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HIP

Capsular ligaments provide a passive stabilizing force to protect the hip against edge loading

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Aims

In the native hip, the hip capsular ligaments tighten at the limits of range of hip motion and may provide a passive stabilizing force to protect the hip against edge loading. In this study we quantified the stabilizing force vectors generated by capsular ligaments at extreme range of motion (ROM), and examined their ability to prevent edge loading.

Methods

Torque-rotation curves were obtained from nine cadaveric hips to define the rotational restraint contributions of the capsular ligaments in 36 positions. A ligament model was developed to determine the line-of-action and effective moment arms of the medial/lateral iliofemoral, ischiofemoral, and pubofemoral ligaments in all positions. The functioning ligament forces and stiffness were determined at 5 Nm rotational restraint. In each position, the contribution of engaged capsular ligaments to the joint reaction force was used to evaluate the net force vector generated by the capsule.

Results

The medial and lateral arms of the iliofemoral ligament generated the highest inbound force vector in positions combining extension and adduction providing anterior stability. The ischiofemoral ligament generated the highest inbound force in flexion with adduction and internal rotation (FADIR), reducing the risk of posterior dislocation. In this position the hip joint reaction force moved 0.8° inbound per Nm of internal capsular restraint, preventing edge loading.

Conclusion

The capsular ligaments contribute to keep the joint force vector inbound from the edge of the acetabulum at extreme ROM. Preservation and appropriate tensioning of these structures following any type of hip surgery may be crucial to minimizing complications related to joint instability.

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Article focus

- This study quantified the stabilizing contributions generated by the hip capsule at extreme range of motion and examined its ability to prevent edge loading.

Key messages

- The capsular ligaments add a contribution to the net joint reaction force that protects the hip against edge loading.
- In deep flexion, every Nm of rotational restraint generated by the ligaments moves the joint reaction force vector inbound by 0.8°.
- For a 5 Nm rotational restraint, the typical tension within an engaged capsular ligament was between 100 N and 150 N; this was found to be true for all the ligaments.

Strengths and limitations

- An indication of the operational forces generated by the hip capsule in vivo has

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been reported and the possible capsular contribution to prevent edge loading is demonstrated.
- This study uses cadaver specimens rather than live patients and only includes the passive ligamentous contributions. The passive resistance provided by surrounding tissues is not considered.

Introduction

Joint-preserving surgery to treat femoroacetabular impingement (FAI), labral tears, and soft-tissue laxity is becoming increasingly popular.[1,2] While soft-tissue anatomy and biomechanics of the hip have been well described, the optimum surgical approach and capsular management continue to be debated.[3,4] Some studies report microinstability and anterior dislocations when capsular closure is not performed, requiring revision surgery or even conversion to total hip arthroplasty (THA).[5-7] Other studies have reported no such problems with an unrepaired capsule, while some have adopted a selective repair approach based on patient-related factors such as preoperative hip stiffness, dysplastic characteristics, and arthritic changes.[8-11] Similarly, following THA, some surgeons consider the problem of dislocation to have been solved by larger head sizes and soft-tissue repair/alternative approaches, while others still report it to be a clinical concern.[12,13] To help resolve this debate, it is important to understand the biomechanics of the capsule and its capacity to stabilize the joint.

Recent in vitro studies have indicated that the capsular ligaments provide passive rotational restraint limiting available range of motion (ROM) in the native hip, protecting the hip against impingement.[14-16] However, an important function of the ligaments could also be to tighten at the limits of ROM and stabilize the hip in these positions. This may contribute a net inbound force to maintain a joint reaction force away from the acetabular rim, thus protecting the healthy native hip against edge loading, subluxation, and dislocation. Previous studies have indicated the capsule resists joint distraction when the hip is in a neutral position, and limits translation when the hip rotates.[17,18] However, the stabilizing contribution of the capsular ligaments to the overall hip joint force vector has never been defined. Moreover, the ability of the capsule to prevent posterior edge loading in deep flexion is yet to be investigated.[19]

Therefore, the purpose of our study was to quantify the net stabilizing force contribution of the capsule to the overall hip joint force vector at extreme ROM, and to examine its ability to prevent edge loading of the native hip.

