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The Shared Contributions of the Capsule, Labrum, and Bone on the Suction Seal of the Hip

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Abstract

The hip capsule, labrum, and bone contribute to hip stability. Abnormalities in these structures are associated with pain and microinstability. Previous studies have quantified the individual stabilizing roles of the capsule and labrum and have associated cam over-resection with decreased hip stability.

The first objective of this thesis was to identify the relative biomechanical contributions of the capsule, labrum, and bone to the hip suction seal, as a representation of hip stability. The second objective was to assess the effectiveness of a labral reconstruction in restoring the suction seal after a cam over-resection.

Ten human cadaveric hips were tested in a combination of different capsule, labrum, and bony conditions. The initial resistive strength of native tissues cannot be recovered after a capsulotomy and labral tear are made, despite a complete repair of all structures. A labral reconstruction after cam over-resection partially restores the suction seal, but not to normal levels.

Keywords

Hip, hip arthroscopy, hip stability, suction seal, hip capsule, hip labrum, femoroacetabular impingement, labral reconstruction, biomechanics.

Summary for Lay Audience

The hip joint is made up of bony and soft tissue structures. The capsule is an outer covering that surrounds the femoral head and socket creating a watertight seal between the joint and overlying muscle. The labrum is a circumferential cartilage layer attached to the rim of the acetabulum that deepens the acetabular socket.

The most common anatomic abnormality of the hip is femoroacetabular impingement (FAI). FAI refers to an abnormal bump of bone at the edge of the femoral head and/or an abnormal bump of bone at the socket rim. When the hip is placed in certain positions, these bumps hit each other and cause pain, labral tears and early wear of the cartilage leading to arthritis. To treat this, the abnormal bumps of bone are surgically removed, and labral tears are repaired.

Previous research has shown that the capsule, labrum, and bone all stabilize the hip and that if too much bone is taken away during surgery, the hip becomes destabilized. However, no research has measured how much each structure contributes to hip stability, or the best way to treat a hip where too much bone has been removed. Therefore, our first goal was to measure how much each structure contributes to hip stability. Our second goal was to see if placing a tendon graft where the labrum used to be helps restore the suction seal when too much bone had been taken away previously. To do this, we completed two studies that tested the force required to break the suction seal in a series of different capsule, labrum, and bony situations. We used hips from people that donated their bodies to research, which were tested by pulling the femoral head away from the socket and measuring the force it took to break the seal in each situation. Overall, we found that as soon as the normal capsule, labrum, and bone was altered, the suction seal would never be as strong. We also found that while a tendon graft improves the suction seal after too much bone has been removed, it does not restore it to a normal level.

Contributions

Chapter 1: Alex Hoffer - sole author

Chapter 2: Alex Hoffer - study design, data collection, data analysis, manuscript creation

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Chapter 3: Alex Hoffer - study design, data collection, data analysis, manuscript creation

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Ryan Degen - study design, data analysis and manuscript review

Geoff Ng - study design, data analysis and manuscript review

Chapter 4: Alex Hoffer - study design, data collection, data analysis, manuscript creation

Stefan St George - data collection, data analysis

Ryan Degen - study design, data analysis and manuscript review

Geoff Ng - study design, data analysis and manuscript review

Chapter 5: Alex Hoffer - sole author

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Chapter 1

1. Introduction

This chapter provides an overview of the relevant hip anatomy, pathology, and treatment in addition to a systematic review of the outcome metrics used to quantify the hip suction seal.

1.1. Anatomy Overview

The hip is an enarthrosis, that is, a ball and socket joint, that is vital to connect the axial and appendicular skeleton and facilitate bipedal ambulation. The interplay between femoral head, acetabulum, capsule, and labrum makes the hip one of the most stable, yet mobile joints in the body.

