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Anatomic Study of Hip Pericapsular Muscle Arrangement on the Joint Capsule

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Background: Despite the recognized importance of pericapsular muscles in hip stability, their specific roles in stability remain debated. For anatomically elucidating how the pericapsular muscles can act on the femoral head and neck through the joint capsule, this study aimed to investigate pericapsular muscle arrangement on the joint capsule with a positional relation to the femoral head and neck and their histological relationships.

Methods: Eight hips of 7 anatomic donors (average age, 72.5 years) fixed with 8% formalin were analyzed. Five hips were macroscopically assessed to determine the arrangement of the pericapsular muscles (iliopsoas, gluteus minimus, gemelli muscles, obturator internus, and externus) on the joint capsule, and 3 were analyzed histologically.

Results: When viewed from the side of the greater trochanter (posterolateral aspect), the pericapsular muscles were macroscopically arranged spirally and ran clockwise around the femoral neck axis on the joint capsule of the right hip. The gluteus minimus had histological continuity to the joint capsule through the tendon. The other pericapsular muscles, including the iliopsoas, obturator externus, and complex of the obturator internus, had histological continuity to the joint capsule through their perimysium.

Conclusions: The pericapsular muscles were arranged on the joint capsule in a spiral pattern, with histologically close continuity to the joint capsule through the perimysium or tendon.

Clinical Relevance: The contraction force of the pericapsular muscles may be generated spirally with their centripetal force because they maintain their spiral running course through histological continuity. The pericapsular muscles may be vital in maintaining the centric position of the femoral head by balancing their centripetal forces through the joint capsule.

Introduction

Improving hip stability without causing iatrogenic instability is vital for hip surgery and postoperative rehabilitation. In general, the osteochondral structure provides joint congruence and hip stabilization mechanisms other than those provided by the osteochondral structure have been classified as static, which are mainly provided by ligaments, and dynamic, which are provided by muscles[1-3]. Recently, the iliofemoral ligament, one of the main stabilizers[4,5], has been reported not to have an independent bundle-like structure, as previously believed[6,7]. Instead, its structure has been found to be identical to the joint capsule connected to the tendon of the gluteus minimus and the deep aponeurosis of the iliopsoas, including the iliocapsularis[6,7]. The tensile inter-relationship between the joint capsule and pericapsular muscles can be interpreted as vital for the hip stabilization mechanism[6,8], and disorder of this mechanism may lead to hip pathology[9-12].

The specific roles of pericapsular muscles in hip stability have been biomechanically analyzed using musculoskeletal models based on their running pattern, in which the periarticular muscles straightly converge from the origins to the insertions[13-18]. However, theoretically, pericapsular muscles should not run straight because they run on the curved surface of the joint capsule. Thus, the running pattern in the models is different from the actual structures, owing to the lack of incorporation of the joint capsule in the model[13-18]. The anatomic consideration of how pericapsular muscles

Disclosure: The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (http://links.lww.com/JBJSOA/A753).

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act on the hip bone through the joint capsule may be vital on a biomechanical basis and for a better understanding of the hip stabilization mechanism.

The pericapsular muscles are mainly composed of the iliopsoas, gluteus minimus, gemelli inferior and superior, and obturator internus and externus[2,6,19]. The approximate location of the pericapsular muscles being continuous in gross anatomy to the joint capsule has already been investigated[2,6]. However, the detailed running patterns of these muscles on the whole joint capsule, based on their positional relationship with the femoral head and neck, remain unclear. Such precise arrangements may provide insights into the action of the pericapsular muscles on the femoral head and neck through the joint capsule. Furthermore, histological analysis of the relationship between the pericapsular muscle and the joint capsule may be required to consider the action of the pericapsular muscles through the joint capsule. However, such information is limited to the anterior joint capsule[6,10], and the histological relationship between the joint capsule and gemelli muscles, obturator internus, and externus remains unclear.

