BJJ: Hip Capsule Biomechanics after Arthroplasty - The Effect of Implant, Approach and Surgical Repair

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Figure 3.jpg
Figure 4.jpg
Abstract

Aims

The hip’s capsular ligaments passively restrain extreme range of motion (ROM) by wrapping around the native femoral head/neck. We determined the effect of resurfacing (HRA), dual mobility total hip arthroplasty (DM-THA), conventional THA and surgical approach on ligament function.

Methods

Eight paired cadaveric hip joints were skeletonised, retaining the hip capsule. Capsular ROM restraint during controlled internal (IR) and external rotation (ER) was measured before and after HRA, DM-THA and conventional THA, with a posterior (right hips) and anterior capsulotomy (left hips).

Results

Hip resurfacing provided a near native ROM with between 5-17° increase in internal/external rotation (hypermobility) compared to the native hip for the different positions tested, which was a 9-33% increase. DM-THA generated a 9-61° (18-121%) increase in ROM. Conventional THA generated a 52-100° (94-199%) increase in ROM. Thus, for conventional THA, the capsule function that puts a leash on ROM is lost. It is restored to some extent by DM-THA, and almost fully restored by hip resurfacing.

In positions of low flexion/extension, the posterior capsulotomy provided more normal function than the anterior, possibly because the capsule was shortened during posterior repair. However, in deep flexion positions, the anterior capsulotomy functioned better.

Conclusion

Native head-size and capsular repair preserves capsular function after arthroplasty. The anterior and posterior approach differentially affect postoperative biomechanical function of the capsular ligaments.

Clinical Relevance

- Hip capsular function is affected by surgical approach, capsular management and choice of implant
Hip resurfacing arthroplasty restores native head diameter and keeps the femoral neck thus enabling the hip ligaments to function more normally.

Keywords: Hip Arthroplasty, Dual-Mobility, Resurfacing, Capsule, Approach, Stability
Background

The native hip is stabilised by the bony congruence between the femoral head and acetabulum, the surrounding hip capsule and muscle activity. The hip capsule provides a passive restraint to extreme range of movement (ROM) by wrapping around the native femoral head (1). The posteriorly located ischiofemoral ligament is the primary restrictor of excess internal rotation in flexion. The anteriorly located iliofemoral ligament is the primary restrictor of both internal and external rotation in extension, and external rotation in flexion (1, 2). In addition to preventing extreme ROM, the hip capsule may prevent instability, bony impingement, edge-loading and associated wear (1, 3-6).

Hip resurfacing arthroplasty (HRA) and dual-mobility (DM) implants have been developed as alternatives to conventional THA. Modern HRA was developed by McMinn (7) and Wagner (8) in the 1990s. The native femoral head is conserved and is resurfaced by an implant which restores the head diameter. When combined with capsular repair, the native sized femoral head implant thus reduces the surrounding volume of dead-space within the capsule after arthroplasty. DM-THA was developed 40 years ago in France by Bousquet and refers to a small femoral head articulating within a polyethylene liner that articulates inside a larger acetabular shell (9, 10). The liner moves in the shell, and thus acts as a near-native sized femoral head to improve the range of movement before impingement and reduce dislocation risk.

A variety of surgical approaches have been developed to access the hip joint for total hip arthroplasty (THA) and can broadly be categorised into those that transect the anterior capsule or posterior capsule. Approaches through the anterior capsule include the direct anterior approach and anterolateral approach. Anterior approaches predominantly incise the iliofemoral ligament and may extend medially towards the pubofemoral ligament; the posterior approach incises the ischiofemoral ligament (11, 12). Choice of surgical approach and thus the capsulotomy is largely based on a surgeon’s preference. Furthermore, some excise the capsule to improve exposure, considering it of little consequence, while others preserve and repair it after inserting the implants which is technically challenging and increases the duration of the operation.
In this study, we compared capsular biomechanics in the native hip to that after conventional THA, dual-mobility THA and hip resurfacing arthroplasty in a cadaveric model, after anterior or posterior capsulotomy. We hypothesised that hip ligament function is restored with a native head-size implant (HRA or DM-THA) and repair of the hip capsule, independent of surgical approach.
Methods

Specimen preparation and set-up

This study was granted local research ethics committee approval and performed in a dedicated cadaveric biomechanics laboratory. Eight fresh-frozen cadaveric pelvises with full-length femora (from five males and three females, mean age 57, range 31-67, and no history of hip surgery) were computed tomography (CT) scanned to quantify their bony morphology (Table 1).

