Original Research

Cadaveric Biomechanical Evaluation of Capsular Constraint and Microinstability After Hip Capsulotomy and Repair

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Investigation performed at Western University, London, Ontario, Canada

Background: It remains unclear if capsular management contributes to iatrogenic instability (microinstability) after hip arthroscopy.

Purpose: To evaluate changes in torque, stiffness, and femoral head displacement after capsulotomy and repair in a cadaveric model.

Study Design: Controlled laboratory study.

Methods: A biomechanical analysis was performed using 10 cadaveric hip specimens. Each specimen was tested under the following conditions: (1) intact, (2) portals, (3) interportal capsulotomy (IPC), (4) IPC repair, (5) T-capsulotomy (T-cap), (6) partial T-cap repair, and (7) T-cap repair. Each capsular state was tested in neutral (0°) and then 30°, 60°, and 90° of flexion, with forces applied to achieve the displacement-controlled baseline limit of external rotation (ER), internal rotation (IR), abduction, and adduction. The resultant end-range torques and displacement were recorded.

Results: For ER, capsulotomies significantly reduced torque and stiffness at 0°, 30°, and 60° and reduced stiffness at 90°; capsular repairs failed to restore torque and stiffness at 0°; and IPC repair failed to restore stiffness at 30° ($P < .05$ for all). For IR, capsulotomies significantly reduced torque and stiffness at 0°, 30°, and 60° and reduced stiffness at 90°; and capsular repairs failed to restore torque or stiffness at 0°, 30°, and 60° and failed to restore stiffness at 90° ($P < .05$ for all). For abduction, IPC significantly decreased torque at 60° and 90° and decreased stiffness at all positions; T-cap reduced torque and stiffness at all positions; IPC repair failed to restore stiffness at 0° and 90°; and T-cap repair failed at 0°, 60°, and 90° ($P < .05$ for all). For adduction, IPC significantly reduced torque at 0° and reduced stiffness at 0° and 30°; T-cap reduced torque at 0° and 90° and reduced stiffness at all positions; IPC repair failed to restore stiffness at 0° and 90°; and T-cap repair failed at 0°, 60°, and 90° ($P < .05$ for all). There were no statistically significant femoral head translations observed in any testing configurations.

Conclusion: Complete capsular repair did not always restore intact kinematics, most notably at 0° and 30°. Despite this, there were no significant joint translations to corroborate concerns of microinstability.

Clinical Relevance: Caution should be employed when applying rotational torques in lower levels of flexion (0° and 30°).

Keywords: hip; biomechanical; capsulotomy; capsular repair

As the indications for and utilization of hip arthroscopy continue to grow, so must the understanding of procedural effects on hip joint biomechanics. Iatrogenic instability, or "microinstability,"[10] is of particular concern as a cause for postoperative pain and need for revision surgery.[8,22,23] Despite concerns over iatrogenic laxity from capsular incisions, and supporting biomechanical evidence of the importance of the capsular ligaments in directional joint stability, a consensus is lacking on routine capsular management.

Previous studies have evaluated the impact of progressive capsular injury on joint kinematics, concluding that rotational laxity is increased with injury, and near-native kinematics can be reestablished with repair.[1,17] In these studies, joint laxity was quantified as changes in rotational range of motion (ROM) limits; however, changes in the constraint torque attributed to the altered ligaments were not measured. Others have explored the involvement of the individual capsular ligaments during laxity tests[7,11,15,18] without consensus. Additionally, translations[12,13,20] risk being affected secondary to alteration of the hip capsule, where discrepancies in degree and directionality still exist in the literature.

During daily activities, the hip is rarely brought to its ROM limits, particularly in internal-external (IE) or abduction-adduction (AA) rotation.[4] Many cadaveric biomechanical studies have evaluated kinematics when the

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joint is taken beyond the native physiologic ROM, which may not be relevant for many daily activities. Thus, observing biomechanical behavior throughout the native joint ROM may be a better way to evaluate for potential adverse biomechanics and whether different capsular states may produce concerning joint kinematics.

In this study, we aimed to evaluate joint torques, stiffness, and femoral head translation through stages of capsular injury and repair at discrete flexion angles. It was hypothesized that unrepaired capsulotomy states would significantly decrease the required torque and stiffness to achieve end ROM while increasing femoral head translation, whereas repairs would restore near-native joint behavior.

METHODS

Specimen Preparation

Institutional review board approval was received for the study protocol. The performed tests were carried out on 10 fresh-frozen cadaveric hemipelvis specimens (6 male, 4 female; 2 pairs; age, 48-69 years), which were acquired from a tissue bank for the purpose of medical and academic research. Specimens were screened to rule out the presence of osteoarthritis or hip dysplasia (lateral center-edge angle, $<25^\circ$). Specimens were left to thaw at room temperature for up to 36 hours before testing. All extra-capsular soft tissue was removed from the specimens. The neutral position for both flexion-extension and AA of each specimen was established using literature-reported averages of maximum hip extension (10°) and abduction (45°), after which a central pin was placed to hold this position for potting.[19,21] The pelvic bone was osteotomized to remove much of the ilium (from the anterior inferior iliac spine to the greater sciatic notch) and pubis to allow potting within our acetabular fixture (Figure 1). The fixture holding the acetabulum is oriented 45° relative to vertical on our joint motion simulator, and to adjust for the 7° mechanical axis of the femur, the femur was held at a 38° angle with respect to vertical during potting[5] (Figure 1).