Methods

Summary of previous experimental research. Ethical approval for the study was provided by our institution's ethics committee (Imperial College Healthcare Tissue Bank). A set of torque-rotation curves were obtained from nine human cadaveric specimens (six male and three female) to define the rotational restraint contributions of the capsular ligaments: lateral and medial iliofemoral ligament, ischiofemoral ligament, and pubofemoral ligament.[15] Angular rotation at an applied 5 Nm torsion in internal and external rotation was recorded for each specimen in six flexion angles and three ab/adduction angles, making a total of 36 torsion/rotation datapoints per specimen. In each tested position, the principle of superposition was used to determine the contribution to rotational restraint of each ligament. Full details of how these data were generated can be found in previous research.[15]

Capsular ligament effective moment arms. From the experimental data, the mean average torque contributions across the nine specimens were taken, excluding values: a) where the ligament was not functioning in tension; b) the ligament contribution was not statistically significant; or c) where ligaments only contributed a small amount to rotational restraint (< 20% of net restraint) (see Supplementary Table i).

The experimental data were imported into a custom MATLAB model of the hip (R2018b; MathWorks, USA). The International Society of Biomechanics (ISB) hip joint coordinate system was adopted, consistent with experimental positions tested.[20,21] Lateral iliofemoral, medial iliofemoral, ischiofemoral, and pubofemoral ligament attachment sites were defined by scaling the centroid of enthesis data from the Twente Lower Limb Model 2.0 to the morphology of each of the nine specimens by aligning coordinate systems and scaling to femoral head diameter.[22] The attachment positions were rotated throughout ROM using transformation matrices,[23] and ligament lines of action were calculated. Wrapping surfaces were generated based on anthropometrically matched femur and pelvis geometries. The anatomical wrapping path of ligaments was simulated in each position and calculated using a contact-based wrapping method implemented in an open source biomechanical simulation platform, ArtiSynth 3.6.[24–26] In positions where ligament wrapping was detected, contact point data from the simulation were used to update the ligament lines of action. The positions where wrapping affected the computational model were validated through comparison to experimental observations and photographs. An illustration of this method is provided for the ischiofemoral ligament in Figure 1. Finally, the effective moment arms of each ligament were obtained by using a 3D geometrical method which considers the relative angle between ligament line of action and axis of rotation, called the 'twist angle'. Thus, the effective moment arm is calculated in 3D as the perpendicular distance (in mm) between the ligament line of action and axis of rotation multiplied by the sine of the twist angle.[27]

Functioning capsular ligament forces and stiffness. In each position, the functioning ligaments generated a tension force "s" along its line of action; this tension force was related to the effective moment arm "r" (with units of length) and the passive torque restraint "T" according to the equation $s = T/r$. Using this relationship,

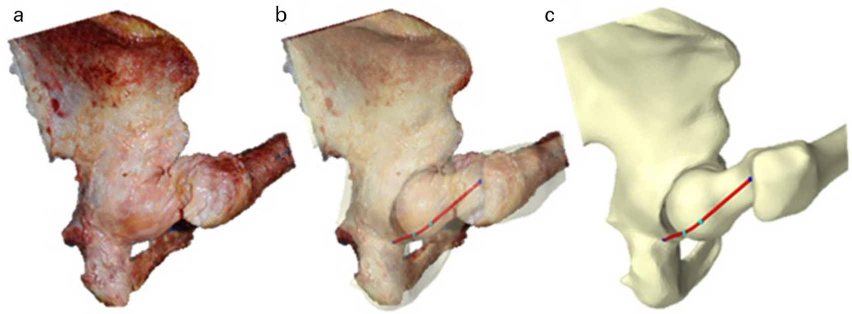

Fig. 1

Posterolateral view of a right hip in 90° flexion with adduction and internal rotation (FADIR). a) Photograph showing ischiofemoral ligament fibres taut and wrapped around the femoral head. b) The dominant ischiofemoral ligament line-of-action emphasized by overlapping images (a and c). c) Hip model showing dominant ischiofemoral ligament line-of-action (red) with contact points (blue) wrapping around the femoral head.