1.1.1. Bony Congruity

The femoral head is the "ball" that makes up the ball and socket hip joint. The femoral head is a conchoid shape rather than a true sphere, which may improve stability and facilitate rolling and gliding between the femoral head and the acetabulum resulting in less wear (FIGURE 1).[1] Sixty to seventy percent of the femoral head is covered with articular cartilage, which articulates with the acetabulum.[2] The fovea capitis is located in the central portion of the head, is devoid of articular cartilage and serves as the insertion of the ligamentum teres which has a role in femoral head blood supply during development.

The femoral neck connects the femoral head to the femoral shaft. The average neck-shaft angle is 125° the average anteversion is 20°.[2] These anatomic relationships provide the necessary lever arms for the abductor and short external rotator muscles to move the hip in multiple planes. Acetabular retroversion is associated with impingement between the femur and acetabulum at lower hip flexion angles, such as in FAI.[3]

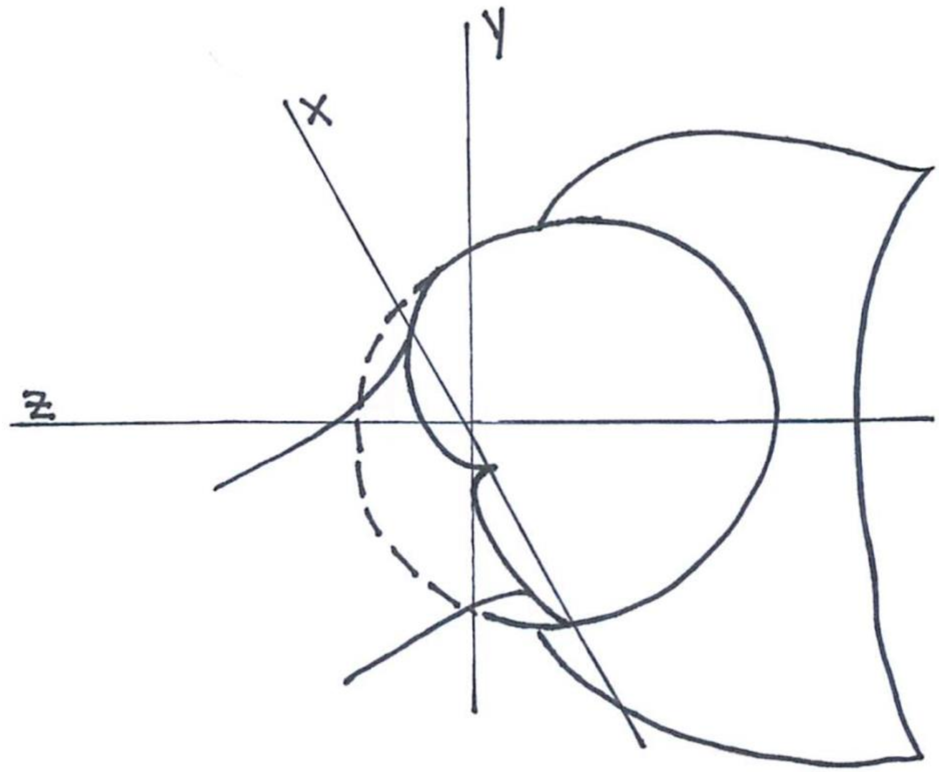

Figure 1-1. Conchoid Femoral Head Shape

A coronal view of the femoral head demonstrates its conchoid shape compared to a spherical femoral head shape, identified with a dashed line.

The acetabulum is the “socket” of the ball and socket hip joint, and is formed through the fusion of the ilium, ischium, and pubis during development.[4] The articular cartilage portion of the acetabulum is a horseshoe shape and extends to the acetabular rim, continuous with the labrum. The cotyloid fossa is the central region devoid of cartilage that serves as the acetabular attachment of the ligamentum teres.