Alignment

The Advanced Mechanical Technologies Inc (AMTI) VIVO is a 6 degrees of freedom (DoF) servohydraulic joint motion simulator. This joint motion simulator can apply prescribed motions (accurate to 0.05 mm/0.1°) and loads (accurate to 4.6 N and 0.2 N·m) to joint specimens and resolves forces

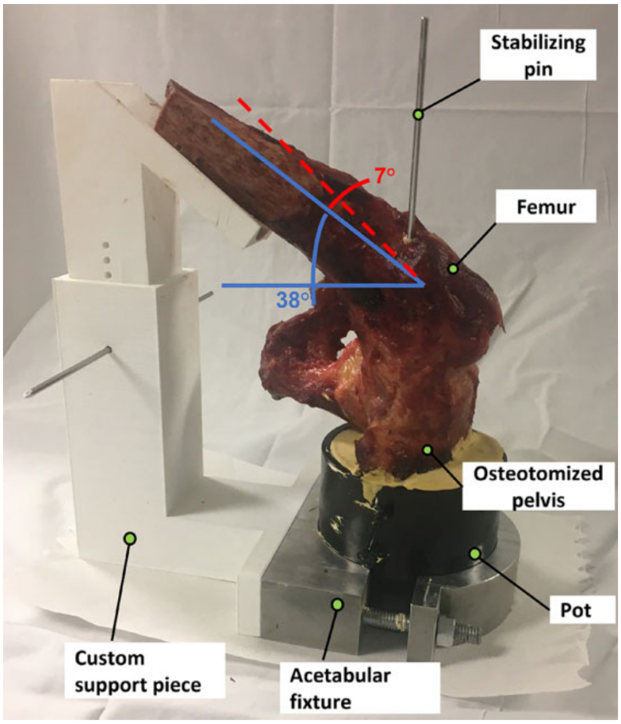

Figure 1. Osteotomized and potted pelvis, pinned rigid in surgeon-established neutral orientation.

and motions using Grood and Suntay[9] joint coordinate conventions. While the as-delivered AA ROM of the system is ±25°, in-house customization of fixtures and the introduction of a high-torque stepper motor enabled us to achieve adductions up to 35° and abductions up to 90°.

The osteotomized acetabulum was secured with screws and dental cement (Golden Denstone Labstone; Modern Materials; Kulzer GmbH) in a 3.5-inch (8.9 cm) inner diameter polyvinyl chloride pipe coupling and held in the aforementioned custom acetabular fixture. Neutral orientation in the transverse plane was achieved by rotating the acetabular pot until the stabilizing pin lies parallel to the coronal plane of the joint motion simulator, making the entire joint neutrally rotated with respect to the machine. The stabilizing pin was removed to allow for circumduction of the joint to identify its center of rotation (COR). During manual circumduction, femoral motion was measured using an optical tracker (Optotrak Certus; Northern Digital Inc) temporarily secured to the lateral-distal aspect of the femur, and the acetabulum was fixed. A sphere-fitting algorithm was used to resolve the COR of the femur, assumed to

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Ethical approval for this study was obtained from Western University (reference No. 114018).

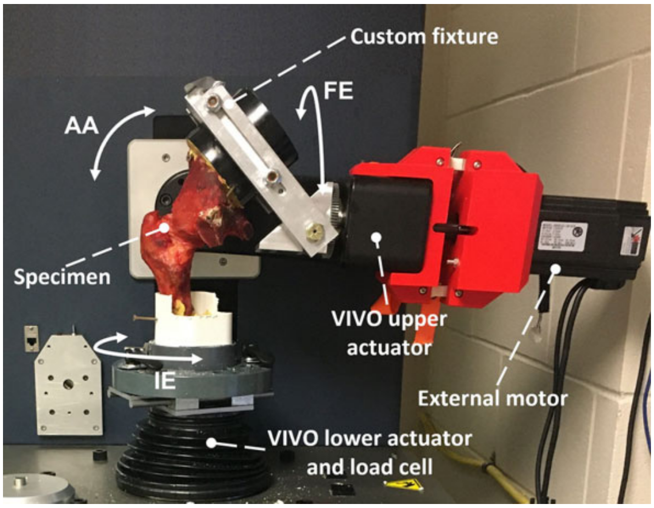

Figure 2. Mounted specimen and direction of actuator motions as they act on the hip joint. AA, abduction-adduction; FE, flexion-extension; IE, internal-external.

be at the center of the femoral head, with respect to the joint motion simulator's mechanical COR. The acetabulum fixture was translationally adjusted until the femur's COR was <2 mm from the VIVO's mechanical COR. A surgeon (R.M.D.) reconfirmed neutral IE rotation and flexion of the femur with respect to that previously established before pinning, as well as neutral abduction, the position of which was further corroborated by reconfirming the 7° angle of the femur, measured via a goniometer. In this position, the distal femur was cemented in place, held in a pot attached to the joint motion simulator's lower actuator (Figure 2).

