Contributions of the Capsule and Labrum to Hip Mechanics in the Context of Hip Microinstability

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Background: Hip microinstability and labral pathology are commonly treated conditions with increasing research emphasis. To date, there is limited understanding of the biomechanical effects of the hip capsule and labrum on controlling femoral head motion.

Purpose/Hypothesis: The purpose of this study was to determine the relative role of anterior capsular laxity and labral insufficiency in atraumatic hip microinstability. Our hypotheses were that (1) labral tears in a capsular intact state will have a minimal effect on femoral head motion and (2) the capsule and labrum work synergistically in controlling hip stability.

Study Design: Controlled laboratory study.

Methods: Twelve paired hip specimens from 6 cadaveric pelvises (age, 18-41 years) met the inclusion criteria. Specimens were stripped of all soft tissue except the hip capsule and labrum, then aligned, cut, and potted using a custom jig. A materials testing system was used to cyclically stretch the anterior hip capsule in extension and external rotation, while rotating about the mechanical axis of the hip. Labral insufficiency was created with a combined radial and chondrolabral tear under direct visualization. A motion tracking system was used to record hip internal-external rotation and displacement of the femoral head relative to the acetabulum in the anterior-posterior, medial-lateral, and superior-inferior directions. Testing variables included baseline, postventing, postcapsular stretching, and postlabral insufficiency.

Results: When comparing the vented state with each experimental pathologic state, increases in femoral head motion were noted in both the capsular laxity state and the labral insufficiency state. The combined labral insufficiency and capsular laxity state produced statistically significant increases ($P < .001$) in femoral head translation compared with the vented state in all planes of motion.

Conclusion: Both the anterior capsule and labrum play a role in hip stability. In this study, the anterior hip capsule was the primary stabilizer to femoral head translation, but labral tears in the setting of capsular laxity produced the most significant increases in femoral head translation.

Clinical Relevance: This study provides a physiologic biomechanical assessment of the hip constraints in the setting of hip microinstability. It also sheds light on the importance of the hip capsule in the management of labral tears. Our study demonstrates that labral tears in isolation provide minimal changes in femoral head translation, but in the setting of a deficient capsule, significant increases in femoral head translation are seen, which may result in joint-related symptoms.

Keywords: hip microinstability; capsular laxity; labral tear

Pathologic femoral head motion without dislocation, known as microinstability, has been implicated as a source of symptomatic hip pain in patients with and without normal bony morphology.[5,13,14,21,22,25] The hip capsule is composed of the iliofemoral ligament, pubofemoral ligament, and ischiofemoral ligament. Among these structures, the iliofemoral ligament is the most important for hip stability.[14,21] The predominant theory of microinstability with normal bony architecture is that capsular laxity results in pathologic femoral head motion.[8,13,14,21] Causes for capsular laxity include generalized ligamentous laxity (which is not necessarily pathological), repetitive stretching from sports activity, iatrogenic laxity after hip arthroscopy, or traumatic injury to the capsule. Several prior studies[8,11,12] have assessed the role of the iliofemoral ligament in controlling femoral head motion and have displayed increased motion with capsular laxity. Furthermore, later studies[7,10,15,18] have demonstrated the clinical importance of the anterior hip capsule, and early studies[3,13,15] demonstrated favorable outcomes with capsular plication in patients with

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symptomatic microinstability. However, the importance of other structures that constrain hip motion, such as the acetabular labrum, ligamentum teres, and surrounding muscular forces, has not been explored relative to the capsular laxity state, and the implications of these structures are not as well understood.[18]