The average lateral opening and anteversion of the acetabulum are 50° and 20° respectively, which helps enable high degrees of abduction and flexion of the femur. The acetabular depth is measured by the lateral centre edge angle (LCEA) and anterior centre edge angle (ACEA) (FIGURE 2A, 2B). The normal acetabular depth and femoral head coverage varies considerably but is commonly quantified as an LCEA of 25-40°.[5] Dysplasia occurs when the acetabulum is shallow and there is relative femoral head uncoverage, defined as an LCEA less than 18°.[5] An LCEA of 18-25° is considered a "hip at risk". Over-coverage is defined as an LCEA greater than 40°, and may be associated with femoroacetabular impingement (FAI) or protrusio.[4]

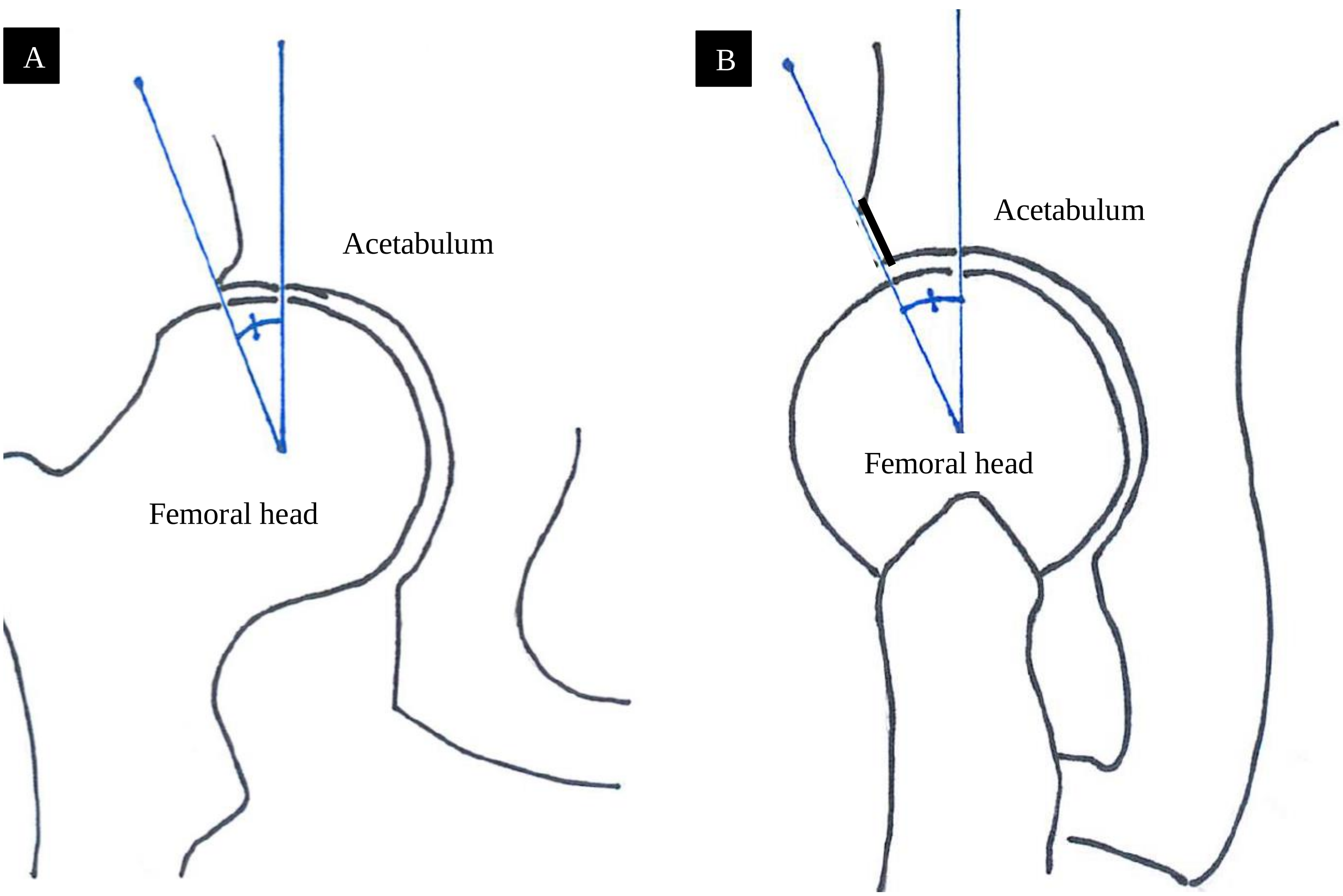

Figure 1-2. Assessment of Femoral Head Coverage

A radiographic assessment of femoral head coverage includes the lateral centre-edge angle (A), and anterior centre-edge angle (B). The lateral centre-edge angle quantifies the superolateral femoral head coverage on an antero-posterior radiograph. The angle is made between a vertical line through the centre of the femoral head and a second line connecting the centre of the femoral head to the lateral border of the acetabulum. A normal angle is between 25-39°, borderline dysplasia between 20-25° and dysplasia less than 20°.[6] The anterior centre-edge angle quantifies the anterior femoral head coverage on a false-profile radiograph. The angle is made between a vertical line through the centre of the femoral head and a second line connecting the centre of the femoral head to the anterior border of the acetabulum. A normal angle is between 25-40°, dysplasia less than 20°, and FAI greater than 40°.[7]

A systematic review and meta-analysis completed as part of this thesis identified seven biomechanical studies that have assessed the effect of bony changes on hip stability.[8–14] Three studies assessed the effect of sequential acetabular rim trimming, [9,13,14], two assessed the effect of FAI morphology,[10,12] one assessed the effect of cam over-resection,[11] and one assessed the effect of end range hip position.