Manual Determination of Limits

Under concentric joint loading, each specimen's ROM limits were determined in internal rotation (IR), external rotation (ER), abduction, and adduction, at 4 discrete flexion angles of 0°, 30°, 60°, and 90°. Concentric joint reduction was achieved with a combined load of 10 N pushing medially and 10 N pushing superiorly, while ROM limits were defined as the angular position achieved when 5 N·m of torque was applied in a given direction.[1,3,17] When AA ROM limits were tested, IE rotation was constrained at neutral, and vice versa.

Displacement Control Kinematic Tests

To establish a displacement-controlled baseline, the intact joint was rotated through its ROM, starting at 0° and ending at the maximum angular position recorded during the previously conducted force-controlled trials under the same compressive loading. Sixteen intact runs were completed, 1 in each of the 4 directions, at 4 flexion angles. During displacement-controlled trials, angular position was the independent variable driving joint movement in the observed direction (ie, IRs were applied while IE torques were recorded). Each joint was rotated to specimen-specific limits that were established during force loading of the intact state as the points where the observed direction reached 5 N·m of torque. All torque versus rotation values up to this ROM limit were recorded during each trial. While the torque values referred to throughout this text occurred at specimen-specific ROM limits and were decreased with respect to the intact state as a result of subsequent capsulotomies, stiffness was later calculated as the rate of change of torque with respect to rotation (angle) over the last 10% of the collected profiles. After testing of the intact state, progressive capsulotomies and subsequent repairs were performed, while the displacement-controlled trials—using the same specimen-specific ROM limits during the intact state—were repeated after each intervention. The testing states included portals, interportal capsulotomy (IPC), IPC repair, T-capsulotomy (T-cap), partial T-cap repair, and full T-cap repair.

Capsulotomies and repairs were performed in the same order and in an open manner to replicate arthroscopic techniques by a fellowship-trained hip arthroscopy surgeon (R.M.D.). Portals consisted of two 7-mm incisions positioned at approximately 12 and 3 o'clock, based on prior anatomic studies and a previously validated protocol.[1,16] A straight incision was utilized to connect these portals to create the IPC, measuring approximately 35 mm in length. IPC repair was performed with 4 interrupted high-strength sutures (Ultrabraid; Smith & Nephew). The T-cap was created with the addition of a perpendicular 1.5-cm incision at the midpoint of the IPC, to avoid additional iatrogenic injury to the zona orbicularis.[1,16] The vertical cut was repaired with 2 high-strength sutures for the partial T-cap repair, while the full T-cap repair included the additional 4 sutures for the IPC component.

Torques and positions in the 6 DoF were recorded through the entirety of each trial. After complete repairs, the joint was slowly brought to its predetermined ROM limits via manually controlled rotation while monitoring joint torque to ensure that the repairs did not overconstrain the joint.

Data Analysis and Statistics

Data were collected at a sampling rate of 500 Hz. The following data scaling was done using custom MATLAB (MathWorks) scripts. The data were smoothed via a Butterworth filter and downsampled at 1° increments from 0° to end ROM in a given direction. Within each set, at index points where the rotational position was closest to each nominal degree, data across all kinematic elements were extracted. The data were then interpolated to 100 points in length for each specimen. Torque and angle data were normalized to a percentage scale as a solution to interspecimen variability of ROM limits and experienced torque at these limits during the intact state. Similarly, translations were observed as relative displacement with respect to the intact state to negate any bias influenced by potting differences.

The results were reported as the mean ± SD of torque with respect to the intact state for all specimens. In addition, capsule stiffness (N·m/deg) as the joint approached the