The labrum plays an important role in hip biomechanics.[22,23] Among its many purported functions, the labrum acts to support the suction seal and fluid mechanics across the hip, deepens the hip socket, and supports load across the hip joint.[4,9,19] Prevalence studies[6,26] have shown labral pathology on advanced imaging in more than 50% of adults, and the majority of these patients are asymptomatic. It remains unknown why some individuals have symptomatic labral tears, whereas others with the same lesion have no symptoms. Various theories describe concomitant pathology such as femoroacetabular impingement (FAI), chondral damage, or instability as provocative factors for symptomatic labral pathology.[2,7] Clear relationships have been demonstrated between FAI and labral pathology, but the relationship between instability and labral pathology is less understood.[16] We theorize that labral tears may become symptomatic because of increased femoral head motion, which may be present in the patient with a stretched or deficient capsule. Thus, patients with a labral tear and intact capsule may have normal hip mechanics, but those with both a labral tear and capsular laxity are more likely to have symptomatic hip motion and hip pain.[21]

Previous cadaveric biomechanical studies[1,2,7,9,11,20] have focused on the relative relationship between capsulotomy, capsulectomy, and the labrum. These studies often failed to replicate the capsular laxity state or adequately evaluate hip microinstability. Other studies have assessed the effect of capsulotomy and labrum in a normal hip (normal capsuloligamentous structures), and there is not a single study with pathologic biomechanics of hip capsular laxity.[1,2,7,9,11,20]

Using a validated capsular laxity model, we aimed in this study to determine the relative role of the capsule and labrum in atraumatic hip microinstability.[12] Our hypotheses were that (1) labral tears in a capsular intact state have a minimal effect on femoral head motion and (2) the capsule and labrum work synergistically in controlling hip stability.

METHODS

In total, 12 hips from 6 fresh-frozen cadaveric pelvises with full femurs (mean age, 29 years [range, 18-41 years]; 4 males, 2 females) were used in the study. To best replicate the hip arthroscopy population, a strict age cutoff of <45 years at the time of death was utilized. Specimens were obtained from commercial, licensed, third-party organizations. These companies have access to the donor's medical history, and only donors with no history of hip surgery were eligible for this study. Internal review board approval was not necessary, as this was a cadaveric laboratory-based study.

All specimens underwent radiographic assessment of the hip joint to confirm the absence of arthritis, FAI, dysplasia, or previous trauma. This study used a previously described, validated model for creating capsular laxity in the hip.[12] Specimens were dissected and skeletonized, preserving the hip capsule. All specimens were aligned using a custom jig, with markers placed to determine the mechanical axis of the femur. Specimens were then cut through the ilium and midshaft femur and potted in polymethylmethacrylate. A materials testing system (Instron Corporation) and motion tracking system (3D Creator, Boulder Innovation Group) were used for data collection, with an estimated margin of error (as previously tested in our laboratory) of 0.1 mm and 0.1°, respectively (root-mean-square error).

Using a matched-pair design, in a randomized fashion, 1 hip was designated to the capsular laxity state, whereas the other hip from the same pelvis had the capsule intact. Specimens were preconditioned, and baseline hip internal-external range of motion and femoral head translation were recorded with the hip in 0° of extension and the hip in maximal extension. The 0° of hip extension was determined before potting by aligning the mechanical axis of the femur in the sagittal plane parallel to the plane of the anterior superior iliac spine and pubic symphysis using a custom jig.[12] Hip maximal extension was then determined by manually pulling the femur into extension while maintaining a neutral coronal mechanical axis of the femur and 0° of rotation using the posterior condylar axis of the femur as a reference. Once a firm endpoint was palpated, the degrees of hip extension were recorded using a digital goniometer.[12] Internal-external arc of rotation (IR-ER) and femoral head motion were recorded in the anatomically neutral rotational plane (determined by the posterior condylar axis). All specimens were vented to control for the suction-seal effect of the capsule and labrum at baseline. We felt it was necessary to isolate the mechanical effects of each structure, as the capsule was minimally incised later in the study to create the labral injury. An 18-gauge needle was introduced from the inferomedial position of the hip capsule along the transverse acetabular ligament with a 100-N distractive and 50-N lateral translation force. A release in distractive force was noted on the materials testing system after venting to confirm proper needle positioning.