This study aimed to investigate the pericapsular muscle arrangement on the joint capsule with a positional relation to the femoral head and neck and the histological relationships between the pericapsular muscles and the joint capsule. We hypothesized that all pericapsular muscles were arranged around the femoral neck axis in a curved rather than straight pattern, owing to their extending over a curved joint capsule surface, and that they had histologically close continuity with the joint capsule.

Materials and Methods

Anatomic Specimen Preparations

Nine hips from 8 anatomic body donors (6 men and 2 women; 6 right and 3 left sides; mean age at the time of death, 75.0 years [range, 49-95 years]) donated to the Department of Anatomy were used in this study. Sample size calculations are currently not methodologically standardized in anatomic research[20]; therefore, our sample size was determined based on previous descriptive anatomic studies that comprised macroscopic and histological analyses[21-23]. Donors without joint contractures in the lower limbs (e.g., donors without the hip flexion contracture) or a history of hip surgery were included in this study. The exclusion criteria were evident bony deformities including hip dysplasia (center-edge angle, <20°) or pathological muscular changes (e.g., cancer-infiltrated muscle) in the hip. All donors were fixed in 8% formalin at the Department of Anatomy and preserved in 30% ethanol 6 months before the dissection. Using a diamond saw (EXAKT 312; EXAKT Advanced Technologies), we obtained hip specimens from donors by cutting horizontally from the level of the iliac crest to the lesser trochanter. The osseous morphology was assessed using micro-computed tomography (micro-CT; InspeXio SMX-100CT; Shimadzu) with a resolution of 200 μm and ImageJ software (version 1.54; National Institutes of Health). No specimens had an obvious bony deformity (minimum value in the center-edge angle on the micro-CT was 22.8°); however, cancerous tissue infiltrating the pericapsular muscles was identified macroscopically and excluded in one specimen. To avoid macroscopic dissection bias during the evaluation for histological continuity, 5 and 3 of the remaining 8 hips were randomly assigned for macroscopic and histological analyses, respectively. Random assigning of specimens involved a lottery method based on the donor numbers assigned to the specimens.

Macroscopic Analysis

Because the hip pericapsular muscles in direct contact with the joint capsule are the iliopsoas, gluteus minimus, gemelli muscles, obturator internus and externus, and rectus femoris[6], the superficial muscles, including the gluteus maximus and medius, piriformis, tensor fasciae latae, sartorius, and hip adductor muscles, were removed to expose the outer surface of the pericapsular muscles. In accordance with 2 previous studies[6,7], the iliocapsularis was not separated from the iliacus and was included in iliacus analysis. The outer surface of the obturator internus in the pelvis was also visualized by removing the sacrotuberous and sacrospinous ligaments and sacrum and ala of ilium posterior to the greater sciatic notch. Because the muscular portion of the rectus femoris is in contact with the joint capsule through loose connective tissue and because only the proximal tendinous portion is in direct contact with the joint capsule[6,10], a portion of the rectus femoris was resected distal to the origin of the anterior inferior iliac spine. Therefore, in this study, the hip pericapsular muscles were defined as the iliopsoas (including iliocapsularis), gluteus minimus, gemelli muscles, and obturator internus and externus, and their arrangement on the joint capsule was observed. After this, the specimens were cut at the base of the femoral neck to observe the positional relationships among the femoral neck, joint capsule, and pericapsular muscles.

Histological Analysis

For histological analysis of the 3 specimens, sectioning was performed superior to the anterior inferior iliac spine and posterior to the ischial tuberosity. Based on the femoral neck axis identified by micro-CT images[24], hip specimens were cut on the oblique-sagittal plane perpendicular to the femoral neck axis at the greater trochanter. Subsequently, these specimens were serially sectioned based on the cutting plane into 5-mm-thick segments using a band saw (WN-25-3; Nakajima Seisakusho) after being embedded in a 3% agar solution and frozen at –80°C. Four blocks were harvested from the oblique-sagittal sections perpendicular to the femoral neck. These blocks included the joint capsule and iliopsoas, the joint capsule and obturator externus, the joint capsule and the complex of the obturator internus, including the gemelli muscles, and the joint capsule and gluteus minimus. After 3 weeks of decalcification with Plank-Rychlo solution[25], each block was dehydrated, embedded in paraffin, serially sectioned (5 μm thickness), and stained using Masson's trichrome staining protocol[6,7,10,26]. Two persons (M.T. and A.N.) specializing in anatomy with a Doctor of Philosophy degree in medical sciences read the staining images.