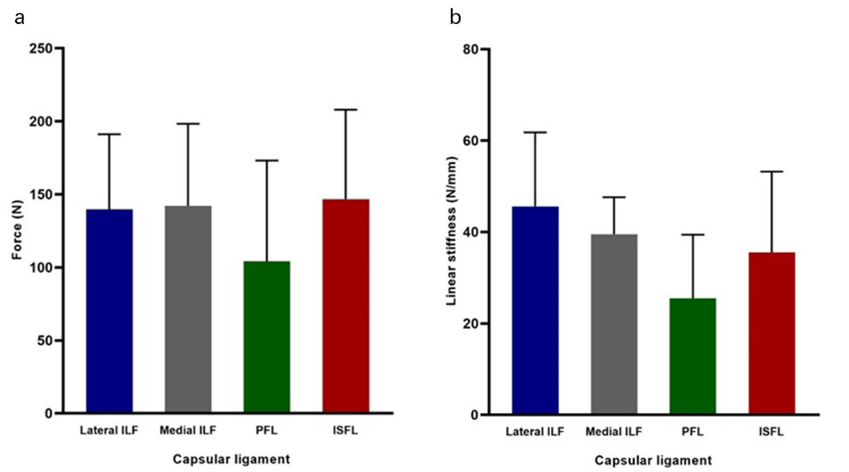

Fig. 2

Mean with standard deviation of a) functional forces and b) linear stiffness, generated in capsular ligaments at 5 Nm rotational restraint throughout extreme range of motion (ROM). ILF, iliofemoral; ISFL, ischiofemoral; PFL, pubofemoral.

the functioning ligament forces that resulted in 5 Nm of passive restraint (the maximum torque applied in the experiment) were evaluated using the torque contribution data from cadaveric experiments[15] and ligament effective moment arm prediction. The linear stiffness for each ligament was determined from the gradient of the experimental torque-rotation curves between 4 Nm and 5 Nm of passive restraint.[16]

Net reaction force vectors generated by capsular ligaments. In each position, the contribution of engaged capsular ligaments to the joint reaction force was evaluated as a 3D vector that was equal and opposite to force generated by the ligaments, acting through the hip centre of rotation, following a protocol previously applied to study muscle lines of action.[28]

Capsular ligament prevention of edge loading. To contextualize the magnitude and direction of the ligament forces and then evaluate the possible beneficial effect they may have on adverse hip loading scenarios, a posterior edge loading model was created. The acetabulum was modelled using a subtended angle of 160° approximated from a healthy acetabular rim profile[29] with 20° anteversion and 45° inclination (radiological definition).[30] The hip was positioned in 90° flexion, 24° adduction, and 10° internal rotation (FADIR), a position known to be at risk of posterior edge loading.[28,31] First, the hip was modelled without the capsular ligaments and was assumed to be posterior edge loading by applying a force of magnitude 1,320 N, based on the peak hip contact force measured during a sitting-down movement,[32] with direction from joint centre to posterior cup rim. Then, the capsular contributions to the joint reaction force were added into the posterior edge loading hip model, and the change in direction of the joint reaction force was calculated. The ligament forces and change in direction of the joint reaction force were then re-evaluated for increasing levels of passive rotational restraint, modelling the effects of additional movement which further tightens the capsular ligaments, based on rotational stiffness experimental data.[16]

Sensitivity analysis. A series of Monte Carlo simulations were performed to evaluate the sensitivity of our model to the position of the ligament attachment sites. Attachment sites were randomly generated using a Gaussian distributed perturbation from their nominal location, with