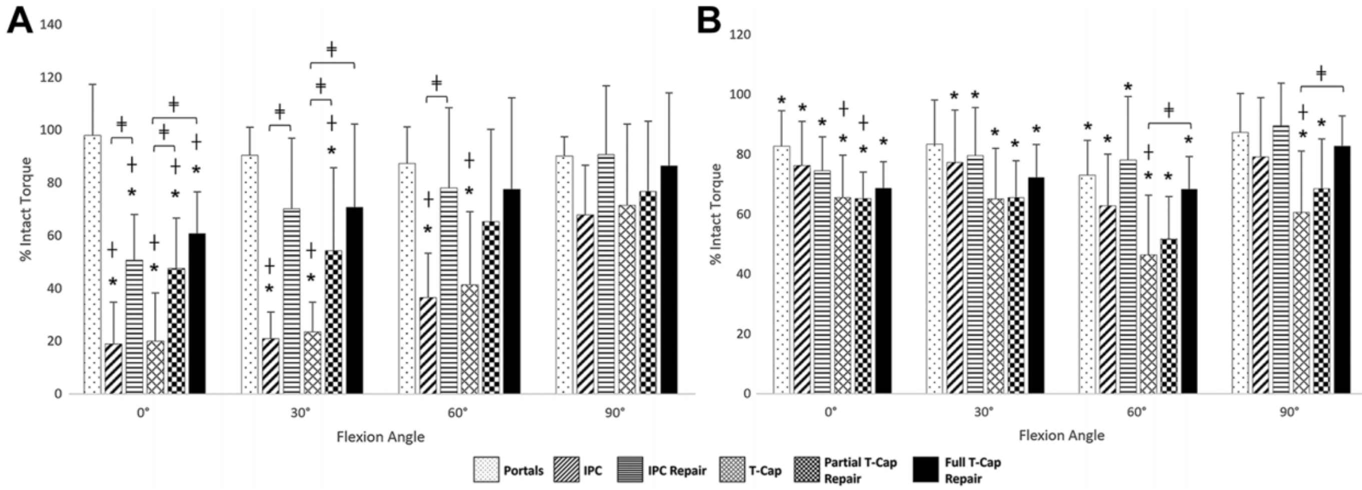

Figure 3. Mean relative torque (± SD) at end range of motion during (A) external rotation and (B) internal rotation during 6 varied capsule states with the hip flexed to 0°, 30°, 60°, and 90°. *Significantly different from intact. ⁺Significantly different from portals. ǂSignificantly different after repairs. IPC, interportal capsulotomy; T-cap, T-capsulotomy.

end of ROM was measured, over the last 10% of the cycle. Statistical comparisons were confined within a given flexion angle. At each, the following were compared: (1) intact versus all subsequent conditions, (2) portals versus all subsequent conditions, (3) IPC versus IPC repair, (4) T-cap versus full T-cap repair, and (5) T-cap versus partial T-cap repair. One-way repeated-measures analysis of variance with subsequent post hoc analysis with Bonferroni corrections for multiple comparisons was used to assess significant differences at the 4 discrete flexion angles, in which a P value <.05 was considered statistically significant for all tests. Accepting 2-tailed paired t tests with Bonferroni correction for the 14 comparisons listed above, we found that a sample size of 10 specimens satisfies a Cohen d of 1.6 (to detect very large effect sizes) with a statistical power of 80%.

RESULTS

Relative Torque

External Rotation. The change in ER torques at all flexion angles is presented in Figure 3A. At 0° of flexion, all capsulotomies and repairs, except portals, were significantly different from the intact state. Between the capsulotomy and repair states, repair significantly increased end ROM torque for both IPC repair with respect to IPC and partial and full T-cap repair after T-cap; however, the repair states remained significantly different compared with the intact state. At 30° of flexion, IPC, T-cap, and partial T-cap repair were significantly different from the intact state, while the repair states (IPC repair, full T-cap repair) restored torques to near-intact values. At 60° of flexion, IPC and T-cap states differed significantly compared with the intact state, while IPC repair and partial or full T-cap repair increased stiffness to near-intact values. Also, at 60°, IPC repair significantly increased torque required to achieve end ROM versus IPC. No statistically significant differences existed between any states at 90° of flexion.

Internal Rotation. Changes in IR torque at all flexion angles are presented in Figure 3B. At 0° of flexion, all capsulotomies (including portals) and subsequent repairs were significantly different from the intact state, with reduced torque required to achieve end ROM. This was also true at 30° of flexion, with the exception of the portal state, which had a comparable torque with the intact state. At 60° of flexion, all capsulotomies and repairs remained significantly different from the intact state. However, at 90° of flexion, only the T-cap and its partial repair differed significantly with respect to the intact state. Additionally, at 60° and 90° of flexion, full T-cap repair resulted in significant increases in end ROM torque compared with the T-cap state.

Abduction. Changes in abduction torques at all flexion angles are presented in Figure 4A. At 0° of flexion, T-cap and partial T-cap repair significantly differed from the intact state, with lower required abduction torque to achieve end ROM. No significant differences were observed after repair compared with the intact state. At 30° of flexion, only T-cap significantly differed from the intact state. At 60° of flexion, IPC, T-cap, and partial T-cap significantly differed from the intact state, while repairs did not. Finally, at 90° of flexion, IPC and T-cap resulted in significantly reduced torques compared with the intact state.

Adduction. Changes in adduction torques at all flexion angles are presented in Figure 4B. At 0° of flexion, IPC and T-cap resulted in significantly lower adduction torques to achieve end ROM. No significant differences were observed after repair compared with the intact state. At both 30° and 60° of flexion, there were no significant differences between any states. At 90° of flexion, T-cap and partial T-cap repair demonstrated significantly lower torques compared with the intact state.