Source of Funding

JSPS KAKENHI (grant number JP 22k17645).

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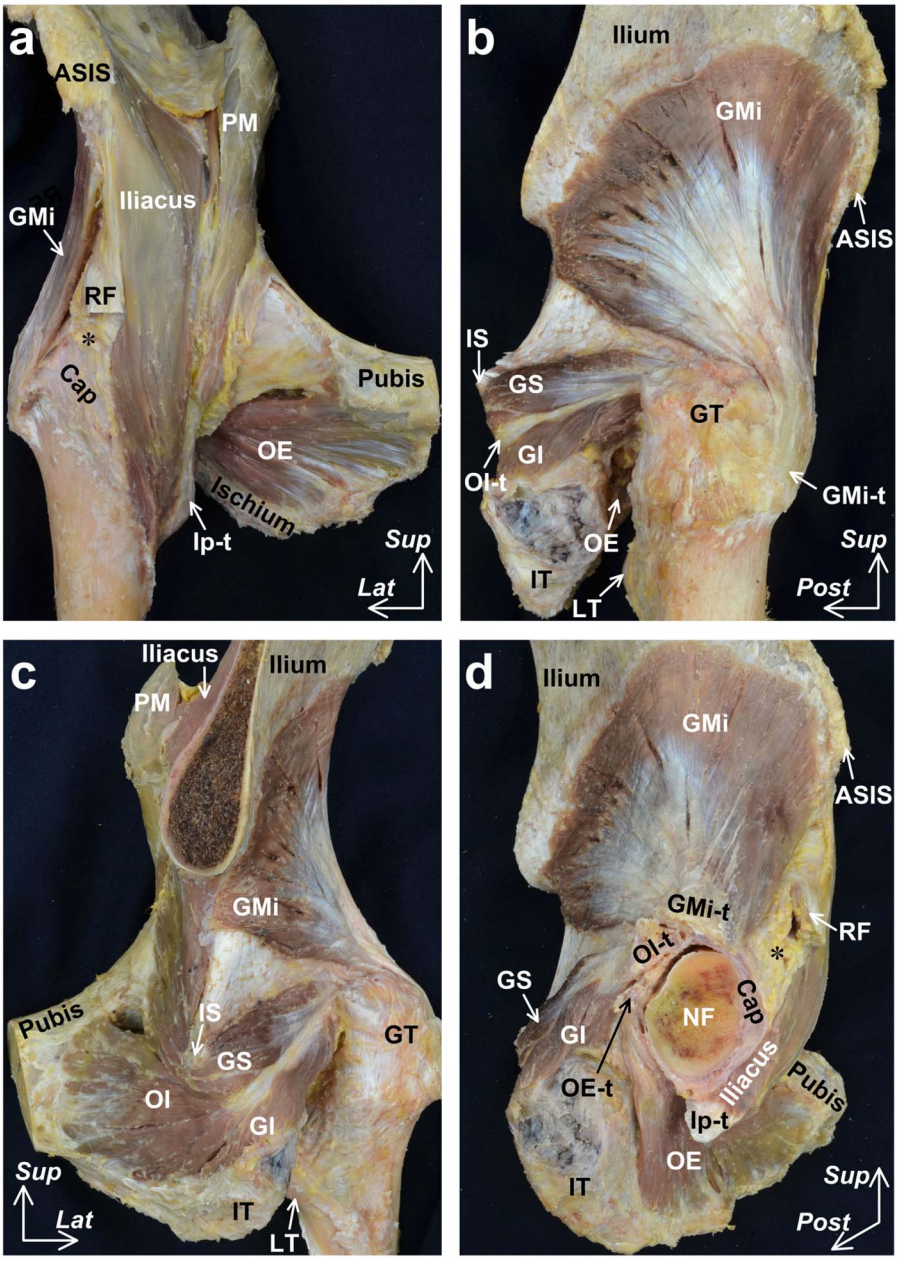

