequately designed to resist such a bowstringing. A proximally directed pull on an isolated iliopsoas specimen in cadavers has been shown to pull the musculotendinous unit up and away from the underlying femoral head and lateral part of the superior pubic ramus (Yoshio et al., 2002). Upon a simple inspection on a skeletal model, it is apparent that at some point beyond about 110° of hip flexion, the lesser trochanter region of the femur (i.e., the distal attachment site of the iliopsoas) becomes positioned anterior and lateral to the lateral part of the superior pubic ramus. An iliac fascia rendered taut by activation of the psoas minor could theoretically provide counter-tension against the iliopsoas, potentially preventing or at least limiting its bowstringing away from the joint. Excessive bowstringing of the iliopsoas tendon away from the femoral head would increase the muscle's hip flexion moment arm, which in the anatomic position is normally about 1.8 cm in the adult (Dostal et al., 1986). An increased moment arm results in less rotation of the joint (flexion of the hip, in this case) bone per linear unit of muscle contraction (Neumann, 2010b). Excessive bowstringing of the iliopsoas tendon may, in theory, reduce slightly the full range of active hip flexion, which may interfere with activities like tying one's shoe, for example. Whether the psoas minor has the physiologic capability for generating sufficient active counter-tension in the iliac fascia to provide the aforementioned function for the iliopsoas is not known, although this hypothesis warrants further investigation.

There are several examples in the body where a fascial sheath of connective tissue helps stabilize the position of underlying muscle or tendons. Consider for example, the fibrous lacertus with elbow flexion, the annular pulley system with interphalangeal joint flexion, or the extensor retinaculum with ankle dorsiflexion or wrist extension (Neumann, 2010b). What is interesting about the iliac fascia is that its tension can likely be controlled by muscle—the psoas minor—and thus indirectly controlled through the nervous system. The possibility of the nervous system perceiving tension in the iliac fascia (via the psoas minor) is a provocative thought. We do not know, however, the degree to which the psoas minor's muscle, tendon or associated iliac fascia contains sensory organs capable of perceiving tension or stretch.

The notion of one muscle serving another muscle in a stabilization role as postulated above is not unique. Consider the quadratus plantae in the foot stabilizing the position of the common tendon of the flexor digitorum longus. Consider also the palmaris longus muscle stabilizing the palmer aponeurosis in the hand. This arrangement helps stabilize the proximal attachments of the thenar and hypothenar muscles, as well as prevent bowstringing of the extrinsic digital finger flexor tendons and median nerve during extreme wrist flexion. Although not proved in this study, we feel it reasonable to propose the hypothesis that the psoas minor is a dedicated accessory muscle to the iliopsoas. Perhaps the psoas minor and iliopsoas (or psoas major) are activated in phase with each other during actions that require vigorous movements involving high flexion angles, such as cycling or running up hill. What is needed is a method to assess the activation of both muscles simultaneously. Assessing the activation of the psoas minor through electromyography would be problematic given the muscle's retrovisceral and retroperitoneal location coupled with its relatively small size and variable presence. No studies using any type of measurement system could be found that have attempted to analyze the timing and magnitude of the psoas minor during movement.

Our dissections (Video available online) clearly showed a structural mechanism by which forces produced by the psoas minor could be transferred to the iliac fascia located immediately over the iliopsoas. Furthermore, our dissections showed that forces from the psoas minor could be transferred through the iliac fascia posterior-medially to the fascial membrane covering the obturator internus, and distally to the fascia lata of the proximal thigh. We are not aware of the functional implications of these anatomical interconnections. It is well known, however, that the gluteus maximus and tensor fascia lata muscles connect into the lateral aspect of the fascia lata, ultimately transferring force distal to the knee via the iliotibial band. To be precise, based on this study, the psoas minor should be included along with these muscles as having distal attachments, albeit much smaller and indirect, into the anterior region of the proximal fascia lata of the thigh.