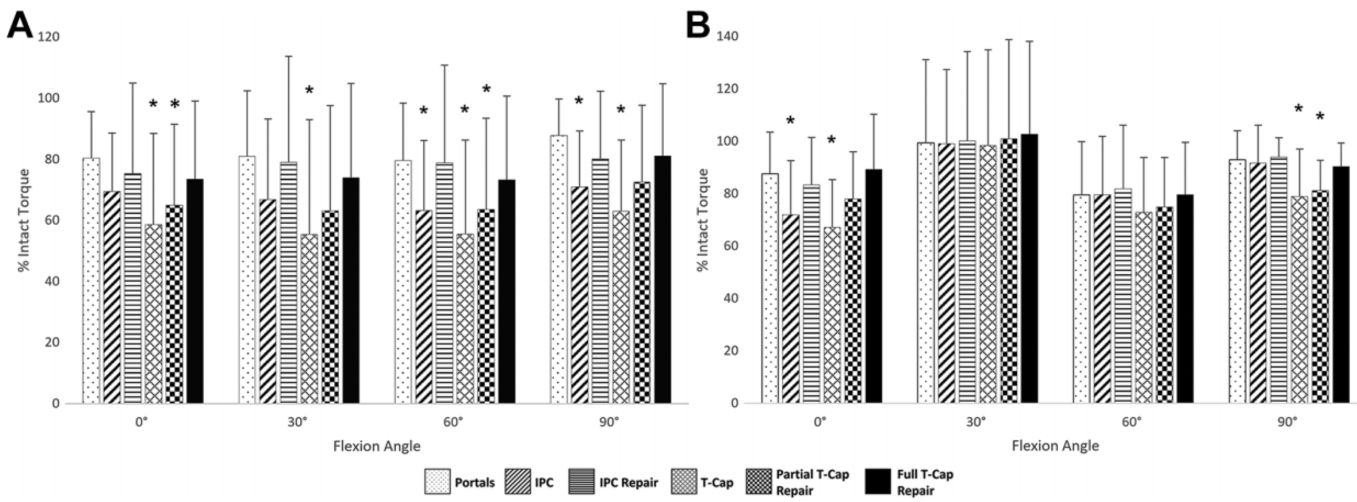

Figure 4. Mean relative torque (± SD) at end range of motion during (A) abduction and (B) adduction during 6 varied capsule states with the hip flexed to 0°, 30°, 60°, and 90°. *Significantly different from intact. IPC, interportal capsulotomy; T-cap, T-capsulotomy.

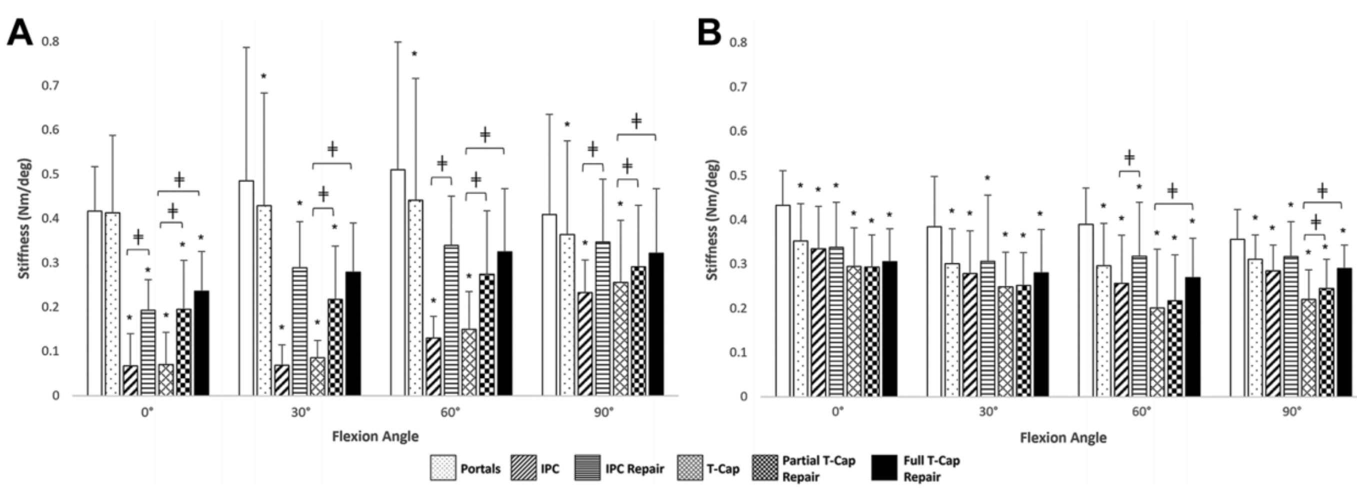

Figure 5. Mean capsule stiffness (± SD) over the final 10% of (A) external rotation and (B) internal rotation range of motion during 7 capsule states including intact (white bars), with the hip flexed to 0°, 30°, 60°, and 90°. *Significantly different from intact. ‡Significantly different after repairs. IPC, interportal capsulotomy; T-cap, T-capsulotomy.

Stiffness

External Rotation. Changes in ER stiffness at all flexion angles are presented in Figure 5A. At 0° of flexion, stiffness was significantly decreased with respect to the intact state after all states, except portals. Between the capsulotomy and repair states, repair significantly increased the stiffness for both IPC repair versus IPC and partial and full T-cap repair versus T-cap. At 30° of flexion, all capsulotomy states resulted in significantly reduced stiffness compared with the intact state. IPC repair and partial T-cap repair continued to demonstrate significantly reduced stiffness, while full T-cap repair restored near-intact stiffness. At 60° and 90° of flexion, similar findings were observed with significant reductions in stiffness after IPC and T-cap. IPC repair and partial and full T-cap repair restored stiffness to near-intact stiffness.