Fig. 1

Macroscopic analysis of the arrangement of pericapsular muscles. The right hip specimen was viewed from the (**Fig. 1-A**) anterior, (**Fig. 1-B**) posterolateral, and (**Fig. 1-C**) posteromedial aspects and (**Fig. 1-D**) after cutting at the level of the neck of the femur (NF) from the posterolateral aspect. The pericapsular muscles run on the joint capsule (Cap) in a clockwise direction around the NF axis as viewed from the greater trochanter (GT) side and are arranged in a spiral pattern. ASIS = anterior superior iliac spine; asterisk = fat pad and loose connective tissue on the anterior Cap; GI = gemellus inferior; GMi = gluteus minimus; GMi-t = tendon of the GMi; GS = gemellus superior; Ip-t = tendon of the iliopsoas; IS = ischial spine; IT = ischial tuberosity; *Lat* = lateral; LT = lessor trochanter; OE = obturator externus; OE-t = tendon of the OE; OI = obturator internus; OI-t = common tendon of the GI, GS, and OI; PM = psoas major; *Post* = posterior; RF = rectus femoris; and *Sup* = superior.

Results

Macroscopic Analysis of the Pericapsular Muscle Arrangement

The iliopsoas, particularly the iliacus, ran on the anterior-inferior surface of the joint capsule while descending across the femoral neck (Fig. 1-A). The obturator externus ran on the inferior-posterior surface of the joint capsule while ascending across the femoral neck (Figs. 1-A and 1-B). The complex of the obturator internus, including the gemelli muscles, ran on the posterior-posterosuperior surface of the joint capsule while ascending across the femoral neck (Figs. 1-B and 1-C). The

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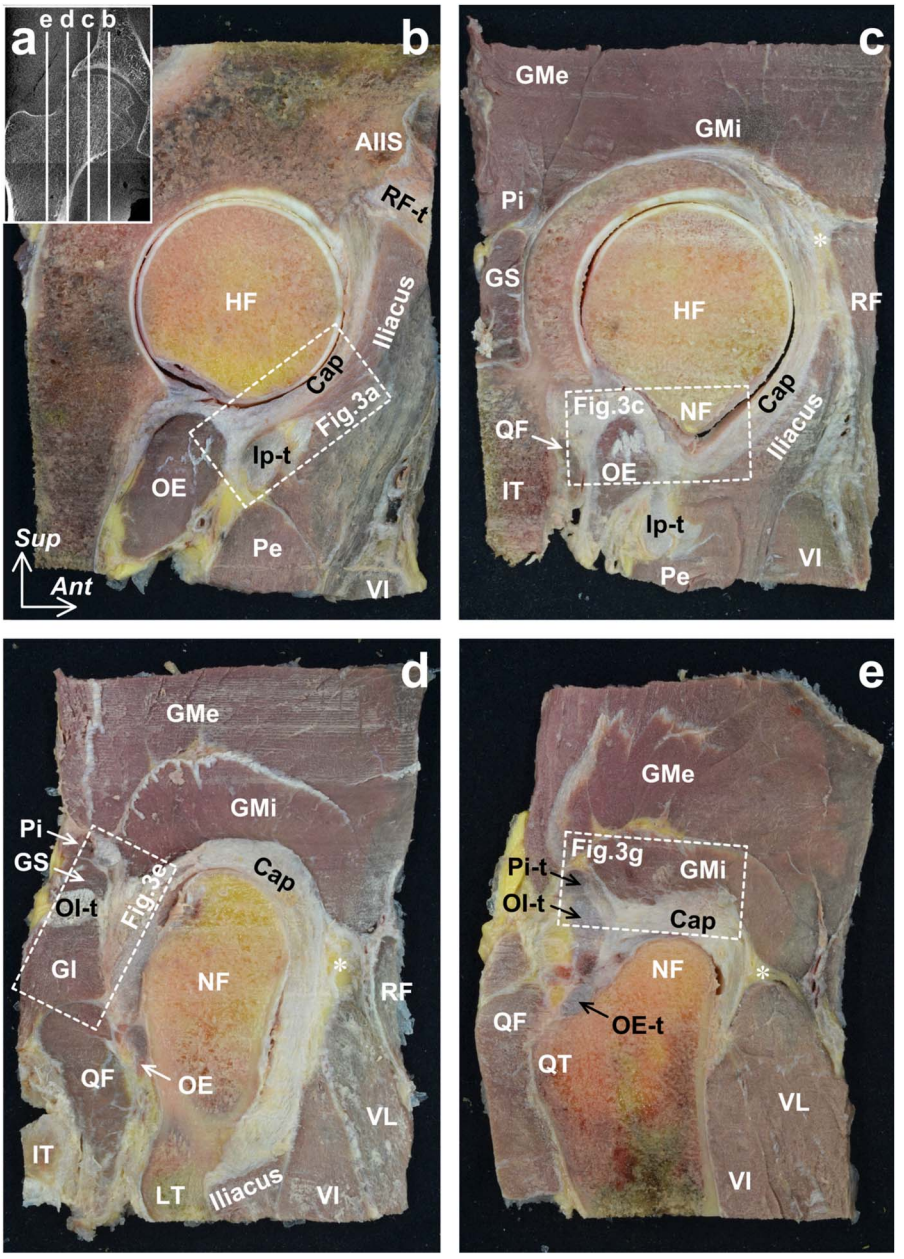