[8] Overall, while a native acetabular rim provides the greatest degree of stability, acetabular rim trimming has minimal effect until 4 to 6mm or more is removed, and chondrolabral separation may have a larger negative effect on stability compared to rim trimming alone.[9,13,14] The presence of FAI decreases the acetabular seal and increases contact pressures between the femoral head and acetabulum.[10,12] While femoral osteochondroplasty up to the physeal scar does not affect distractive stability, cam over-resection results in decreased distractive stability.[11] Finally, contact forces between the posterosuperior femoral head and acetabulum are maximized during hyperextension, adduction and external rotation stress testing.[8]

1.1.2. Hip Capsule

The hip capsule surrounds the femoral head and acetabulum to create a fluid-tight environment for lubricating synovial fluid. The iliofemoral, ischiofemoral and pubofemoral ligaments make up the capsule and play a vital role in joint functional mobility and stability.[15] The hip capsule consists of a high proportion of collagen type-I, similar to all other ligaments.[16] The iliofemoral ligament has medial and lateral components that come together to attach from the anterior superior iliac spine of the pelvis to the intertrochanteric line of the femur, known as the Y ligament of Bigelow.[15] The iliofemoral ligament is the primary restraint for external rotation in hip flexion (lateral arm) and internal rotation in extension (both arms). [17] The ischiofemoral ligament attaches to the pelvis at the ischium and posteroinferior acetabular rim, and it inserts onto the posterior intertrochanteric line.[15] The ischiofemoral ligament provides restraint to internal rotation in both neutral and combined flexion-adduction-internal rotation (FADIR) hip positions[17] Last, the pubofemoral ligament attaches to the superior pubic ramus of the pelvis and combines with the medial iliofemoral and inferior ischiofemoral ligaments to attach to the femur.[15] The pubofemoral ligament provides restraint to abduction and external rotation, predominantly while the hip is in an extended position.[17]