Internal Rotation. Changes in IR stiffness at all flexion angles are presented in Figure 5B. Stiffness was decreased significantly with respect to the intact state across all capsulotomies and repairs at all flexion angles. Between the capsulotomy and repair states, at 60° of flexion, complete repairs of IPC repair and full T-cap repair significantly increased stiffness compared with IPC and T-cap, respectively. At 90° of flexion, partial and full T-cap repair both resulted in a significant increase with respect to T-cap.

Abduction. Changes in abduction stiffness at all flexion angles are presented in Figure 6A. All capsulotomy states and subsequent repairs demonstrated significantly decreased stiffness with respect to the intact state, except

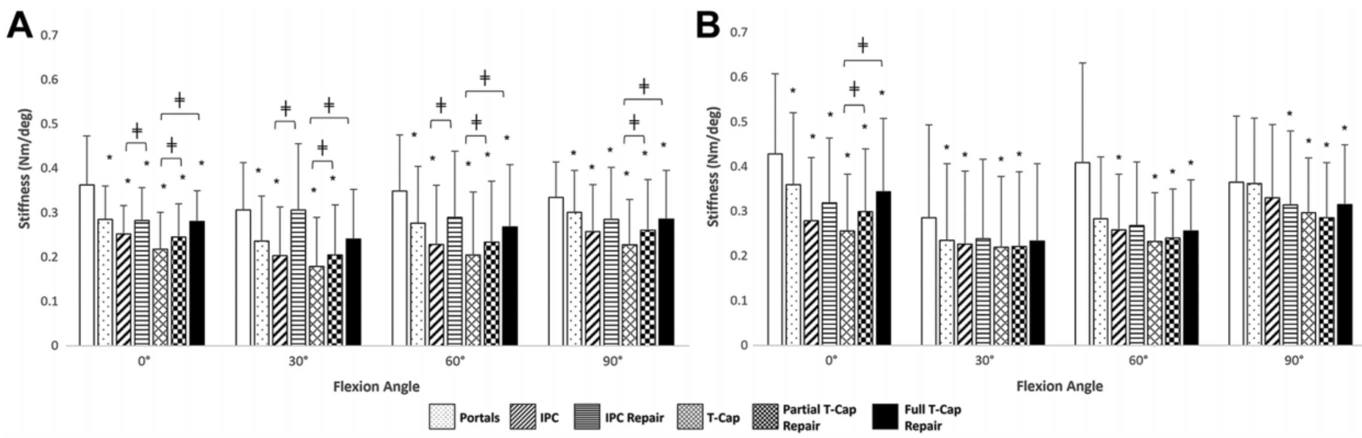

Figure 6. Mean capsule stiffness (± SD) over the final 10% of (A) abduction and (B) adduction range of motion during 7 capsule states including intact (white bars), with the hip flexed to 0°, 30°, 60°, and 90°. *Significantly different from intact. ⁺Significantly different after repairs. IPC, interportal capsulotomy; T-cap, T-capsulotomy.

for IPC repair at 30° and 60° of flexion and full T-cap repair at 30° of flexion. Between the capsulotomy and repair states, IPC repair significantly increased stiffness compared with IPC at 0°, 30°, and 60°. Partial and full T-cap repair both significantly increased stiffness with respect to T-cap at all flexion angles.

Adduction. Changes in adduction stiffness at all flexion angles are presented in Figure 6B. At 0° of flexion, all capsulotomy and repair states were significantly different from the intact state. Regarding the effect of repair, both partial and full T-cap repairs resulted in significantly increased stiffness compared with T-cap but demonstrated continued differences from the intact state. At 30° of flexion, portals, IPC, T-cap, and partial T-cap repair were statistically different from the intact state, while IPC repair and full T-cap repair restored stiffness to near-intact values. At 60° of flexion, IPC, T-cap, partial T-cap repair, and full T-cap repair all had significantly decreased stiffness with respect to the intact state. Only IPC repair restored stiffness to near-intact values. At 90° of flexion, IPC repair, T-cap, and partial and full T-cap repair all resulted in significant reductions in stiffness compared with the intact state.

While repairs resulted in increased stiffness compared with capsulotomies at most flexion angles, no significant increases were observed between the capsulotomy and repair states at any flexion angle other than 0°.

Translations

Changes in medial-lateral and anterior-posterior femoral head translation at all flexion angles are presented in Figure 7. None of the flexion positions demonstrated statistically significant differences in joint translation between the capsulotomy and repair states when compared with the intact state.

DISCUSSION

The present study evaluated joint torques, stiffness, and femoral head translation after capsular injury and repair under displacement-controlled IE torques and AA torques. The most important findings included persistent alterations in the rotational torques and stiffness required to achieve displacement-controlled ROM limits, even after complete capsular repair. The most persistent differences after capsular repair tended to occur in lower positions of flexion (0° and 30°). Finally, there were no significant differences in femoral head translation in any of the testing states or configurations.