Each pelvis was then defrosted and skeletonised, removing all soft-tissue structures except the hip capsule. The sixteen hip joints (hemi-pelvis and hip joint) were then prepared for testing using an established procedure that has been previously described in detail (13-15). In short, references holes were drilled into the pelvis and femora prior to bisecting the pelvis and transecting the femora 10cm distal to the lesser trochanter. Specimens were then potted in metal fixtures using these reference holes and polymethyl methacrylate bone cement. These pots allowed each hip to be repeatedly positioned in a custom testing apparatus that could apply controlled flexion/extension, ab/adduction and internal/external rotation movements to the hip (1), according to the definition recommended by the International Society for Biomechanics (16).

Testing

Capsular ligament function was first quantified for the native hip by applying 5 Nm torque to the hip and measuring the range of motion (ROM) allowed before the capsular ligaments became taut to restrain any further hip movement. Hip arthroplasty was then performed, and the ROM tests were repeated to quantify each procedure’s effects on ligament function.

Loading Conditions

Six positions of hip flexion and ab/adduction were defined for each specimen, grouped into low flexion/extension positions and deep flexion positions (Table 2). When combined with internal or external rotation, these positions span a full range of hip motion and include typical positions of instability after direct anterior approach and posterior approach hip arthroplasty.
The hip was sequentially fixed in each of these hip positions, and the testing apparatus applied internal rotation to 5Nm of torque over 20 seconds, returned to neutral, and then applied external rotation to 5Nm of torque over 20 seconds, while recording the angle of rotation when it reached 5Nm of passive restraint (Figure 1A). Two cycles were performed in each testing condition, with the first cycle used to precondition the specimen, and the ROM (in degrees) recorded from the second cycle. Throughout testing, 110 N load, angled 20° medial to the mechanical axis of the femur, was applied to the hip to ensure contact between the femur and acetabulum, with the angle replicating typical loading direction during activities of daily living (17). Subluxations were free to occur in response to the applied movement and load. Where the hip dislocated prior to registering 5Nm of passive restraint, no rotation value was recorded.

Surgical Procedures

The specimens were dismounted before an L-shaped capsulotomy mimicking the posterior approach to the hip (18) was performed on the eight right-sided hips (Figure 1B) whilst an inverted T-shaped capsulotomy mimicking the anterolateral (19) and direct anterior approach (20) was performed on the corresponding eight left-sided hips (Figure 1C). Hip resurfacing arthroplasty components (Birmingham Hip Resurfacing System, Smith & Nephew, Hull, UK) sized to the patient’s native anatomy were implanted using the manufacturer’s recommended technique by two expert hip surgeons (XXX and XXX). Femoral offset, neck length and hip joint centre was re-measured before the specimens were remounted, and the range of internal/external rotation in the six positions was then re-tested.

For right-sided hips, a mid-substance repair of the posterior capsule was performed (21) with 5mm bites of tissue using non-absorbable braided suture (Number 5 Ethibond Excel, Ethicon, Somerville, USA), restoring the anatomical location and native length of the capsule, before the specimen’s internal/external rotation ROM was re-tested. For left-sided hips, a mid-substance repair of the anterior capsule was performed (both horizontal and vertical limbs, with 5mm bites of tissue, Figure 1E), before the range of internal/external rotation in the six positions was re-tested.

With the same protocol, Dual Mobility THA (Trinity Dual Mobility System, Corin, Cirencester, UK) and conventional THA (CSF Plus System, JRI, Sheffield, UK) was performed after the specimen was
The testing order was randomised between conventional THA and DM-THA. For THA, surgeons removed the knotted, uncut sutures from the capsular repair, performed a conventional neck osteotomy and then cemented a bespoke femoral component into the femoral shaft, with the anteversion and head-neck angle matched to native anatomy measured from CT imaging. The femoral component was a laboratory device with a threaded neck-shaft which allowed neck lengthening after insertion (13). The femoral head (DM-THA: 22mm diameter for with acetabular cups of 46-48mm, and 28mm with cups of 50mm and over; Conventional THA: 32mm diameter for all specimens) was mounted onto the threaded neck with a 12/14 taper connecting component mimicking the head-neck geometry of contemporary THA.

