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Dynamic changes of the joint capsule in relation to the zona orbicularis: An anatomical study with possible implications for hip stability mechanism

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Abstract

The zona orbicularis, which comprises the inner circular fibers of the joint capsule, is vital for hip stability in distraction. Despite the proximity of the whole joint capsule to the zona orbicularis, their anatomical relationship remains unclear. The aim of this study is to investigate the characteristics of the inner side of the joint capsule comprehensively. Twelve hips from nine bodies donated to science were examined. Six and three of the donated bodies, respectively, were embalmed using 8% formalin and Thiel's method. The joint capsules in three formalin-embalmed bodies were sturied by micro-computed tomography. During formalin fixation of six hips from these three bodies, one side was maintained at hip extension and the other at flexion. The remaining three formalin-embalmed bodies were examined histologically. Micro-computed tomography images revealed that the inward protrusion of the joint capsule narrowed the articular cavity, and the ratio of its narrowest area to that of the femoral neck was less at hip extension than at hip flexion. The Thiel's method specimens showed that the inner surface of the joint capsule protruded inward toward the femoral neck during hip extension. This inward protrusion was not histologically independent of the joint capsule. The zona orbicularis was interpreted as the inward protrusion caused by dynamic change of the joint capsule, rather than the local collar. In other words, the joint capsule could change its morphology dynamically depending on the hip position.

KEYWORDS
anatomy, hip joint, joint capsule, musculoskeletal system

1 | INTRODUCTION

The dynamic stabilizers of the hip joint include the pericapsular muscles: gluteus minimums, iliocapsularis, and rectus femoris (Ward et al., 2000; Walters et al., 2001, 2014). A recent anatomical study

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indicates that the iliofemoral ligament is identical to the joint capsule itself, with a connection to the gluteus minimums tendon and the deep aponeurosis of the iliopsoas (Tsutsumi et al., 2019, 2020). Specifically, the joint capsule transmits musculotendinous or musculoaponeurotic power to the hip joint and could be regarded as the dynamic stabilizer (Tsutsumi et al., 2020). However, to elucidate the transmission of power from the joint capsule to the joint, it is necessary to analyze the dynamic changes in the capsule corresponding to hip position, especially that in the inner layer, which can act directly on the bone.

The hip joint capsule contains both longitudinal and circular fibers (Neumann, 2016). The zona orbicularis, which comprises its inner circular fibers, has been recognized as a key structure for hip stability in distraction (Bedi et al., 2011; Ito et al., 2009). According to previous reports, the fibers of the zona orbicularis are not really circular, as classically described, but spiroid (Domb et al., 2013; Malagelada et al., 2015). They tighten during hip extension but unwind or loosen during flexion (Domb et al., 2013; Malagelada et al., 2015; Shindle et al., 2006). The zona orbicularis surrounds the narrowest area of the articular cavity and forms a tight collar around the thinnest part of the femoral neck without a direct bony attachment (Elze, 1954; Fick, 1904; Ito et al., 2009; Neumann, 2016). Therefore, its tightness must change according to its anatomical relationship to the joint capsule. However, few studies have investigated this relationship. The characteristics of the inner side of the joint capsule, such as the differences in its morphology between hip flexion and extension, could help to explain how the tightness of the zona orbicularis changes with hip movement.

The aim of this study was to elucidate the dynamic changes in the inner layer of the capsule with hip position using macroscopic, micro-computed tomography (micro-CT) and histological observations focusing on the zona orbicularis, a specific part of the hip capsule: tightening in extension, loosening in flexion.

2 | MATERIALS AND METHODS

2.1 | Cadaveric specimen preparation

Twelve hips from nine Japanese bodies (five males, four females; mean age at death 77.1 years; range 47–92 years) donated to the Department of Anatomy were used in this study. All donors had voluntarily declared before their death that their remains were to be donated for education and study. The study design was approved by the Ethics Committee of our institution (#M2018-044). Cadavers that conformed to the inclusion criteria—no apparent osteoarthritic changes and no previous operations on the hip—were included.

Six or three cadavers were embalmed using 8% formalin or Thiel's method (Thiel, 1992), respectively; the choices were random. Embalming the cadavers with formalin served to fix the tissue at a certain hip position for histological examination. Three of the formalin-embalmed cadavers were assessed by micro-CT (inspeXio SMX-100CT Micro Focus X-Ray CT System, Shimadzu, Kyoto, Japan) for analysis of the joint capsule, and the other three were examined histologically. Embalming cadavers using Thiel's method maintains the smooth and flexible joint movements observable in fresh cadavers and leaves the joint more mobile; the tissues are not fixed as rigidly as by formalin injection (Thiel, 1992). Therefore, the three cadavers embalmed by Thiel's method were used for dynamic assessment of the hip.