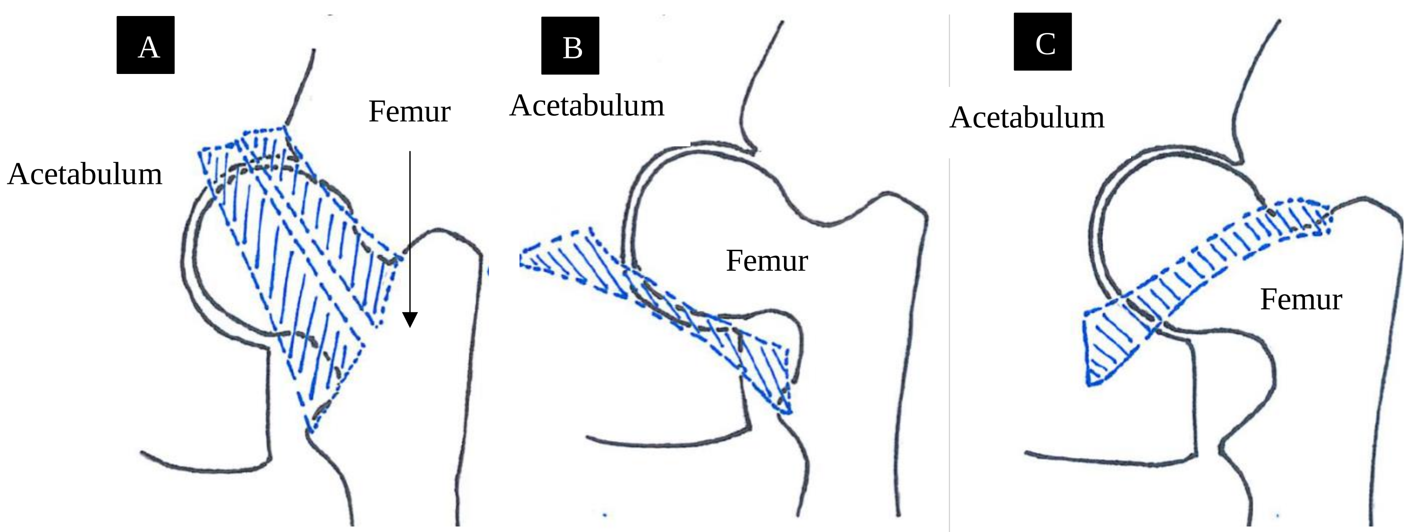

Figure 1-3. Ligaments of the Hip Capsule

The hip capsule consists of the iliofemoral ligament (A), the pubofemoral ligament (B), and the ischiofemoral ligament (C).

During hip arthroscopy, an interportal capsulotomy approximately four centimetres (cm) in length is made perpendicular to the iliofemoral ligament to aid visualization and instrumentation within the joint. A second capsular incision, known as a T-extension is made perpendicular to the interportal capsulotomy, parallel to the iliofemoral ligament, to gain access to the femoral head-neck junction when a cam resection is indicated. The size and pattern of the capsulotomy may influence postoperative stability and subsequent functional outcomes.[18] Multiple biomechanical studies have suggested that a capsular repair, plication, or reconstruction may improve stability and restore resistance to femoral head translation compared to a capsulotomy alone.[11,19–33] However, clinical studies have not reliably exhibited the same findings.[34,35] Further investigation regarding the pattern and size of intra-operative capsulotomy, the management of said capsulotomy at the conclusion and the influence of the clinical context and concomitant pathology is warranted.