The native anatomical acetabular inclination and anteversion (as defined by Murray (22) and measured in relation to the 3D anterior pelvic plane (23)), and the femoral neck anteversion (as defined by Jarrett and colleagues (24)) were measured from CT scans of the cadavers in a custom 3D surgical planner which used for pre-operative templating. For THA and HRA, femoral component anteversion, and acetabular component size and orientation were matched to these CT measurements of the patient’s native anatomy. For THA, femoral component anteversion was set in relation to the medial calcar at the level of the osteotomy. Acetabular component orientation was guided by the transverse acetabular ligament (25) and confirmed using a goniometer. Following component insertion, native neck length, offset and hip joint centre were restored by extending or shortening the femoral neck to minimise the difference between native and post-arthroplasty conditions. The remaining error was then used to quantify the accuracy of hip centre restoration. Each specimen was re-tested using the same protocol, before and after capsular repair. The implants were then replaced with either DM-THA or conventional THA (Figure 1E), depending on the randomisation order, and re-tested.

The testing protocol is summarised in Figure 2. All experiments on a given specimen were performed on the same day at room temperature, and specimens kept moist throughout testing with regular water spray.

**Statistical analysis**
ROM data were analysed in SPSS (v25, IBM, NY, USA) and Prism (v8, GraphPad Software, La Jolla, California USA). Data were confirmed normal with a Kolmogorov-Smirnov test. Following conventional THA with a posterior approach, the hip capsule alone was not sufficient to prevent our cadaveric model from dislocating in deep hip flexion positions resulting in some missing data points. Thus, to allow for repeated measures analyses of variance (RMANOVA), two different analyses were performed:

1) An extension/low flexion analysis for all implants, with independent variables of hip position (Extension-Adduction, Extension-Abduction, Neutral, Heel-strike), implant (HRA, DM-THA, conventional THA) and capsulotomy (repaired anterior, repaired posterior)

2) A deep flexion analysis excluding conventional THA, with independent variables of hip position (Sitting, Squatting), implant (HRA, DM-THA) and capsulotomy (repaired anterior, repaired posterior).

Post-hoc paired t-tests were applied when differences across tests were found (CI=95%). Adjusted p-values, multiplied by the appropriate Bonferroni correction factor in SPSS, were reported with significance determined at <0.05. All values in text are reported as mean differences ± 95% CI.
Results

The hip joint centre was restored with an absolute mean error (±S.D.) of 2 ± 2mm from native to HRA, 3 ± 3mm from native to DM-THA, 3 ± 3mm from native to conventional THA. Acetabular cup orientation was restored for all implants with a difference from the native orientation of 2 ± 2° in inclination and anteversion, indicating that our technique for arthroplasty and then specimen positioning was within clinically acceptable limits.

Figure 3 illustrates the internal/external rotations measured for the different hip positions, implant types and capsular repair state for the anterior approach. Figure 4 shows the same data for the posterior approach. For the two separate analyses of i) extension to low flexion positions and ii) deep hip flexion positions, there was no three-way interaction between position, implant and approach (p=0.079 and p=0.768, respectively), indicating that a further breakdown of the effects of hip position was not required. Therefore, the effects and of implant and approach were analysed across the different hip positions for each of the analyses.

Extension and low-flexion positions (with capsule repaired)

There was a two-way interaction (p=0.006) between implant and approach, i.e. the effect of implant choice on the range of hip rotation depended on the approach (anterior or posterior capsulotomy) and vice-versa, when averaging the range of hip rotation data across all hip positions.

For the anterior approach, hypermobility increased compared to the native hip for all three implant designs (all p<0.001). This hip rotation hypermobility was smallest for the HRA (mean increase 17°), then the DM-THA (mean increase 61°), then the conventional THA (mean increase 100°) (Figure 5).

Comparing implants, differences were detected for all possible pairwise comparisons with the hypermobility for HRA < DM-THA < THA (all p<0.001).