Fig. 2

Macroscopic oblique-sagittal sections of the pericapsular muscles. The micro-CT oblique coronal image along (**Fig. 2-A**) the femoral neck axis indicates (**Figs. 2-B through 2-E**) the locations of macroscopic sections, which are oblique sagittal sections perpendicular to the femoral neck axis, indicated by white lines. The white dotted box regions in (**Figs. 2-B through 2-E**) indicate the selected parts for histological analysis in Figure 3. AIIS = anterior inferior iliac spine; *Ant* = anterior; asterisk = fat pad and loose connective tissue on the anterior joint capsule; Cap = joint capsule; GI = gemellus inferior; GMe = gluteus medius; GMi = gluteus minimus; GS = gemellus superior; HF = head of the femur; Ip-t = tendon of the iliopsoas; IS = ischial spine; IT = ischial tuberosity; LT = lessor trochanter; NF = neck of femur; OE = obturator externus; OE-t = tendon of the OE; OI = obturator internus; OI-t = common tendon of the GI, GS, and OI; Pe = pectineus; Pi = piriformis; Pi-t = tendon of the Pi; QF = quadratus femoris; QT = quadrate tubercle; RF = rectus femoris; RF-t = tendon of the RF; *Sup* = superior; VI = vastus intermedius; and VL = vastus lateralis.

gluteus minimus ran along the posterosuperior-anterosuperior surface of the joint capsule while descending across the femoral neck (Figs. 1-A, 1-B, and 1-C). The pericapsular muscles were arranged in a spiral pattern and ran on the joint capsule in a clockwise direction around the femoral neck axis at the right hip, as viewed from the greater trochanter side (Fig. 1-D).

Histological Relationships Between the Pericapsular Muscles and Cap

In the anteroinferior region (Figs. 2 and 3-A), the joint capsule formed an aponeurosis-like epimysium surrounding the iliopsoas. The perimysium of the iliacus continued directly to the joint capsule (Fig. 3-B). In the posteroinferior region (Figs. 2 and 3-C),