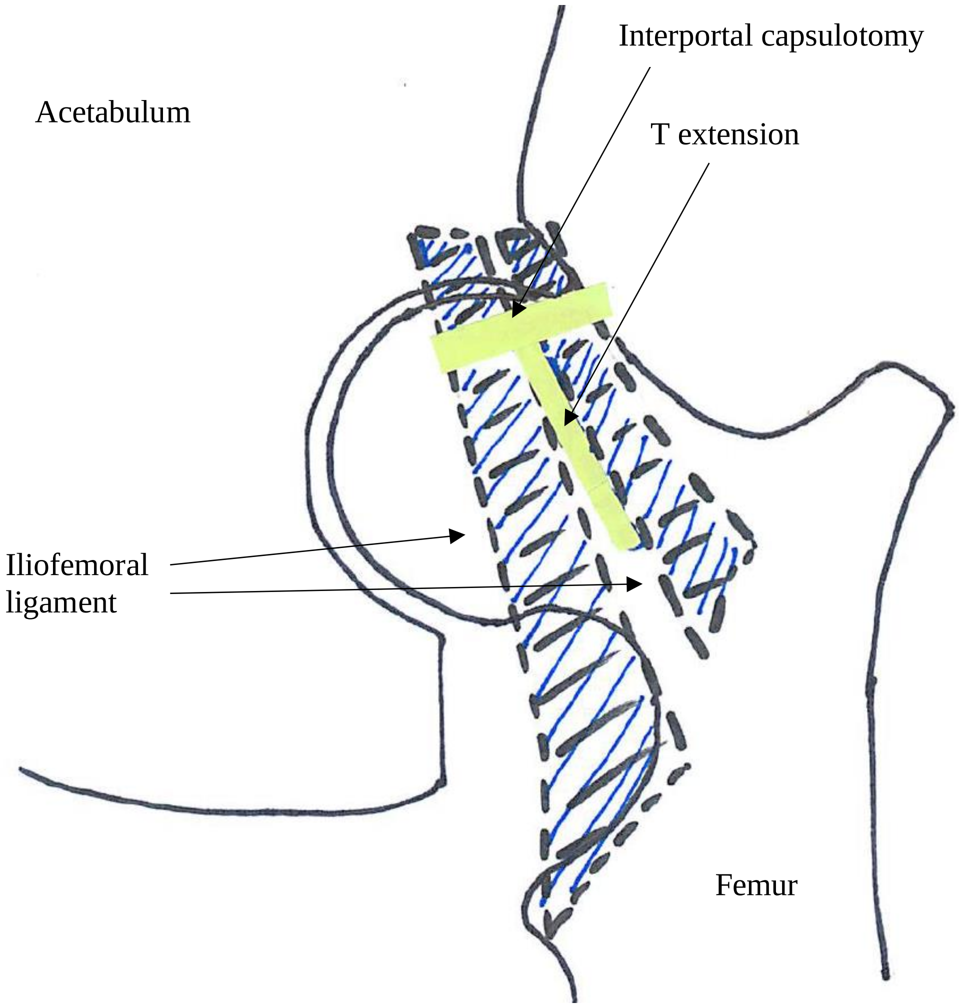

Figure 1-4. Hip Capsule T Extension

An interportal capsulotomy is made perpendicular and across the fibres of the iliofemoral ligament. A T extension is made parallel to the iliofemoral ligament fibres to gain access to the femoral head-neck junction.

1.1.3. Hip Labrum

The hip labrum is an intracapsular, incomplete ring of fibrocartilage that attaches to the acetabular rim, helps deepen the acetabular socket, and stabilize the hip joint.[36] The labrum extends from approximately 8 to 4 o'clock on the acetabular clock face. The transverse acetabular ligament is continuous with the labrum, extends from 4 to 8 o'clock on the acetabular clock face and together with the labrum creates a stabilizing ring that increases the jump distance of the femoral head to over half its diameter. [37,38] The most important function of the labrum is its contribution to hip stability, achieved by increasing the articular surface area by 22%, acetabular volume by 33% and providing a sealing effect to maintain negative pressure within the joint. [39–41]