2.2 | Micro-CT analysis of the joint capsule in hip extension and flexion

To compare the inner aspects of the joint capsules between hip extension and flexion, six hips from three formalin-enbalmed cadavers (two males, one female; mean age at death, 78.3 years; range 69–92 years) were used. The areas of their articular cavities were measured using micro-CT. First, while the cadavers were being enbalmed in 8% formalin, one side of the hip was maintained at 0° extension while the other was flexed at approximately 90°. Both sides of the hips were maintained in neutral position, in hip abduction–adduction and internal–external rotation. These hip angles were maintained in the cadaver after enbalming. Second, after the skin and subcutaneous tissues had been removed, the pericapsular muscles were also removed while their deep aponeuroses or tendinous structures connected to the joint capsule were preserved (Figure 1). Thus, the outer surface of the joint capsule was revealed. Third, after the bony morphology of the pelvis and femur had been evaluated using micro-CT (200 μm resolution), the joint capsule was detached from the acetabular margin and femur to remove all bony elements. Finally, the joint capsules were examined using micro-CT at 200 μm resolution, and three-dimensional models of them in hip extension and flexion were reconstructed using ImageJ software (version 1.52; National Institutes of Health, Bethesda, MD, USA). Based on these 3D models, the micro-CT images of the joint capsules were re-sliced perpendicular to the longitudinal axis of the neck of the femur, and the narrowest cross-sectional areas of the articular cavities were measured using ImageJ. We also measured the narrowest cross-sectional area of the femoral neck perpendicular to its longitudinal axis and calculated the ratio between the areas of the articular cavities and the neck of the femur.

2.3 | Dynamic changes of the joint capsule between hip extension and flexion using the specimens embalmed by the Thiel method

The dynamic changes of the joint capsule between hip extension and flexion were evaluated using three hips from three cadavers (two males, one female; mean age at death 82.6 years; range 73–89 years) embalmed by Thiel's method. To examine the intact inner aspect of the joint capsule, the acetabular fossa was removed from the medial aspect of the pelvis without cutting or detaching the joint capsule. The head of the femur was then identified and removed proximal to the level of the thinnest part of the femoral neck. This was done by moving the hip joint slightly and grinding the bone little by little,