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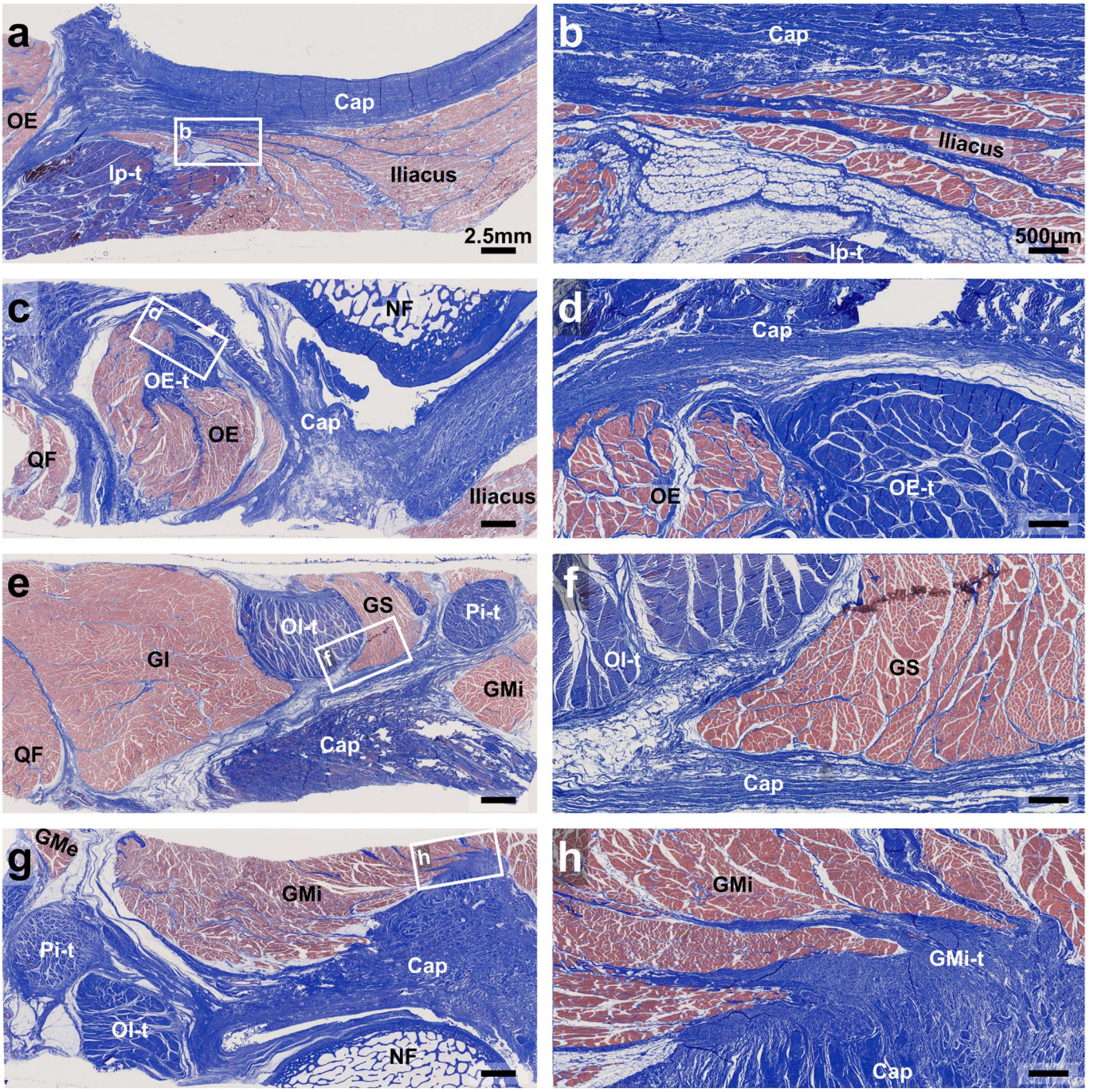