Possible Clinical Ramifications of a Psoas Minor and Iliac Fascia Connection

Could there be a pathoanatomic or pathomechanic relationship between the amount of tension generated within the psoas minor–iliac fascia complex and inflammation or excessive contact stress between the distal region of the iliopsoas and adjacent structures? This question is especially relevant considering the array of poorly understood musculoskeletal painful conditions or pathologies reported in the anterior hip region (Lewis, 2010; Nunley et al., 2010; Philippon et al., 2011; Philippon et al., 2014). For example, consider the condition of an iliopsoas-related "snapping hip syndrome," whereas the muscle (or its tendon) is believed to "catch" on the underlying iliopubic eminence and adjacent lateral region of the superior pubic ramus, hip capsule, or iliopsoas bursa (Byrd, 2006; Lewis, 2010; Philippon et al., 2014). The mechanics of this syndrome have been specifically described as an uncontrolled and rapid medial-to-lateral translation (snap) of the iliopsoas tendon over the iliopectineal eminence as the hip is moved from flexion to extension (Ilizaliturri et al., 2011). Why the tendon is poorly controlled in persons with this specific condition is not known. Our observed firm attachment of the psoas minor–iliac fascia complex to the inner pelvic brim appears optimally designed to restrain a lateral displacing iliopsoas tendon. Could the psoas minor adjust the tension in the iliac fascia as a way to optimally guide the iliopsoas relative to the underlying structures? Perhaps this guiding mechanism serves to reduce contact stress. Furthermore, could an activated psoas minor–iliac fascia complex limit excessive forward migration of the femoral head against the acetabular labrum? Such an abnormal migration of the femoral head has been theorized as one of several possible causes of attrition of the adjacent acetabular labrum (Lewis et al., 2007). Excessive wear and damage of the acetabular labrum is an important topic because it is considered as one potential precursor to the development of hip osteoarthritis (McCarthy et al., 2001).

This study raises many questions. Is there a functional or even measurable biomechanical consequence of lacking a psoas minor, which is apparently the case in 40–60% of people? Would the muscle's absence or poor control predispose any of the mechanical, frictional-based, inflammatory conditions described above? Does our proposed theory that the iliac fascia naturally stabilizes the position of the underlying iliopsoas depend not only on the presence of a psoas minor but also on its state of increased or decreased reflexive tone, possibly related to pain inhibition? Such questions cross both scientific and clinical arenas; questions that are important in the light of the reported painful and even debilitating mechanical disturbances that occur in the general region where the iliac fascia covers the iliopsoas. Answers to these questions through additional research could add to the basic anatomic science of the hip and shed light on the cause as well as therapeutic and potential surgical treatment of some iliopsoas-related disorders.

There are limitations to this study. The relatively limited number of cadavers available for analysis may limit the extent to which our findings can be extrapolated across all human hips. Also, the accuracy of our approximate 5 pound estimate of the maximal in vivo force produced by the psoas minor is limited by the high variability of our measured CSA of the muscle coupled with the high variability of referenced "specific tension" conversion factors cited in the literature. Furthermore, the actual transfer of forces between the psoas minor–iliac fascia complex and the iliopsoas was not measured, but only assumed based on the anatomy.

To conclude and summarize, this descriptive and semiquantitative cadaveric study was performed to better comprehend the anatomy and especially distal attachments of the psoas minor, when present. The study also focused on analyzing the spatial characteristics of the iliac fascia that drapes over the more distal part of the iliopsoas muscle. Our main findings on these matters are summarized below:

1. In 21 of 32 hip specimens that had a psoas minor, 100% of the muscles attached firmly into the iliac fascia that covers the distal iliopsoas. All but two of the psoas minors also attached distally into pelvic bone. To our knowledge, this finding has not been previously published.
2. We generated data on anatomic measurements of the psoas minor (CSA, volume, mass, length, and so forth), which may serve as comparative information for future research on this topic.
3. We described the specific attachments of the iliac fascia that covers the distal, pretendinous region of the iliopsoas. Although the iliac fascia has been generally described in the anatomic literature, we contributed significant detail regarding its attachments to pelvic bone, other fascia, and, most notably, the tendon of the psoas minor.

Based on the anatomic findings of this study, we feel justified in advancing the following two recommendations. First, future editions of anatomy textbooks should consistently include both the pelvic bone and iliac fascia as equal primary distal attachment of the psoas minor. Second, further anatomical–biomechanical study is needed to test the hypothesis that a significant function of the psoas minor–iliac fascia complex is to enhance the biomechanical stability and function of the underlying iliopsoas. Such a study may require a combination of research methods involving: (a) dissection using a larger sample of cadaver specimens to determine or reconfirm CSA, pennation angle, sensory innervation of the psoas minor, moment arms relative to hip joint and lumbosacral junction, and strength and stiffness characteristics of iliac fascia), (b) instrumenting the psoas minor–iliac fascia complex and cadaveric hips with force (strain) and kinematic measurement hardware, (c) computer and mathematical modeling, and (d) in vivo electromyographic analysis, perhaps in animal models if not practical for in vivo human experiments. One specific question is to analyze whether the psoas minor is physiologically capable of generating enough force through the iliac fascia to effectively stabilize the position of the iliopsoas relative the hip, for a range of hip positions. Ultimately, research may be justified to determine if an association exists between the presence or absence of a psoas minor (perhaps determined through magnetic resonance imaging) and the likeliness of developing anterior hip pain and associated pathologies involving the iliopsoas and anterior hip region.

Although this investigation has generated more questions than it has answered, we feel the information and hypotheses generated should be shared with anatomists, kinesiologists, physical therapists, surgeons, and other clinicians who treat musculoskeletal problems involving the hip.

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