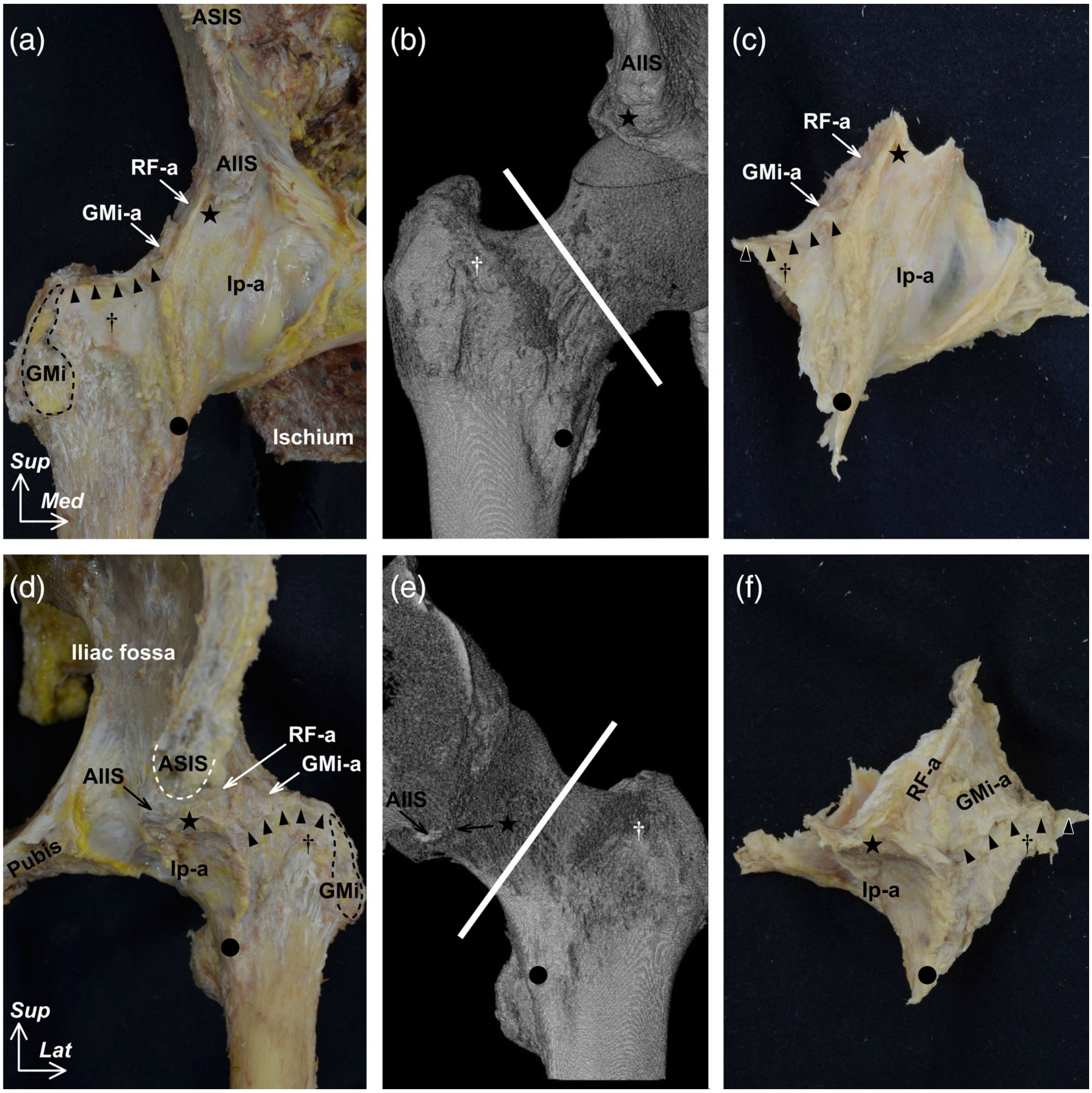

FIGURE 1 Preparation of the joint capsule for examination by removing the bony elements. Anterior aspects of the joint capsule at hip extension (right hip; a–c) and flexion (left hip; d–f). First, the pericapsular muscles were carefully removed while their deep aponeuroses connected to the joint capsule were preserved (a and d). The connection between the gluteus minimus tendon and the joint capsule was cut (arrowheads). Second, the bony morphology of the pelvis and femur was examined using micro-CT, and the narrowest cross-sectional area of the neck of the femur perpendicular to its longitudinal axis were measured (b and e: white lines indicate the measurement plane). Finally, the joint capsule was detached from the acetabular margin and femur, and all bony elements were removed (c and f). AIIS, anterior inferior iliac spine; ASIS, anterior superior iliac spine; Circle, inferomedial end of the intertrochanteric line; Dagger, superolateral end of the intertrochanteric line; Ip-a, deep aponeurosis of the iliopsoas; GMi, insertion of the gluteus minimus on the greater trochanter; GMi-a, deep aponeuroses of the gluteus minimus; RF-a, proximal deep aponeurosis of the rectus femoris; Star, inferior area of the AIIS; *Lat*, lateral; *Med*, medial; *Sup*, superior

taking care not to damage the inner surface of the joint capsule. We then recorded the dynamic changes in the morphology of the joint capsule from the medial aspect using photographs and videos.

2.4 | Histological examination of the joint capsule in coronal section

Three hips from three formalin-enbalmed cadavers (one male, two females; mean age at death 70.3 years; range 47–87 years) were used. First, we removed the skin, subcutaneous tissues, gluteus maximus, and hip adductor muscles to identify the osseous appearance of the pelvis and femur. Second, the bony configuration of the pelvic bone and femur was examined using micro-CT. On the basis of the osseous appearance and the micro-CT images we identified the coronal plane of the hip joint, which is reportedly a well-defined plane for the zona orbicularis (Wagner et al., 2012). We then harvested en bloc specimens using a diamond saw in two small regions: the coronal sections of the joint capsule superior and inferior to the neck of femur. The en bloc specimens were decalcified for 3 weeks in Plank-Rychlo solution ($AlCl_3.6H_2O$ [70.0 g/L], HCl [85.0 mL/L], and HCOOH [50.0 mL/L]) and were dehydrated (Plank & Rychlo, 1952). After fixation, they were embedded in paraffin and serially sectioned (5 mm thickness) and stained by the Masson trichrome method.