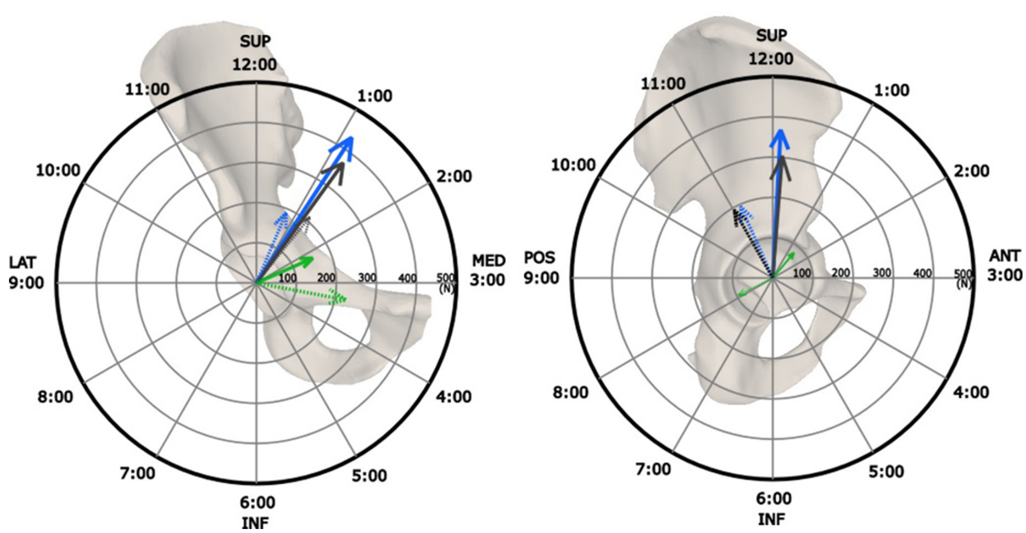

Fig. 3

Net force vector generated by capsular ligaments at 5 Nm rotational restraint in extension, in the coronal plane (left) and sagittal plane (right); in internal rotation (dashed) and in external rotation (solid). Colours denote hip abduction/adduction: adduction (blue); neutral (black); and abduction (green). ANT, anterior; INF, inferior; LAT, lateral; MED, medial; POS, posterior; SUP, superior.

standard deviations (SDs) of 5 mm in the anteroposterior (AP), mediolateral (ML), and superoinferior (SI) directions. A standard deviation of 5 mm was chosen based on measurements of the insertional footprints for the capsular ligaments previously reported.[33] One dominant joint position was investigated for each ligament: extension-adduction-internal rotation for the medial and lateral iliofemoral ligament, extension-abduction-external rotation for the pubofemoral ligament, and flexion-adduction-internal rotation for the ischiofemoral ligament. The mean ligament torque contribution was input into the random models and the resultant force contributions were analyzed. A total of 500 simulations were justified for each ligament by verifying that the mean of the force contribution over the last 10% of the simulations varied by less than 2%. Pearson's correlation coefficient was used to quantify the correlation between the output force contributions and attachment site location for each ligament.

Results

Among the 36 functional positions investigated, only three positions did not meet the inclusion criteria. These were when the hip was fully abducted, internally rotated, and at 60°, 90°, and full flexion.

Capsular ligament effective moment arms. The effective moment arm of the ischiofemoral ligament was affected by the wrapping path around the femoral head in all internally rotated positions. The effective moment arm of the pubofemoral ligament was affected by wrapping in externally rotated abducted positions, while the effective moment arm of the medial iliofemoral ligament was affected in extension and neutral flexion positions. Through the range of hip motion examined, the mean effective moment arms were 26 mm, 15 mm, 11 mm, and 17 mm for the lateral iliofemoral, medial iliofemoral, pubofemoral, and ischiofemoral ligaments, respectively. The effective moment arm for the lateral iliofemoral ligament was not affected by wrapping, however it varied the most, ranging from 6 mm to 37 mm, as the line of action transitioned from acting almost parallel to the axis of rotation to almost perpendicular to it. The effective moment arm for the pubofemoral ligament varied the least, ranging from 8 mm to 14 mm (Supplementary Table ii).