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Ethical approval was not sought for the present study.

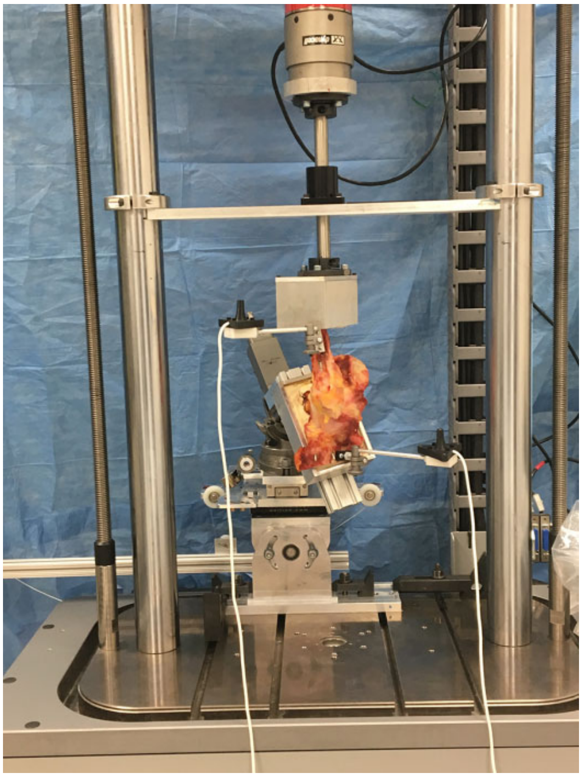

Figure 1. Image of the experimental setup on the materials testing system.

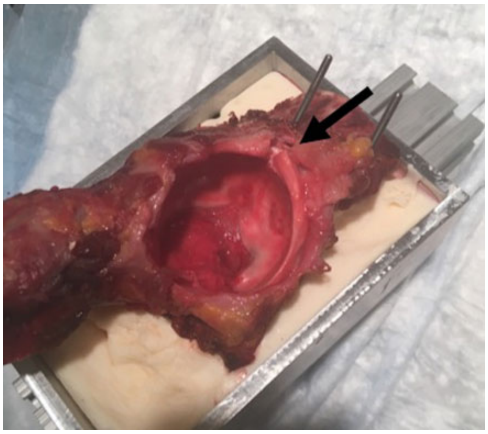

Figure 2. Postdissection view of the acetabulum demonstrating the combination of the chondrolabral and radial tears of the superior-lateral labrum (arrow).

The capsular laxity state was created through cyclic stretching of the anterior hip capsule (Figure 1). This was performed with a cyclic, repetitive external rotation torque of 30 N·m with the hip in maximal extension for 100 cycles.[12] To maintain these increases in external rotation, specimens then underwent an additional rotation controlled test for 1000 cycles at 0.5 Hz, with the rotation endpoints of cycle 100 of the initial cyclic test.[12] A constant superiorly directed compressive load of 10 N was maintained during the cyclic stretching protocol. The labral insufficiency state was created at the most superior-lateral portion of the acetabulum near the 12-o'clock position. This position was chosen because prior in vivo studies have associated hip instability with laterally based labral pathology.[13,14,24] A 1-cm transverse incision through the capsule at the capsulolabral junction was performed, and using an 11-blade, a full-thickness 1.5-cm chondrolabral separation was made. Next, at the 12-o'clock position, a full-thickness radial tear, in the midpoint of the chondrolabral separation, was created (Figure 2). We felt that this combination of a superior-lateral chondrolabral tear and a radial tear best simulated labral insufficiency, as it disrupted the hoop stresses of the labrum and disrupted the suction-seal at the chondrolabral junction. After creation of the labral insufficiency state, the small capsular incision was closed with interrupted No. 3-0 nylon sutures.