3 | RESULTS

3.1 | Three-dimensional micro-CT images of the joint capsule at hip extension and flexion

The joint capsules at both hip extension (Figure 2a–c) and flexion (Figure 2d–f) had an inward protrusion; however, no independent bundle-like structure was observed on the inner side in either case. This inward protrusion narrowed the articular cavity, which was not spheroid but ovoid. All measurements of the narrowest cross-sectional areas of the articular cavities and their ratios to those of the neck of the femur are shown in Table 1. The mean area of the articular cavity was narrower at hip extension (Figure 2c) than flexion (Figure 2f). The mean area ratio of the articular cavity to the neck of the femur at hip extension was also narrower than that at flexion.

3.2 | Dynamic changes of the joint capsule between hip extension and flexion

After the acetabular fossa had been removed from the medial aspect of the pelvis (Figure 3a), the head of the femur was also removed to reveal the relationships between the inner surface of the joint capsule and the neck of the femur (Figure 3b). During hip extension, the inner surface of the joint capsule protruded inward and closed around the femoral neck, similar to the closing of a lens aperture. During hip flexion, the inward protrusion of the joint capsule decreased and the space around the femoral neck widened (Figure 3c). These dynamic changes are shown in Video S1.

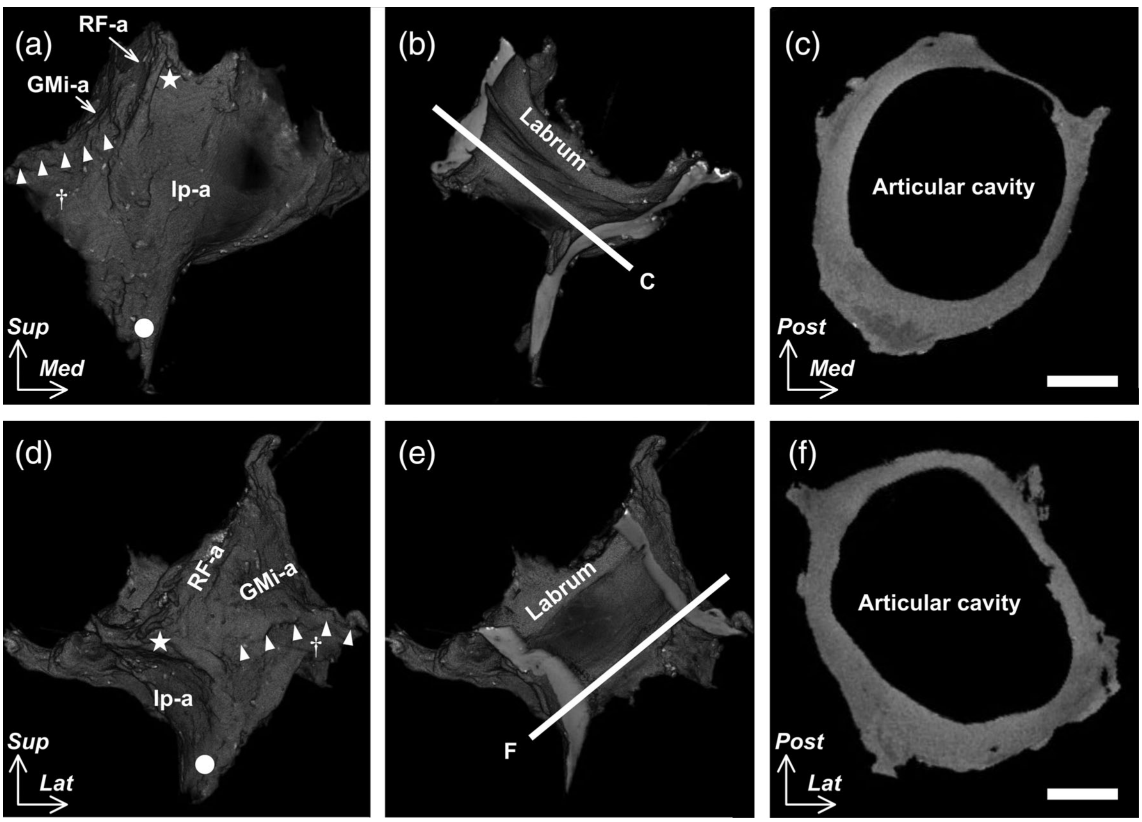

FIGURE 2 Micro-CT analysis of the joint capsule and its articular cavity at hip extension and flexion. Three-dimensional images of the joint capsule at hip extension (a–c) and flexion (d–f). The images on the anterior aspect of the joint capsule (a and d) correspond to Figure 1c,f, respectively. By evaluating the inner side of the joint capsule (b and e), the narrowest area of the articular cavity was measured perpendicular to the femoral neck (c, f: cross-sections along lines b and