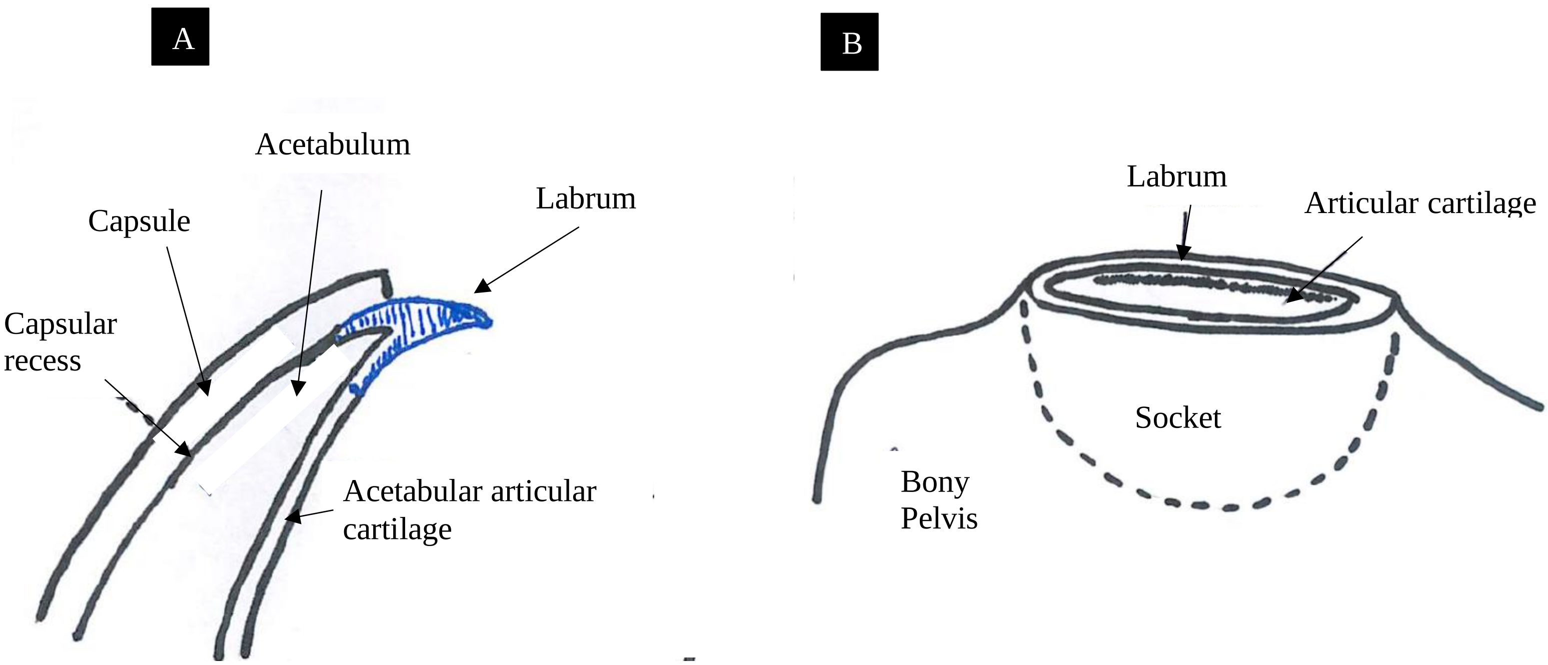

Figure 1-5. Anatomy of the Hip Labrum

The labrum increases the depth of the hip socket, has circumferential capsular attachment and is continuous with the articular hyaline cartilage (A). The labrum is continuous with the transverse acetabular ligament to form a ring at the acetabular rim (B).

Labrum tears occur due to trauma, FAI, capsular laxity, hip hypermobility, dysplasia, and degeneration.[42] Symptoms of a labrum tear may include pain, stiffness, and a catching or locking sensation in the hip.[43] The initial management for a labrum tear in isolation is generally non-operative, with hip-specific physiotherapy.[44] However, hip labrum tears rarely occur in isolation, and commonly the underlying etiology, such as FAI, prompts surgical management. In the clinical setting, labrum repair is favoured compared to labrum debridement due to improved long term clinical outcomes and a lower 10-year conversion rate to total hip arthroplasty.[45–47]

Recently, in the clinical scenario of an irreparable or calcified labrum, a labral reconstruction with various types of allografts has been shown to have short- and mid-term improvement in patient reported outcomes and functional scores postoperatively.[48] While long term outcomes are awaited, labrum reconstruction may be a viable option when the labrum is irreparable, when the labrum is calcified or in the context of multiple revision attempts at labrum repair.