Data were collected for each hip specimen at the point of baseline position, postventing, postcapsular laxity (if in the capsular laxity arm), and postlabral insufficiency. At each time point, the IR-ER and femoral head translations in the anterior-posterior (A-P), medial-lateral (M-L), and superior-inferior (S-I) planes were recorded with the hip in 0° of extension (neutral) and at maximal extension.[12] During mechanical testing, a 10-N constant axial force was applied to maintain the seating of the femoral head in the acetabulum. Rotation was tested with a 5-N·m torque, and 50-N translational loads were applied in each plane using a custom pulley system.[12] The McKibbin index[17] was determined by the addition of the femoral and acetabular version values (normal range, 20°-58°). The femoral version was manually measured with a goniometer, whereas the acetabular version was calculated by geometric modeling using the motion capture system.[12] Motion of the femoral head was reported relative to the pelvic coordinate system. Internal and external rotations and displacements were reported as the net motion along the axis of loading.

A mixed-effects linear model was fitted to the data, with testing condition as a fixed effect and specimen as a random effect. As this was an exploratory study, a power analysis was not completed, and sample sizes were determined based on previous cadaveric studies.[4,12] Tukey contrasts for multiple comparisons of means were used to examine the differences between testing conditions. Significance was set at $P < .05$.

RESULTS

All data reported are using the anatomic neutral position with the hip in neutral extension. Unless otherwise noted, all values are presented with mean ± SD.

Baseline Data

No specimen was excluded because of radiographic abnormalities. The average McKibbin index was 50.25 (range, 35-63). The average maximum extension in the anatomic neutral plane was 10.4° (range, 5°-15°).

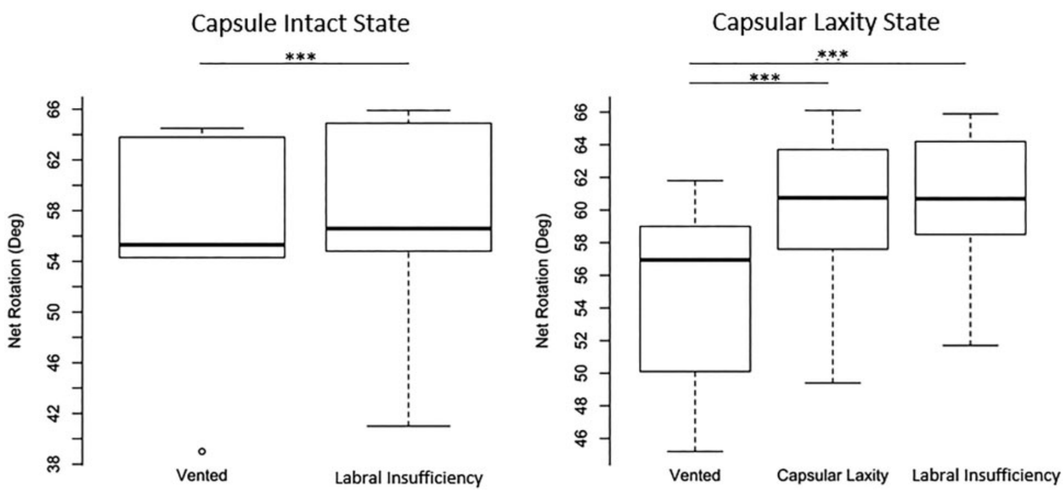

Figure 3. Internal-external rotation. Box plots displaying the average change in internal-external arc of rotation at each time point. Data presented are in the hip neutral and anatomic neutral hip position. The midline represents the median, with the lower and upper limits of the box denoting the first and third quartiles, respectively. The whiskers extend to 1.5 times the interquartile range from the top (bottom) of the box to the furthest datum within that distance. The small circles located above or below some of the boxes represent individual points that are beyond that distance and may be possible outliers. ***$P < .001$.