e, respectively). Scale bars in c and f = 10 mm. Arrow head, cutting line of the connection between the gluteus minimus tendon and the joint capsule; Circle, inferomedial end of the intertrochanteric line; Dagger, superolateral end of the intertrochanteric line; Ip-a, deep aponeurosis of the iliopsoas; GMi-a, deep aponeuroses of the gluteus minimus; Labrum, acetabular labrum; RF-a, proximal deep aponeurosis of the rectus femoris; Star, inferior area of the anterior inferior iliac spine; *Lat*, lateral; *Med*, medial; *Post*, posterior; *Sup*, superior

TABLE 1 Area of the articular cavity and its ratio to the neck of femur

	Hip joint position							
	Flexion ($n = 3$)				Extension ($n = 3$)			
	No. 1 (Rt.)	No. 2 (Lt.)	No. 3 (Rt.)	Mean ± SD	No. 1 (Lt.)	No. 2 (Rt.)	No. 3 (Lt.)	Mean ± SD
Neck of femur (cm^2)	8.9	5.5	7.6	7.3 ± 1.7	9.0	5.4	7.8	7.4 ± 1.8
Articular cavity (cm^2)	11.6	7.4	10.1	9.7 ± 2.2	10.1	6.8	9.2	8.7 ± 1.7
Articular cavity /Neck of femur	1.3	1.3	1.3	1.3 ± 0.02	1.1	1.3	1.2	1.2 ± 0.1

Note: The narrowest cross-sectional area of the neck of the femur perpendicular to its longitudinal axis, and those of the articular cavities perpendicular to the same axis, were measured.
Abbreviations: SD, standard deviation; Lt., left side of the hip; Rt., right side of the hip.

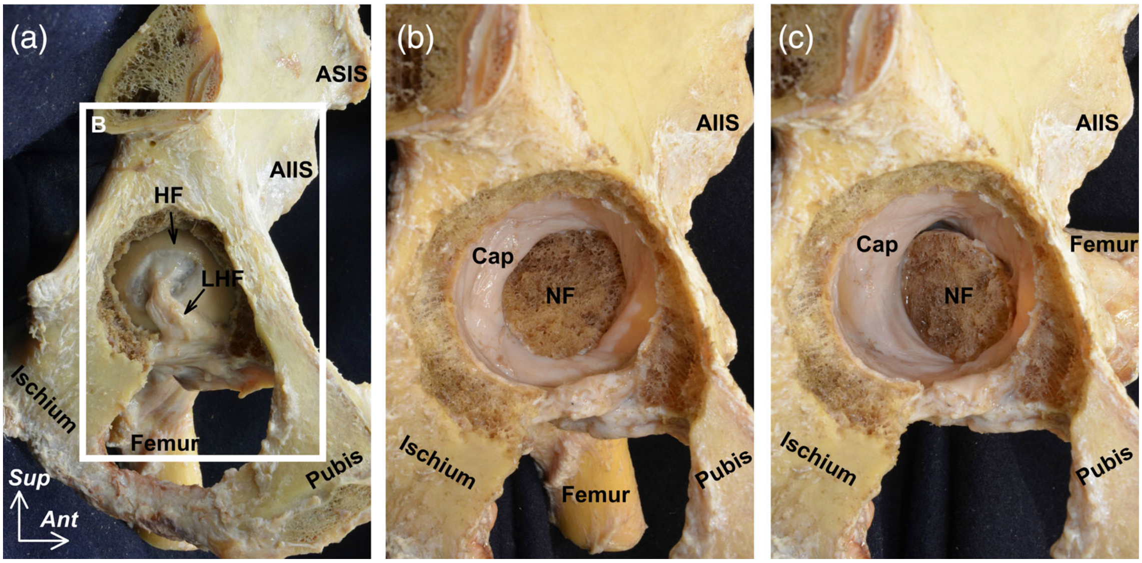

FIGURE 3 Dynamic changes of the joint capsule at hip extension and flexion using specimens fixed by Thiel embalming. (a) Medial aspect of the left hip at hip extension. The acetabular fossa was removed from the medial aspect of the pelvis to identify the head of femur (HF). (b) Magnified image of the boxed region in A. The HF was removed at the level of the femoral neck (NF) to reveal the inner surface of the joint capsule (Cap) at hip extension. (c) Inner surface of the Cap at hip flexion. AIIS, anterior inferior iliac spine; ASIS, anterior superior iliac spine; LHF, ligament of the head of the femur; *Ant*, anterior; *Sup*, superior