For the posterior approach, hypermobility increased compared to the native hip for all implant designs. Following HRA it increased the least (mean increase 8°, p=0.014), then DM-THA (mean increase 31°, p=0.001), then conventional THA (mean increase 52°, p<0.001). Comparing the implants to each other, it was found the HRA resulted in the least hypermobility compared to the DM-THA and conventional
THA (mean reduction 23°, \( p=0.001 \), and mean reduction 44°, \( p=0.008 \) respectively). However, no difference was detected between the DM-THA and conventional THA (\( p=0.496 \)).

Comparing the two approaches, there was no difference in capsular biomechanics between the approaches with repair following HRA (\( p=0.492 \)). However, there was increased hypermobility for the anterior approach compared to the posterior approach for both the dual mobility and conventional THAs (mean increase 24°, \( p<0.001 \) and 42°, \( p=0.021 \), respectively) (Figure 5).

**Deep flexion positions (with capsule repaired)**

In the deep flexion positions, conventional THA resulted in recurrent dislocations so no data were collected. For HRA and DM-THA, the effects of implant again depended on the approach and vice-versa (two-way interaction \( p<0.001 \) when averaging across the two deep flexion hip positions). For the anterior approach, hypermobility increased following both HRA and DM-THA (mean increase 9°, \( p=0.004 \) and 12°, \( p<0.001 \), respectively). However, no difference in hypermobility was detected between the two implants (\( p=0.855 \)) (Figure 6).

For the posterior approach, hypermobility increased by 5° following HRA compared to the native hip (\( p<0.022 \)). After DM-THA, hypermobility increased by 34° compared to the native hip (\( p<0.001 \), 29° more than the HRA (\( p<0.001 \)) (Figure 6). In contrast to extended positions, this difference came from an increase in external rotation ROM rather than internal rotation for the dual mobility implant (Figure 3).

Comparing the two approaches, for the HRA, the anterior approach resulted in greater hip rotation hypermobility (mean increase 5°, \( p=0.031 \)). However, for the DM-THA, the opposite was true, the posterior approach resulted in greater ROM hypermobility (mean difference 21°, \( p=0.001 \)) (Figure 6).
Discussion

This was a small study using cadavers and, therefore, conclusions should be applied clinically with caution. However, we showed with confidence that implant type, procedure, and capsular management affect the capsular ligaments’ biomechanical function.

The most important findings of this study are that:

1) native-sized femoral head implants, i.e. hip resurfacing arthroplasty, combined with capsular repair re-enabled the ligaments to wrap and tension around the head’s surface and restored the capsule’s leash on range of motion to much the same as the native hip. Near-native sized femoral head implants, i.e. dual-mobility THA, restored this function to some extent, but only when the hip was in a position that allowed the ligaments to wrap around the large diameter polyethylene bearing insert, and thus depended on movement of the liner. In contrast, the capsule’s leash on range of motion was lost after conventional THA due to the decreased head-diameter preventing capsular engagement, irrespective of repair.

2) In extended positions, posterior capsulotomy caused less hypermobility compared to anterior capsulotomy. This was due to less internal rotation hypermobility, and may be because during a posterior repair, the ligaments are inadvertently shortened, thus enabling them to function better against the reduced diameter femoral head. However, in flexed positions, the anterior capsulotomy provided less hypermobility than the posterior capsulotomy, possibly for the same reason. In positions of higher flexion, even a repaired posterior capsule was not sufficient to restrain conventional THA from dislocating.

Our study is the first to measure the biomechanics of the hip capsular ligaments after different types of hip arthroplasty. However, the findings can be compared to prior work that considered hip dislocation. Our data with a 32mm femoral head diameter confirms previous findings that smaller than native femoral head implant sizes leaves the capsule slack (13), resulting in the loss of one of the native hip’s stability mechanisms (1, 3-6). This may increase the risk of dislocation, particularly when implant components are sub-optimally positioned (26), when muscle function is lost (27) and considering that other passive hip stabilisers such as the acetabular labrum and ligamentum teres are necessarily excised during arthroplasty (1, 3, 5, 21). Increasing femoral head size in conventional THA theoretically increases jump-distance to reduce dislocation (28), but this may not be enough to take up the slack.
Increasing neck length (and thus offset) may partly restore capsular function by pre-tensioning the ligaments (13) and theoretically increase the moment arm of the abductor mechanism (29), but can cause pain and dysfunction (30). Dual-mobility THA reduces the dislocation risk (9, 31, 32) and our results may partly explain a mechanism for this by its improved engagement with the hip ligaments. HRA is associated with a very low dislocation risk and our model shows for the first time that the preservation of native head-size not only improves stability by increasing jump-distance, but also by allowing for capsular biomechanics to be restored. Hip resurfacing function outperforms THA in the younger patient (33, 34), and is comparable to THA in the older patient (35, 36). The almost normal biomechanical function of the ligaments with hip resurfacing may partly explain improved function of this device compared to THA. However, metal on metal resurfacing is at risk of edge-loading (37) and impingement at extremes of ROM (38) which can lead to ‘run-away’ wear of metal bearing surfaces. Re-enabling wrapping of the capsular ligaments provides a passive restraint and may reduce the risk of impingement and edge-loading and the terminal consequences.