Fig. 3

Histological relationships between the pericapsular muscles and joint capsule (Masson's trichrome staining). Histological sections showing the relationships between the joint capsule (Cap) and (**Figs. 3-A and 3-B**) iliacus, (**Figs. 3-C and 3-D**) obturator externus (OE), complex of the gemellus inferior (GI), gemellus superior (GS), (**Figs. 3-E and 3-F**) obturator internus (OI), and (**Figs. 3-G and 3-H**) gluteus minimus (GMi). The dotted box regions in Figures 2-B through 2-D correspond to (**Figs. 3-A, 3-C, 3-E, and 3-F**), respectively. The boxed regions in (**Figs. 3-A, 3-C, 3-E, and 3-F**) are magnified to (**Figs. 3-B, 3-D, 3-E, and 3-G**), respectively. GMe = gluteus medius; GMi-t = tendon of the GMi; Ip-t = tendon of the iliopsoas; NF = neck of femur; OE-t = tendon of the OE; OI-t = common tendon of the GI, GS, and OI; Pi-t = tendon of the piriformis; QF = quadratus femoris; and RF = rectus femoris.

the joint capsule formed an aponeurosis-like epimysium surrounding the obturator externus and the perimysium continued directly to the joint capsule (Fig. 3-D). In the posterosuperior region (Figs. 2 and 3-E), the joint capsule formed an aponeurosis-like epimysium surrounding the complex of the obturator internus and the perimysium of the gemelli inferior and superior

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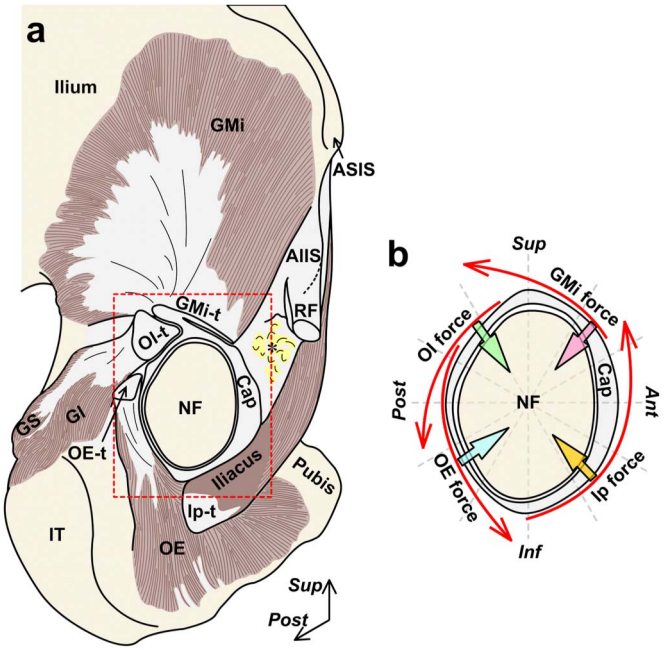

Fig. 4

Schematic diagram of the pericapsular muscle arrangement and their role in the femoral head and neck stability. (**Fig. 4-A**) Posterolateral aspect of the right hip cutting at the level of the neck of the femur (NF). As viewed from the NF toward the head of the femur, the pericapsular muscles run on the joint capsule (Cap) in a clockwise direction (counterclockwise if in the left hip) around the NF axis and are arranged in a spiral pattern. (**Fig. 4-B**) Based on the histological findings that the pericapsular muscles and Cap were in close contact, the contraction force of the pericapsular muscles may be generated spirally as a result of keeping their spiral running course (indicated by red linear arrows). The centripetal force (indicated by colored block arrows) of each spirally generated contraction force can adjust the position of the femoral head and neck through the Cap. AIIS = anterior inferior iliac spine; *Sup* = superior; *Ant* = Anterior; ASIS = anterior superior iliac spine; asterisk = fat pad and loose connective tissue on the anterior Cap; GI = gemellus inferior; GMi = gluteus minimus; GMi-t = tendon of the GMi; GS = gemellus superior; *Inf* = inferior; Ip = iliopsoas; Ip-t = tendon of the Ip; IT = ischial tuberosity; OE = obturator externus; OE-t = tendon of the OE; OI = obturator internus; OI-t = common tendon of the GI, GS, and OI; *Post* = posterior; and RF = rectus femoris.

directly continued to the joint capsule (Fig. 3-F). In the superior region (Fig. 2 and 3-G), the joint capsule formed an aponeurosis-like epimysium surrounding the gluteus minimus and the gluteus minimus tendon directly continued to the joint capsule (Fig. 3-H). By contrast, the main tendons of the other pericapsular tendons were distinguished from the joint capsule.