3.3 | Histological features of the joint capsule in coronal section

We examined coronal sections of the joint capsule histologically to characterize its inward protrusion at hip extension (Figure 4a). The joint capsule, which was continuous from the superficial surface of the acetabular labrum, was folded and protruded inward at both the superior and inferior regions of the neck of the femur (Figure 4b,c). The protrusion was not histologically independent of the joint capsule. It formed a capsular thickening composed of dense connective tissue, similar to the surrounding region of the joint capsule.

4 | DISCUSSION

Micro-CT images revealed that the inward protrusion of the joint capsule narrowed the articular cavity, and the ratio of the narrowest area of the articular cavity to that of the neck of the femur was narrower at hip extension than flexion. The dynamic changes of the joint capsule meant that its inner surface protruded inward and closed around the neck of femur during hip extension. Histologically, this inward protrusion was not independent of the joint capsule and formed a capsular thickening composed of dense connective tissue. If this inward protrusion generated by hip extension can be identified as the zona orbicularis, then the zona orbicularis is a component of the joint capsule formed by hip movement rather than the local collar.

Images of the joint capsule, including the zona orbicularis, have been analyzed previously. However, these studies have mainly focused on the ability to visualize (Malagelada et al., 2015; Wagner et al., 2012) or the capsular thickness (Kay et al., 2020; Strickland et al., 2018); the articular cavity surrounded by the joint capsule has never been studied quantitatively. Micro-CT analysis in the present study revealed that the inward protrusion of the joint capsule surrounded the narrowest area of the articular cavity, which was ovoid