Capsule Intact State

In the setting of an intact capsule, the addition of a labral insufficiency state caused an increase in IR-ER by 1.3° ± 0.6° ($P < .001$) (Figure 3). Labral insufficiency resulted in 0.3 ± 0.3 mm increased femoral head motion in the M-L plane ($P = .016$), 0.5 ± 1.2 mm in the A-P plane ($P = .273$), and 0.0 ± 0.3 mm in the S-I plane ($P = .765$) relative to the vented state alone (Figure 4A).

Capsular Laxity State

Relative to the vented state, creation of the capsular laxity state caused an increase in IE-ER by 4.7° ± 1.7° ($P < .001$) (Figure 3). Capsular laxity resulted in 1.2 ± 0.9 mm increased femoral head motion in the M-L plane ($P < .001$), 0.5 ± 0.5 mm in the A-P plane ($P = .104$), and 0.4 ± 0.7 mm in the S-I plane ($P = .211$) (Figure 4B).

In the setting of capsular laxity, the addition of a labral insufficiency state caused an increase in IE-ER by 0.6° ± 0.9° ($P = .614$). Relative to the capsular laxity state alone, capsular laxity combined with labral insufficiency resulted in 0.7 ± 0.5 mm increased femoral head motion in the M-L plane ($P = .060$), 0.7 ± 0.7 in the A-P plane ($P = .021$), and 0.5 ± 0.4 in the S-I plane ($P = .107$). There were statistically significant differences in the M-L, A-P, and S-I planes when comparing femoral head motion in the combined labral insufficiency and capsular laxity state with the vented state ($P < .001$).

Labral Insufficiency: Capsular Laxity Group Versus Capsular Intact Group

In the setting of labral insufficiency, the capsular laxity state demonstrated 3.7° ± 7.0° more IR-ER than the capsular intact group ($P = .259$). The labral insufficiency state resulted in more femoral head translation in the capsular laxity group relative to the capsular intact group by 1.8 ± 2.1 mm in the M-L plane ($P = .092$), by 1.0 ± 1.5 mm in the A-P plane ($P = .151$), and by 1.1 ± 1.0 mm in the S-I plane ($P = .039$). While trends were seen toward an increased arc of rotation and femoral head translation with the addition of capsular laxity, statistical significance was only achieved in the S-I plane.

DISCUSSION

The results in this study demonstrate that both the capsule and labrum have important roles in controlling femoral head motion. Both the capsular laxity state and labral insufficiency states alone resulted in a greater IR-ER and increased M-L femoral head motion. However, the greatest femoral head motion was seen in the combined capsular laxity and labral insufficiency state. There were trends in all planes and a significant increase in S-I motion (distractability) in the combined capsular laxity and labral insufficiency state, as compared with the labral insufficiency state alone, thereby validating our hypothesis. Further, there were statistically significant increases in all planes of femoral head translation when comparing the combined capsular and labral insufficiency model with the vented state. These changes were much larger than either the capsular laxity state or labral insufficiency states alone. Based on the above data, the capsule appears to constrain the hip joint more effectively than the labrum, and in more planes. Therefore, in this cadaveric study, the capsule can be considered the primary soft tissue stabilizer of the hip, whereas the labrum acts as a secondary stabilizer. This study also lends support to the theory that either labral