Functioning capsular ligament forces and stiffness. Lateral iliofemoral ligament: Across the nine hip models and 16 engaged hip positions, this ligament experienced a tensile force ranging from 90 N to 250 N with a mean value of 140 N (Figure 2a). The largest force occurred when the hip was extended, adducted, and externally rotated. In these positions, the ligament stiffness was between 28 N/mm and 66 N/mm, with a mean value of 43 N/mm (Figure 2b).

Medial iliofemoral ligament: Across the nine hip models and eight engaged hip positions, this ligament experienced a tensile force ranging from 90 N to 200 N with a mean value of 140 N (Figure 2a). The largest force occurred in externally and internally rotated positions in extension with adduction. In these positions the ligament stiffness was between 29 N/mm and 53 N/mm, with a mean value of 39 N/mm (Figure 2b).

Pubofemoral ligament: Across the nine hip models and four engaged hip positions, this ligament experienced a tensile force ranging from 40 N to 160 N with a mean value of 104 N (Figure 2a). The largest force occurred when the hip was extended, abducted, and internally rotated. In these positions, the ligament stiffness was between 13 N/mm and 37 N/mm, with a mean value of 25 N/mm (Figure 2b).

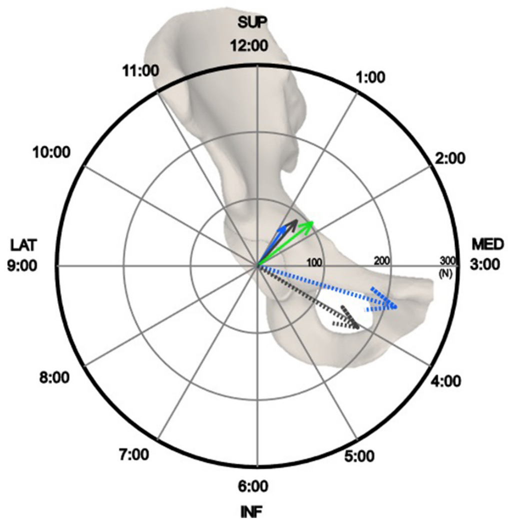

Fig. 4

Net force vector generated by capsular ligaments at 5 Nm rotational restraint in flexion 90°, in the coronal plane (left) and sagittal plane (right); in internal rotation (dashed) and in external rotation (solid). Colours denote hip abduction/adduction: adduction (blue); neutral (black); and abduction (green). ANT, anterior; INF, inferior; LAT, lateral; MED, medial; POS, posterior; SUP, superior.

Ischiofemoral ligament: Across the nine hip models and 15 engaged hip positions, this ligament experienced a tensile force ranging from 50 N to 230 N with a mean value of 150 N (Figure 2a). The largest force occurred when the hip was in 90° flexion, adducted, and internally rotated. In these positions, the ligament stiffness was between 20 N/mm and 58 N/mm, with a mean value of 35 N/mm (Figure 2b).

Net reaction force vectors generated by capsular ligaments. Hip positions in extension and neutral flexion: The net resultant force vector magnitude was largest when the hip was externally rotated and adducted. A resultant magnitude of 440 N and 320 N was generated in the superomedial direction in extension and neutral flexion, respectively (Figure 3). However, abducting the hip while in external rotation decreased the resultant force vector magnitude to 160 N in extension and neutral flexion positions. Internally rotating the hip while abducted generated a mean net resultant force vector of 230 N and 160 N in extension and neutral flexion, respectively.

Hip positions in 30° flexion and 60° flexion: Throughout mid-flexion, the capsular ligaments generated substantially smaller resultant force magnitudes, ranging from 90 N to 160 N.

Hip positions in 90° flexion and full flexion: The net resultant force vector magnitude was largest when the hip was internally rotated and adducted. A resultant magnitude of 230 N was generated in the medial-posterior direction in 90° flexion and full flexion positions (Figure 4). However, externally rotating the hip while in adduction decreased the resultant force vector magnitude to 80 N and 100 N in 90° flexion and full flexion positions, respectively. Externally rotating the hip while abducted generated a resultant magnitude of 140 N and 210 N in 90° flexion and full flexion positions, respectively.