This study has several important limitations, mostly attributable to its testing of cadaveric tissue. Our data may be most applicable to clinical outcomes in the acute post-operative period when dislocations are most common (39), but before the onset of physiological scarring or healing. We posit that capsular function at time-zero may create the appropriate biomechanics for longer-term outcome. Muscles provide significant soft tissue restraint, particularly the obturator internus that follows the line of action of the posterior capsule and may also contribute a wrapping function (40). This study does not account for dynamic stability provided by pericapsular muscles or lower limb muscle activity which generates ground reaction force. All muscles were removed from the cadavers prior to testing, to isolate the passive function of the capsule and its relationship with arthroplasty and surgical repair and minimise bias. Our repeated measures study design required that hip resurfacing arthroplasty was performed first before neck osteotomy and total hip arthroplasty. Although we randomised the order of dual-mobility and total hip arthroplasty, it is possible that tissue fatigue with repeated testing in comparisons between HRA and THA may have occurred.

Conclusions

Preserving capsular ligament function may protect against hypermobility and associated adverse loading following arthroplasty. This study demonstrated that with repair, choosing implants with native
head-size such as hip resurfacing or dual-mobility may have a greater overall effect than surgical
approach on ligament function in the early postoperative period. These findings have important
implications for current trends in surgical approaches and larger head diameter implants, and offers a
biomechanical basis for how wrapping of the capsular ligaments may prevent subluxation, micro-
instability, edge-loading or dislocation.

Funding Sources

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<td>Specimens</td>
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<td>Sides (L:R)</td>
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<td>Age (years)</td>
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<tr>
<td>Body Mass Index (kg/m(^2))</td>
<td>24 ± 3</td>
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<tr>
<td>Femoral head diameter (mm)</td>
<td>50 ± 6</td>
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<tr>
<td>Femoral anteversion (°)</td>
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<tr>
<td>Femoral neck-shaft angle (°)</td>
<td>132 ± 7</td>
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<td>Femoral offset (mm)</td>
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<td>Femoral head/neck ratio</td>
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<td>Femoral alpha angle (°)</td>
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<td>Acetabular centre edge angle (°)</td>
<td>38 ± 12</td>
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Table 1: Descriptive demographic and anatomic parameters of the specimens (mean ± standard deviation)
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<td>Extended to Low-Flexion positions</td>
<td>Ext-Abd</td>
<td>Full extension, full abduction</td>
<td>An extreme of hip motion, a position at high risk of posterior impingement, subluxation and anterior dislocation when the hip was externally rotated.</td>
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<tr>
<td></td>
<td>Ext-Add</td>
<td>Full extension, full adduction</td>
<td>An extreme of hip motion, a position at high risk of posterior impingement, subluxation and anterior dislocation when hip was externally rotated.</td>
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<tr>
<td></td>
<td>Standing</td>
<td>Neutral flexion/extension, neutral ab/adduction</td>
<td>A position at risk of anterior dislocation with excessive external rotation. Commonly studied in in-vitro tests.</td>
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<tr>
<td></td>
<td>Heel strike</td>
<td>30° flexion, neutral ab/adduction</td>
<td>A control position where instability was not expected.</td>
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<tr>
<td>Deep Flexion positions</td>
<td>Sitting</td>
<td>90° flexion, neutral ab/adduction</td>
<td>A position at risk of posterior dislocation with excessive internal rotation. Commonly studied in in-vitro tests.</td>
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<tr>
<td></td>
<td>Flx-Add (Squattin g)</td>
<td>Full flexion, full adduction</td>
<td>The other extreme of hip motion, a position at high risk of anterior impingement, subluxation and posterior dislocation</td>
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Table 2: Summary of the six functional hip positions tested grouped into Extended-Low flexion positions and Deep Flexion positions
Figure 1: Test set-up including A) testing rig schematic adapted from [1], B) photograph of dissected hip joint with posterior capsulotomy and HRA, C) repaired posterior capsulotomy, D) anterior capsulotomy, E) anterior capsulotomy with conventional THA, F) repaired anterior capsulotomy