The results of the present study appear to differ from 2 published studies, both of which reported that capsular repair restored native joint kinematics.[1,17] However, the observed differences in the present study relate to the different testing parameters. The prior referenced studies utilized force-controlled loading protocols, evaluating the implications of capsulotomy and repair on ROM parameters after application of a predetermined torque applied to all states.[1,17] The present study utilized a displacement control loading protocol, evaluating the change in required torque and stiffness to achieve predetermined ROM limits based on native joint kinematics. Differently quantified, our results show that capsulotomies significantly reduce the torque and stiffness required to achieve ROM limits and that persistent differences were observed in both parameters even after capsular repair, especially under rotational loading. However, this is not necessarily a negative result, as this reduction in torque and stiffness was only to achieve the baseline ROM limits and does not necessarily convey adverse kinematics, exemplified by the absence of significant femoral head translations within the protocol. Therefore, one could use the results of this study to support the notion that rehabilitation exercises working within the native joint ROM appear relatively safe, with no adverse kinematics. However, less is known about joint kinematics when surpassing baseline ROM limits, such as after femoral osteochondroplasty, as this was not included in the present study and may be an area of future focus.

Microinstability is a growing area of concern, as it may contribute to procedural failure and ongoing symptoms after hip arthroscopy. With knowledge that provocative