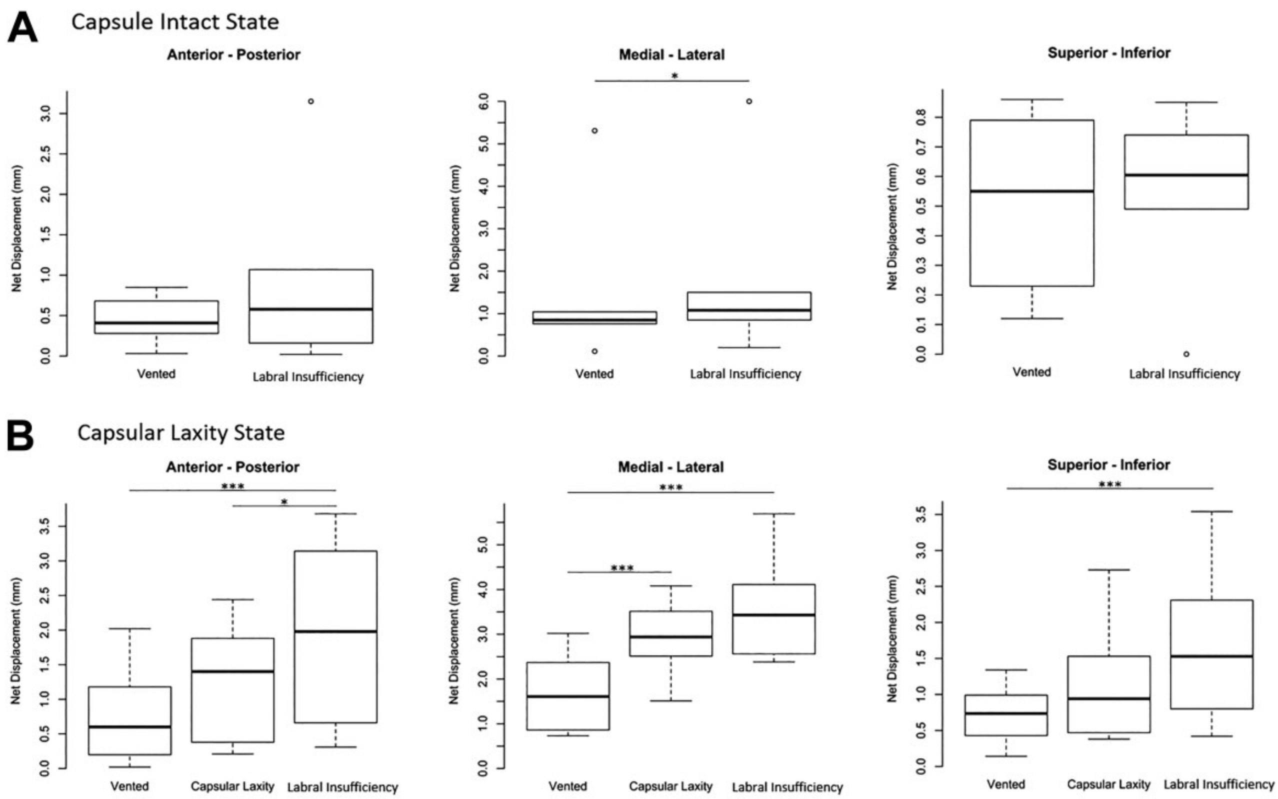

Figure 4. Femoral head translations. Graphical depiction of the average femoral head motions at each time point. Data presented are in the hip neutral and anatomic neutral hip position. The midline represents the median, with the upper and lower limits of the box denoting the third and first quartiles, respectively. The whiskers extend to 1.5 times the interquartile range from the top (bottom) of the box to the furthest datum within that distance. The small circles located above or below some of the boxes represent individual points that are beyond that distance and may be possible outliers. $^*P < .05$, $^{***}P < .001$.

tears or capsular laxity in isolation may have small effects on femoral head motion in a hip joint with no bony abnormality. However, if the capsule is compromised and the labrum is deficient, the most significant increases in femoral head motion occur.