IR/ER: Axes of Internal and External Rotation
Abd/Add: Axes of Abduction and Adduction
Fix/Ext: Axes of Flexion and Extension
LT: Lesser trochanter
GT: Greater trochanter
ASIS: Anterior Superior Iliac Spine
PT: Pubic tubercle
Arrow denotes capsular repair

218x151mm (150 x 150 DPI)
Figure 1A

73x74mm (150 x 150 DPI)
Figure 1B

71x74mm (150 x 150 DPI)
Figure 1C
70x74mm (150 x 150 DPI)
Figure 1D

71x75mm (150 x 150 DPI)
Figure 1E

74x75mm (150 x 150 DPI)
Prepare and mount 16 cadaveric hips

Test Internal and External ROM in 6 positions

Left: Posterior capsulotomy
Right: Anterior capsulotomy

Perform Hip Resurfacing Arthroplasty

Test Internal and External ROM in 6 positions before and after **Capsular Repair**

Perform Total Hip Arthroplasty

Test Internal and External ROM in 6 positions before and after **Capsular Repair**

Randomised order:
- Conventional THA
- Dual Mobility THA

Figure 2: Workflow of testing the cadaveric hips, before and after arthroplasty and capsular repair

ROM: Range of movement
THA: Total Hip Arthroplasty

175x132mm (150 x 150 DPI)
Figure 5: Graph showing sum of internal and external rotation ROM in the Extension to Low Flexion positions for the different implants and surgical capsulotomy (Error bars show 95% Confidence Interval)

HRA: Hip Resurfacing Arthroplasty
DM-THA: Dual-mobility Total Hip Arthroplasty
c-THA: conventional Total Hip Arthroplasty
ROM: Range of Motion

227x126mm (150 x 150 DPI)
Figure 6: Graph showing sum of internal and external rotation ROM in the Deep Flexion positions for the different implants and surgical capsulotomy (Error bars show 95% Confidence Interval)

HRA: Hip Resurfacing Arthroplasty
DM-THA: Dual-mobility Total Hip Arthroplasty
ROM: Range of Motion

232x131mm (150 x 150 DPI)
Figure Legends

Figure 1: Test set-up including A) testing rig schematic adapted from [1], B) photograph of dissected hip joint with posterior capsulotomy and HRA, C) repaired posterior capsulotomy, D) anterior capsulotomy, E) anterior capsulotomy with conventional THA, F) repaired anterior capsulotomy

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Figure 2: Workflow of testing the cadaveric hips, before and after arthroplasty and capsular repair

ROM: Range of movement
THA: Total Hip Arthroplasty

Figure 3: Graph showing effect of implant on the ability of the capsule to restrain hip rotation, after anterior capsulotomy. Internal rotation is positive, and external rotation is negative. The shaded green area represents the passive envelope of motion of the native hip. Dotted lines are values after capsulotomy, and solid lines are values after capsular repair.

HRA: Hip Resurfacing Arthroplasty
DM-THA: Dual-mobility Total Hip Arthroplasty
c-THA: conventional Total Hip Arthroplasty
ROM: Range of Motion
Ext-Add: Maximal Extension and Adduction
Ext-Abd: Maximal Extension and Abduction

Figure 4: Graph showing effect of implant on the ability of the capsule to restrain hip rotation, after posterior capsulotomy. Internal rotation is positive, and external rotation is negative. The shaded green area represents the passive envelope of motion of the native hip. Dotted lines are values after capsulotomy, and solid lines are values after capsular repair.

HRA: Hip Resurfacing Arthroplasty
DM-THA: Dual-mobility Total Hip Arthroplasty
c-THA: conventional Total Hip Arthroplasty
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Ext-Add: Maximal Extension and Adduction
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