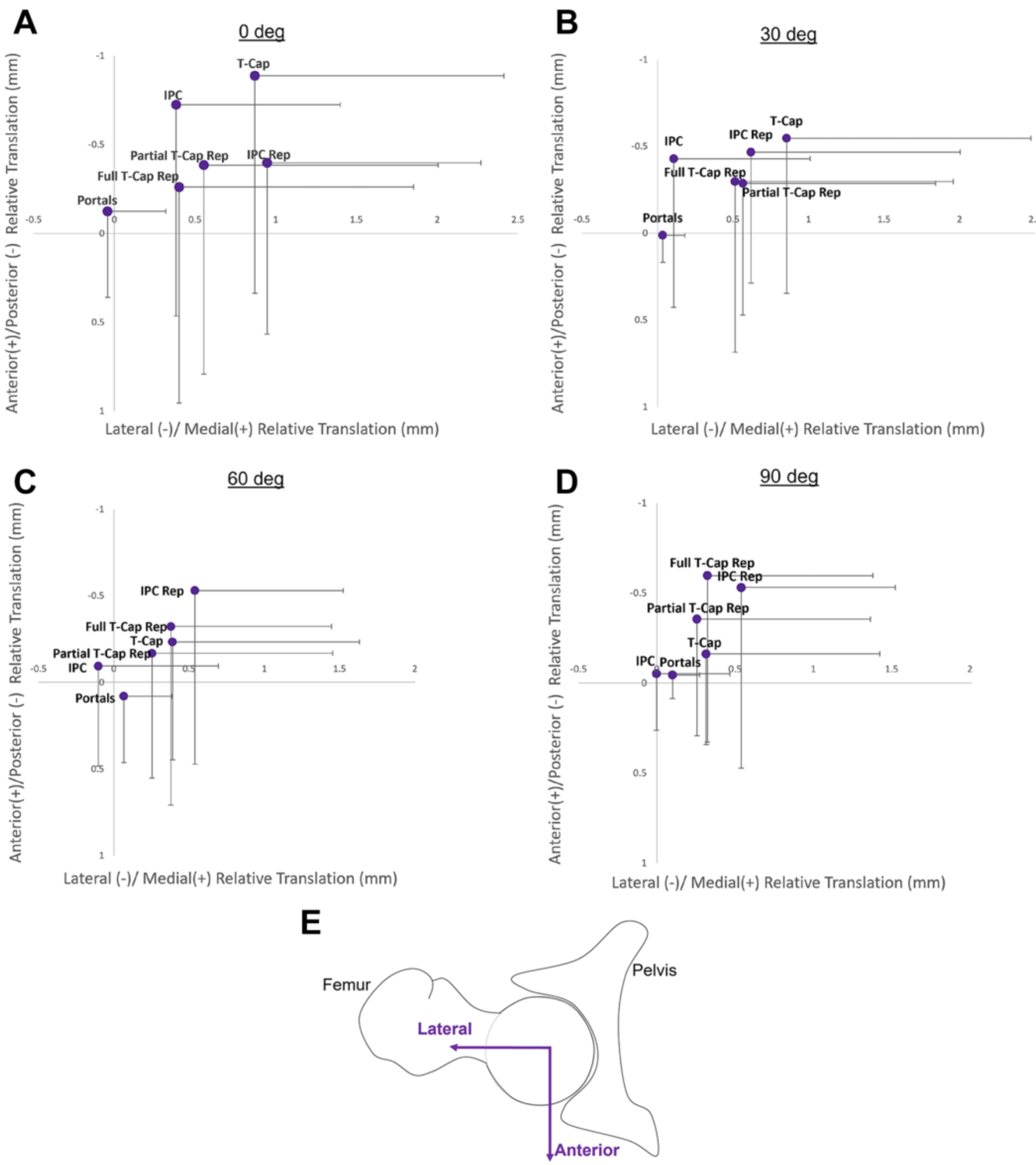

Figure 7. Translations of the femoral head with respect to intact during 6 varied capsule states. Mean total medial-lateral (± SD) and anterior-posterior (± SD) translation as the femur was rotated from neutral to maximum external rotation with the hip flexed to (A) 0°, (B) 30°, (C) 60°, and (D) 90°. (E) Transverse cross section of the femoral head and pelvis indicates direction of measured translations. IPC, interportal capsulotomy; Rep, repair; T-cap, T-capsulotomy.

tests for this condition focus primarily on ER, such as with the hyperextension-ER test, our lens to interpret the results of this study may change and raise some concern. Under ER loading, capsular repair did not restore torque and stiffness in relative extension (0° of flexion). This may be clinically relevant, as positions of relative extension place more strain on anterior capsular ligaments.[2] These positions of neutral or extension are much more dependent on soft tissues to constrain the joint, versus increasing flexion where there is greater joint congruity and osseous constraint. As such, there may be increased concern that rotational ROM in neutral or extension may place more strain on the repaired capsule and contribute to iatrogenic laxity, potentially resulting in microinstability. This is especially true when considering that increased laxity may allow ROM that exceeds the limits studied here and could result in further adverse kinematics and translations. It may therefore be safer to perform early rehabilitation exercises in positions of flexion, where ligamentous strain and constraint is perhaps less critical and coincidentally capsular repairs seem to better restore more normal joint kinematics. However, clinical studies are required to determine the significance, if any, of slight alterations in joint torques and the potential correlation with instability symptoms. These findings are further supported by a recent study by Ng et al,[14] in which they evaluated the implications of capsulotomy and repair, along with femoral osteochondroplasty, on femoral head translation and microinstability. They observed increases in microinstability at 30° and femoral head translation at 90° after capsulotomy and femoral osteochondroplasty, respectively. The authors cautioned that altered kinematics may result after complete cam osteochondroplasty, as it may disrupt the labral seal.

Interestingly, our results do not demonstrate a consistent difference between IPC repair and T-cap repair regarding resulting torque and stiffness, with the exception of ER stiffness at 30°. This should allow surgeons to freely choose either IPC or T-cap for desired access to treat a given pathology, as long as the decision is made to fully repair the incisions made. Both resulted in comparable postprocedural joint behavior; however, results should be interpreted with caution as these findings are only known within preoperative ROM limits, and any differences that may occur outside of that range are not accounted for in this study. It is also noteworthy that there were no conditions in which joint torques or stiffness surpassed native values, suggesting that capsular repair does not overconstrain the joint under the described loading conditions.

Finally, there were no observed differences in femoral head translation under any condition. This is consistent with the results noted by Philippon et al,[17] but contrasts those reported by Baha et al.[1] Philippon et al[17] theorized that the lack of significant translation was due to the maintained presence of a suction seal with the native labrum. The potential explanation for differences with the results reported by Baha et al may relate to differences in loading conditions, as the observed translations may have occurred once the native ROM was surpassed in that study. In our study, displacement control was utilized to keep the joint within a physiologic ROM limit. As such, the suction seal could be maintained, which could explain why there were only effects on femoral head translation.

This study's focus on relative joint biomechanics provides a unique look at changes in translation and torque within established specimen-specific ROM after capsulotomy and repair. Before this, predetermined torque was largely used as the measure of specimen limits,[1,6,17] with the understanding that the hip is rarely brought to, or beyond, its ROM limits during daily activity. Observing relative changes in biomechanics within the working range has the potential benefit of eliminating uncertainty or inconsistencies in applied forces, while offering insight that can be more directly translated to clinical practice.

Limitations

Although novel, this study has several limitations. Elderly cadaveric specimens were utilized, which could limit the generalizability of the results, although specimens were screened and found to be free of degenerative joint disease. The results are also reflective of time-zero joint kinematics, and the results should be interpreted and applied with caution as alterations in kinematics may not correlate with clinical outcomes. Additionally, capsulotomy incisions and repairs were performed in an open manner; therefore, it is possible that arthroscopic repairs may not be as robust and could result in worse kinematic results after repair. Finally, these observed kinematics were present without dynamic muscle actuation. However, this study has established the AMTI VIVO as an appropriate platform for cadaveric hip biomechanics research, having achieved ROM limits that were in agreement with previous studies. This will allow for increasingly complex loading of the hip, enabling application of concentric loads, or more complex combined motions, including simulated activities of daily living.

CONCLUSION

In this cadaveric model, arthroscopic capsulotomy techniques produced alterations in joint torque and stiffness. Complete capsular repair did not always restore intact kinematics, most notably at 0° and 30°. Despite this, there were no significant joint translations to corroborate concerns of microinstability.

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