Recent literature[4,18,23] has emphasized the role of an intact labrum and capsule in adequate hip function. Crawford et al[4] demonstrated that the force necessary to distract the hip decreased after joint venting. This finding reinforced the concept of the suction seal created by the labrum, an important advancement in hip preservation surgery. After creating a labral tear, the authors also found a decrease in the force necessary to distract the hip and an increase in hip rotation and displacement. These findings of altered mechanics after labral tears without capsular insufficiency are different from those found by Myers et al and the current study. Myers et al[18] reported an increase in external rotation after sectioning of the iliofemoral ligament and after the iliofemoral ligament and labrum were sectioned. Labral tears in isolation did not significantly affect the arc of rotation in the Myers et al study. The results presented in the current study did demonstrate that the labrum has a small but significant role in controlling the arc of rotation when the capsule is intact, but the magnitude of this effect lessened in the setting of a deficient or stretched capsule. The most significant changes in femoral head arc of rotation and translation were in the combined capsular laxity and labral insufficiency state. The increase in motion was most notable in the M-L plane, which is in accordance with previous studies.[23] Safran et al[23] tested hip kinematics (range of motion and femoral head motion relative to the pelvis) in 36 positions and different soft tissue conditions. Femoral head translation relative to the acetabulum occurred in all 3 planes, but was greatest in the M-L plane.

Based on these results, it appears the labrum and capsuloligamentous complex of the hip act synergistically to promote joint stability, and pathologic alterations of both structures will likely affect hip motion. It remains unknown how much femoral head translation is needed to cause symptomatic hip microinstability, and this value likely varies between patients depending on bony and muscular constraints. However, this study demonstrates significant differences of up to 2 mm in motion when capsular laxity or labral insufficiency is present, which does correlate with prior in vitro studies.[8,23] Further in vivo studies are needed to determine the level of constraint and femoral head translation in living patients.

This study has several advantages and limitations. This is the first study to use a physiologic biomechanical model to replicate hip motion, capsular laxity, and labral insufficiency. The previously validated model rotates around the mechanical axis of the femur and allows accommodative acetabular motion on a ball bearing system while it rotates. This allows for the dynamic interaction of the proximal femur and acetabulum to closely resemble in vivo biomechanics of the hip. Further, the cyclic stretching protocol of the hip capsule results in a gentle fatigue of the structure and does not violate the capsule as seen in prior studies.[8]

There are limitations of the study. The effect of venting was not reported, but our prior model[12] did demonstrate that it may have an effect on hip constraint. We felt it was important to perform routine venting to limit the variability of the suction-seal effect when the labral insufficiency state was created later in the study. However, we did not study the effect of capsular laxity in a nonvented specimen, which is a potential topic for future research. In addition, during the labral insufficiency state, a small 1-cm incision is created in the hip capsule. This was necessary to gain access to the labrum and was primarily repaired. It should be noted that no cases of failure of the repair were seen, and the iliofemoral ligament remained intact throughout testing, as the capsulotomy was in an area devoid of capsuloligamentous structures. Testing was only performed with the hip in 0° of extension and in maximal hip extension, as clinical reports mostly demonstrate provocative symptoms for microinstability with the hip in extension.[10,14] However, varying degrees of hip flexion-extension may have significant effects on instability that were not captured in this study.

Another limitation is the cadaveric nature of this study. In vivo effects of the capsule and labrum on microinstability have yet to be characterized, as well as the contribution of the surrounding bony architecture, muscles, tendons, ligaments such as the ligamentum teres, and other secondary stabilizers. It remains unknown what magnitudes of femoral head motion are necessary to result in symptomatic microinstability, and it is possible that the statistically significant increases in femoral head translation would not be clinically significant in vivo. However, given the limited in vivo data on this topic, quality cadaveric studies are needed to confirm or refute these biomechanical theories. Another strength of this study is the use of cadaveric hips that are within the generally accepted age range of those of standard hip arthroscopy patients, and thus have soft tissue qualities more similar to those of those undergoing hip arthroscopy, particularly for hip microinstability.

CONCLUSION

This study demonstrates the relative influence of capsular laxity on labral insufficiency on hip biomechanics. Labral insufficiency causes more femoral head translational motion in the capsular laxity state and has less significant effects on femoral head motion when the capsule is intact. These findings are applicable to the treatment of hip microinstability and labral tears in the nonarthritic hip population.

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