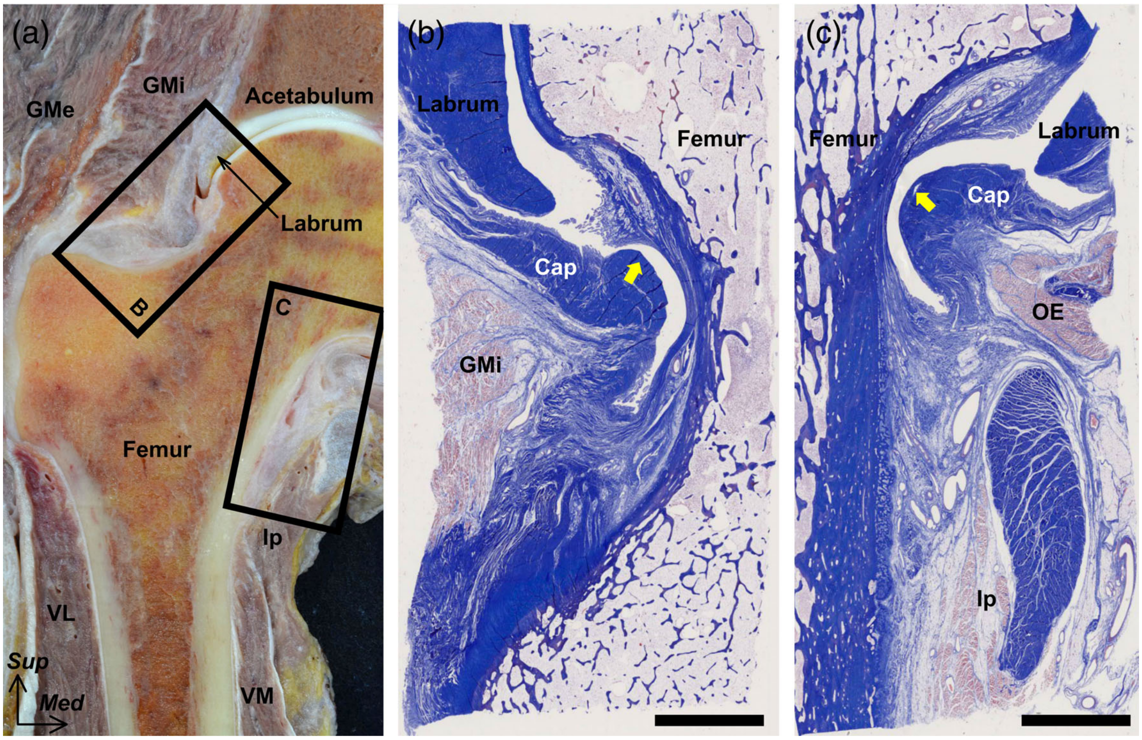

FIGURE 4 Histological examination of the joint capsule in coronal section (Masson's trichrome stain). (a) Coronal section of the right hip. (b and c) Histological sections of the boxed regions (b and c) in (a), respectively. The joint capsule (Cap) is folded and protrudes at the neck of femur (yellow arrows). Scale bars in b and c = 5 mm. GMe, gluteus medius; GMi, gluteus minimus; Ip, iliopsoas; Labrum, acetabular labrum; VL, vastus lateralis; VM, vastus medialis; *Med*, medial; *Sup*, superior

not spheroid. Its area was narrower at hip extension than flexion in relation to the femoral neck. Since the zona orbicularis surrounds the narrowest area of the articular cavity (Elze, 1954), the inward protrusion of the joint capsule can be interpreted as the zona orbicularis. In other words, we found that the size of the articular cavity narrowed by the so-called zona orbicularis was quantitatively different between hip extension and flexion. The non-uniform ovoid morphology of the articular cavity could also suggest that this shape was attributable not to the local circular fibers but to the joint capsule itself, which had a non-uniform thickness (Tsutsumi et al., 2020).

Ng et al. (2019) examined a fresh cadaver and reported that the zona orbicularis closed the articular cavity, much like a lens aperture, during hip extension. In the present study, we found that the movement of the zona orbicularis reported by Ng et al. (2019) caused the inner surface of the joint capsule to protrude inward and close around the neck of the femur. From this perspective, the inward protrusion of the joint capsule can reasonably be interpreted as the zona orbicularis. Moreover, it is possible that this lens-aperture-like closing of the articular cavity explains only the local movement at the level of the femoral neck. If the morphology of the joint capsule changes as a whole, we propose that the articular cavity is three-dimensionally narrowed by the inward protrusion as by the inward curvature of a hyperboloid, which can be generated by twisting one end of a cylinder (Figure 5a,b).

Few studies have shown the histological features of the zona orbicularis. According to Wagner et al. (2012), the zona orbicularis was histologically well-defined in coronal section, with thickening of the joint capsule around the superior and inferior aspects of the femoral neck. Since our study showed that the inward protrusion of the joint capsule formed the capsular thickening around the femoral neck, it can also be histologically interpreted as the zona orbicularis in light of the findings of Wagner et al. (2012).

The present study is clinically relevant because it provides useful information regarding hip stability. First, the "vacuum effect" or "suction seal" of the hip is vital for hip stability in femoral head distraction, and the acetabular labrum is crucial for the hip suction seal (Crawford et al., 2007; Storaci et al., 2020). Although the zona orbicularis is also recognized as a key structure for hip stability during distraction (Bedi et al., 2011; Ito et al., 2009), its contribution to the hip suction seal has not been discussed. The present study revealed that the zona orbicularis is an inward protrusion of the joint capsule during hip extension (Figure 5a,b), possibly pulling the proximal joint capsule toward the neck of femur (Figure 5c). This pulling on the joint capsule could contribute to covering and holding down the labrum, helping the labrum to make close contact with the head of femur and establish the hip suction seal. The joint capsule could thus help to produce the hip suction seal. In light of this, it is reasonable that most surgeons pull the patient's hip in semi-flexed position during arthroscopic surgery.