Discussion

The pericapsular muscles were macroscopically arranged spirally and ran clockwise around the femoral neck axis on the joint capsule of the right hip, as viewed from the outside. All periscapular muscles showed histological continuity with the joint capsule through their tendon or perimysium.

Regarding the pericapsular muscle arrangement on the joint capsule, a previous study has locally investigated their attachment site on the joint capsule[2,6,7,27,28]. However, because the deep aponeuroses of these pericapsular muscles are continuous with the joint capsule[6-8], anatomic knowledge of where the pericapsular muscle runs on the joint capsule is required regardless of the presence or absence of a macroscopical connection. Almost consistent with previous studies[2,6], our macroscopic analysis confirmed that the iliopsoas occupied the anterior-inferior position of the femur; obturator externus, inferior-posterior; complex of the obturator internus, posterior-posterosuperior; and gluteus minimus, posterosuperior-anterosuperior. In addition to this confirmation, we demonstrated that these pericapsular muscles occupying a wide area on the joint capsule were arranged with a certain regularity in a spiral pattern.

Regarding the histological relationship with the joint capsule, only the gluteus minimus and iliopsoas were analyzed among the pericapsular muscles[6,27]. This study revealed that the perimysium of the obturator externus and complex of the obturator internus directly continued to the joint capsule in addition to the histological relationships of the gluteus minimus and iliopsoas to the joint capsule. Thus, this study demonstrated that all pericapsular muscles had the common characteristic of being histologically continuous with the joint capsule through the perimysium or tendons.

As for clinical insights, the spiral arrangement of the pericapsular muscles (Fig. 4-A) indicates that a contraction force may be generated spirally around the femoral neck axis because typical muscle contraction forces occur longitudinally along the muscle[29]. The histological continuity between the pericapsular muscles and the joint capsule can contribute to maintaining their spiral contraction forces during hip motion (Fig. 4-B, red linear arrows). In classical mechanics, the curved force, including force in a spiral direction, accompanies a centripetal force that acts perpendicular to the direction of the force[30]. Thus, each spiral contraction force of the pericapsular muscle mechanically accompanies a centripetal force, which can adjust the centric position of the femoral head and neck through the joint capsule (Fig. 4-B, colored block arrows) as previous studies proposed the iliopsoas and gluteus minimus as femoral head stabilizers[31,32]. Because the term "rotator cuff" defines the musculotendinous unit centralizing the humeral head on the glenoid in the shoulder[33], and the shoulder rotator cuff has a spiral arrangement[34], we propose that the pericapsular muscles (iliopsoas, obturator externus, complex of obturator internus, and gluteus minimus), instead of the gluteus medius[35-37], should be interpreted as "hip rotator cuff." The hip rotator cuff may adjust the centric position of the femoral head and neck through its spiral arrangement on the joint capsule, as with the shoulder rotator cuff.

This study had some limitations. First, this was a descriptive and anatomic study without quantitative data, using formalin-embedded specimens. We cannot rule out the possibility that their advanced age and fixation joint position might affect our findings. Therefore, the hip stabilization mechanism presented in this study has limited applicability to the objective data and needs to be

verified in clinical situations and biomechanical studies including the finite element studies. Second, the sample size was relatively small. Because there are major differences in the biomechanics of the hips between the sexes, analysis of gender differences by increasing the sample size may be necessary in the future. Finally, although an magnetic resonance imaging of the dissected specimens may be useful, we could not perform such an analysis because of the lack of equipment environment.

In conclusion, the pericapsular muscles are arranged on the joint capsule in a spiral pattern with histologically close continuity to the joint capsule through the perimysium or tendon. Future studies should verify whether the pericapsular muscles play an essential role in maintaining the centric position of the femoral head by balancing their centripetal forces through the joint capsule. ■

Note: The authors would like to express their sincere gratitude to the anonymous individuals who generously donated their bodies for this study and to their families.

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