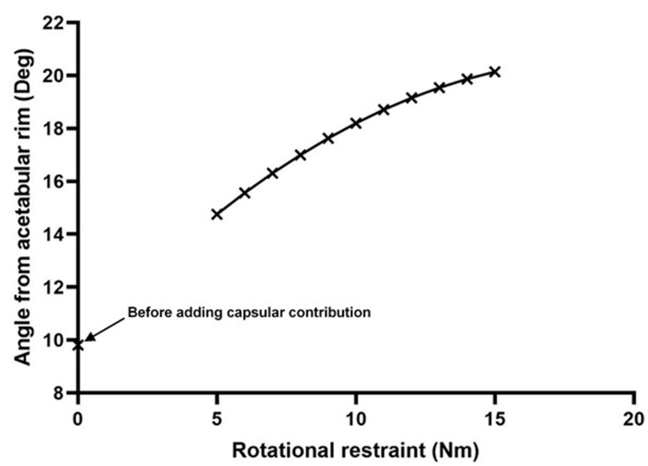

Fig. 5

Angle of hip joint reaction force from acetabular rim for hip positioned in 90° flexion with adduction and internal rotation (FADIR). With no capsule contribution, the force vector was 9.8° from the rim. Adding 5 Nm capsule restraint increased this angle to 14.8°.

Capsular ligament prevention of edge loading. The direction of the capsular ligament force contributions were such that they protected against edge loading. For the representative posterior edge loading scenario, it was found that the joint reaction force moved 0.8° more inbound and away from the acetabular edge for each Nm of passive restraint provided by the hip capsule (Figure 5).

Sensitivity analysis. The largest attachment site sensitivity for each of the ligaments is reported in Table I. Perturbing the attachments in remaining directions did not have considerable effect on the force contribution output ($-0.14 < r < 0.21$). The mean percentage variability of ligament forces across all perturbation directions was within ± 10% of the nominal value, therefore was considered acceptable.

Table I. The attachment direction and location associated with largest sensitivity reported for each capsular ligament. The mean percentage variability (standard deviation) in ligament force for random perturbations from their nominal attachment site. A standard deviation of 5 mm permitted in anterior/posterior, medial/lateral, and superior/inferior directions.

Ligament	Largest sensitivity			Mean variability of ligament force across all directions, % (SD)
	Attachment direction/ location	r	Mean variability of ligament force, % (SD)	
Lateral iliofemoral	AP/Pelvis	0.62	23 (16)	10 (11)
Medial iliofemoral	AP/Pelvis	0.68	20 (15)	8 (10)
Pubofemoral	AP/Femur	0.51	18 (16)	9 (7)
Ischiofemoral	SI/Pelvis	0.66	21 (14)	10 (10)

AP, anteroposterior; SD, standard deviation; SI, superoinferior.

Discussion

The most important finding of this study was that at extreme ROM the hip capsular ligaments add a contribution to the net joint reaction force that protects against edge loading. In deep flexion, every Nm of rotational restraint generated by the ligaments moved the joint reaction force vector inbound by more than 0.8°, protecting the native hip against edge loading. A 10 Nm rotational restraint would therefore move the net joint reaction force approximately 8° inbound from the edge of the acetabulum. The maintenance of a medializing force throughout extreme ROM can be attributed to the favourable lines of action created by the capsular ligaments attaching between the femur and pelvis. A secondary finding of this study was that for a 5 Nm rotational restraint, when the capsular ligaments were engaged, they each generated between 100 N and 150 N tension, giving some indication to the operational forces in vivo.

Our data may help explain clinical observations. We found that tension in the medial and lateral iliofemoral ligaments was such that they moved the net joint reaction force vector inbound from the acetabular anterolateral rim in extension, which may protect the hip from anterior subluxation and dislocation. This may help explain why some studies report postoperative subluxation[5] and anterior dislocations[34,35] if the medial and lateral iliofemoral ligaments are not repaired after FAI surgery. It may also help to explain the improved stability that has been observed with a full capsule repair after FAI surgery, for both interportal and more aggressive T-capsulotomy.[36–38]