Second, most anatomical and biomechanical studies have focused on the hip joint capsule—especially the capsular ligament, which

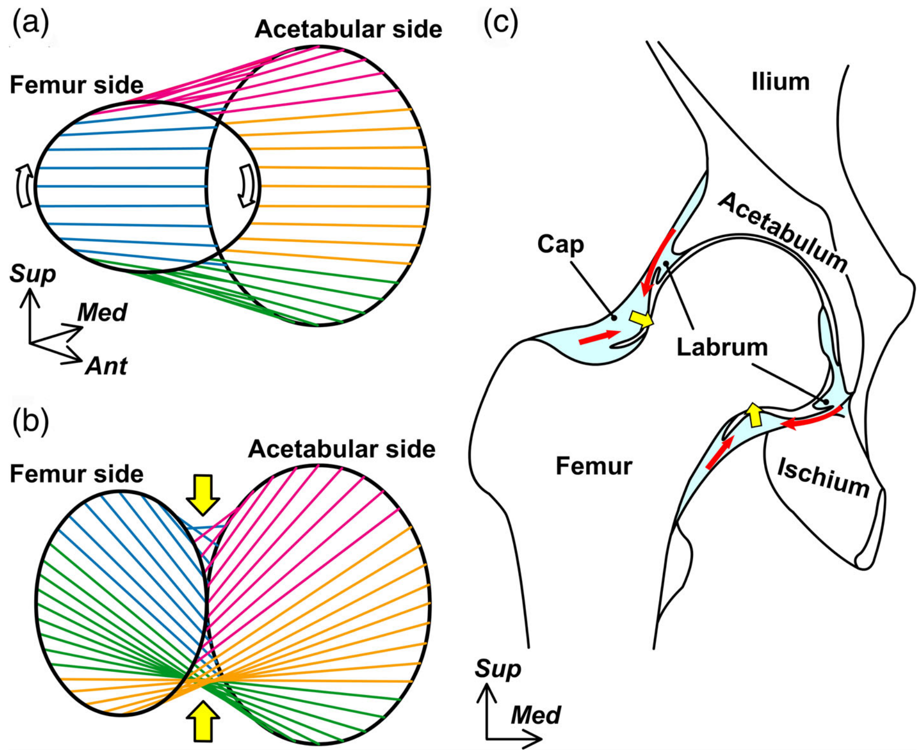

FIGURE 5 Dynamic changes of the inner surface of the joint capsule caused by hip extension. Schematic illustration of the right hip in the anterolateral (A and B) and anterior (C) aspects of the frontal section. Because a hyperboloid can be generated by twisting one end of a cylinder, the inner surface of the joint capsule at hip flexion (A) can protrude inward (yellow arrows) at the level of the femoral neck by hip extension (B). With this inward protrusion, the joint capsule is pulled toward the neck of the femur (red arrows), and this pulling force can contribute to covering and holding down the labrum (C). Cap, joint capsule; Labrum, acetabular labrum; *Ant*, anterior; *Med*, medial; *Sup*, superior

reinforces it—as a static stabilizer (Burkhart et al., 2020; Hewitt et al., 2002; Martin et al., 2008; Telleria et al., 2014; Walters et al., 2014). Some recent anatomical studies have suggested that the iliofemoral ligament is identical to the joint capsule itself, with tendinous and aponeurotic connections, and could be regarded as the dynamic stabilizer (Tsutsumi et al., 2019, 2020). The present study showed that the zona orbicularis is the inward protrusion of the joint capsule generated by its dynamic morphological changes. Recent anatomical studies (Tsutsumi et al., 2019, 2020) and the present study indicate that the joint capsule can change its morphology dynamically depending on the muscular power or the hip position. A biomechanical or in-vivo imaging study focusing on the hip stabilization mechanism, with consideration of the joint capsule, should be performed.

The present study has some limitations. First, it was purely anatomical and limited to uninjured specimens; therefore, our explanations of the mechanism of hip stability remain speculative. Second, although we prepared formalin-embedded cadavers fixed at hip extension and flexion, the range of motion of the hip joint including rotation could not be rigorously defined owing to the nature of cadavers. Finally, the mean age of the study population was approximately 80, which does not reflect the general population of patients with hip arthroscopy. We cannot exclude the possibility that old age affected our findings, which need to be validated by additional biomechanical studies or studies with clinical case imaging.

In conclusion, the zona orbicularis was the inward protrusion generated by dynamic changes of the joint capsule rather than being the local collar. This anatomical knowledge could lead to a better understanding of the hip stabilization mechanism.

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AUTHOR CONTRIBUTIONS

Masahiro Tsutsumi: Study design, acquisition of data, data analysis and interpretation, and drafting of the manuscript. Akimoto Nimura: Study design, acquisition of data, and critical revision of the manuscript. Hajime Utsunomiya: Study design, supervising the work, and critical revision of the manuscript. Keiichi Akita: Supervising the work and commenting on drafts and the final version of the manuscript. All authors gave their final approval and agreed to be accountable for all aspects of the work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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