Posterior to the hip, the ischiofemoral ligament moved the net joint reaction force inbound when the hip was flexed. Just 6 Nm of capsular restraint was found to be sufficient to move an edge loading force vector 5° more inbound. This is particularly relevant in the context of hip resurfacing as it is equivalent to the differences in subtended arc angle between implant designs that were found to be susceptible to edge loading wear, and those that were more tolerant of adverse loading.[39,40] Further, the near native-sized head diameters of these devices mean that the wrapping function of the ischiofemoral ligament is maintained, a factor that also benefits dual mobility THA.[41] It may explain why in previous work, an increased risk of dislocation was found when the ischiofemoral ligament was unrepaired.[41,42]

Anterior to the hip, the straight line of action of the lateral iliofemoral ligament (without wrapping) is likely to remain functional after any THA procedure (not just resurfacing/dual mobility), when native neck length is restored.[42] Anterior capsule repair may therefore reduce the risk of anterior edge loading. While our findings advocate repair of iliofemoral and ischiofemoral ligaments, they also provide knowledge of functional ligament forces for appropriate selection of capsular closure procedures, particularly the choice of suture technique needed to restore capsular strength to native state.

Our data also compare well with previous biomechanical findings. Muscles that insert on the distal femur can create an edge loading vector when the hip joint is in deep flexion, particularly when combined with internal rotation and adduction.[28,43] Our study demonstrates that this dislocation prone position correlates well with higher stabilizing forces produced by the ischiofemoral ligament directed inbound and away from the acetabular edge. This protective mechanism may be responsible for preventing posterior edge loading and reducing the risk of posterior dislocation by providing the necessary contact force between the femoral head and acetabulum in the natural hip. While careful cup positioning[44] and native head sizes have been appropriate measures taken to reduce dislocation,[41,42] repairing the ischiofemoral ligament may also provide the necessary defence against certain posterior edge loading mechanisms previously reported.[19]

Additionally, our study compares well with previously reported mechanical properties of the capsular ligaments. Hewitt et al[45] reported similar magnitudes of ligament tensions and variations among ligament stiffnesses for the iliofemoral and ischiofemoral ligament. More recently, Myers et al[46] predicted capsular behaviour using a computational model, and reported similar mean force and stiffness values for the iliofemoral and ischiofemoral ligament, however they reported markedly higher force and stiffness contributions for the pubofemoral ligament. This may be due to discounting the contributions provided by the labrum in abducted positions.

This study has several important limitations, some of which are associated with the use of cadaveric specimens and others related to the ligament model. Firstly, hip specimens were denuded of all surrounding soft-tissues except the capsular ligaments, ligamentum teres, and labrum. Therefore, the passive resistance provided by other tissues was not considered. Secondly, muscles provide notable contribution to dynamic stability and their contribution to the joint reaction force vector was not accounted for as we solely focused on the contribution of the capsule in providing stability. The possible muscle contribution to stability/edge loading has been described previously.[28] Thirdly, the lines of action of the capsular ligaments were not based on the anatomy of the individual cadaver specimens but rather of an anthropometrically matched model based on a single cadaver specimen, however our sensitivity analysis found that this was an acceptable method. Finally, we only considered simplified anatomy of the hip capsule by modelling each capsular ligament with a single line of action, which does not include the intricate anatomy of the capsule particularly the zona orbicularis and deeper fibril network.[47] The circumferential fibres of the zona orbicularis have been shown to contribute to joint stability in distraction,[17] but further investigation is required to define its functional anatomy and determine whether this structure has a stabilizing role at extreme ROM.

In conclusion, the present study demonstrates that the iliofemoral and ischiofemoral ligaments are important contributors to native joint stability. In addition to providing rotational restraint, the hip capsule appears to have a crucial role in providing a joint force vector to keep the femoral head in the acetabulum at extreme ROM, reducing the likelihood of subluxation, edge loading, or dislocation. Preservation and appropriate tensioning of these structures following all types of hip surgery may be crucial to minimizing complications related to joint instability.

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Supplementary material

Tables showing capsular ligaments considered at each position, and full set of effective moment arms and forces included in this study.

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