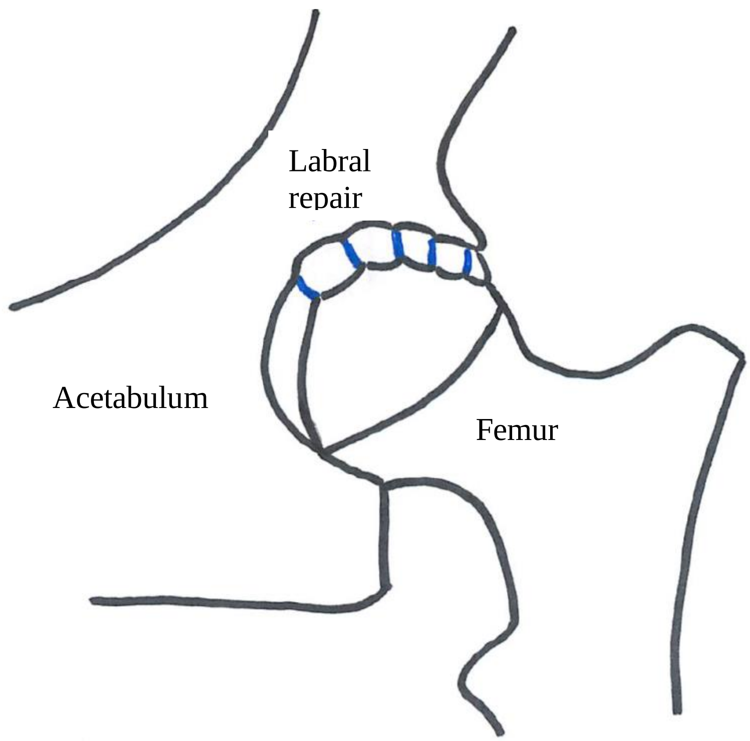

Figure 1-6. Labral Repair

The labrum commonly tears between 1:00 and 2:00 on the acetabular clockface, corresponding with the location of cam morphology in FAI. A labral repair can be completed in a simple looped fashion (visualized in the above figure), or a vertical mattress-through fashion.

Although biomechanical models have identified the labrum as an important contributor to hip stability, they have failed to show clear superiority of a labral repair compared to labral tear with respect to resistance to distraction.[8,13,14,31,49] A systematic review and meta-analysis completed as part of the literature review for this thesis identified 19 studies that assessed the effect of the labrum on hip stability.[8,10,13,14,24,27,30,31,41,49–58] Eight studies assessed the effect of labral debridement compared to an intact labrum, labral tear, repair or reconstruction.[8,27,30,31,41,49,51,55] All 8 studies found that a labral debridement resulted in the greatest loss of stability, regardless of the comparison being made. Four of the 8 studies also assessed hip stability in labral tear and repair conditions.[8,31,49,51] Interestingly, two studies found a labral tear afforded more stability than a labral repair,[8,49] one found no difference,[31] and one found that a repair resulted in greater stability than a labral tear based on fluid efflux from the hip joint.[51] Three studies assessed the effect of a labral reconstruction on hip stability, and found that a reconstruction can partially restore native stability, but not to normal levels.[52,53,56] Two studies assessed the effect of labral height on stability, and found that the wider the labrum the greater the resistance to distraction.[50,56] Last, three studies assessed the effect of hip position on labrum function.[10,51,54] Two studies found that the labrum has less impact on stability in a FADIR position,[10,54] and one study reported than an intact labrum affords greater stability in all positions compared to a labral tear.[51]

1.2. Femoroacetabular Impingement

FAI was originally described in 2003 but the diagnosis remained ambiguous until a consensus was obtained and diagnostic criteria for FAI syndrome were established in 2016.[59,60] The Warwick agreement defines FAI syndrome as “a motion-related clinical disorder of the hip with a triad of symptoms, clinical signs, and imaging findings. It represents symptomatic premature contact between the proximal femur and the acetabulum.”.[59] Clinical symptoms include motion or position-related hip pain with or without mechanical symptoms such as clicking or catching. Clinical signs include reproduction of symptoms with some combination of hip flexion, adduction, and internal rotation. Imaging findings include the identification of cam morphology, which is a flattening or convexity of abnormal bone at the femoral head-neck junction or pincer morphology, which refers to the global or focal over coverage of the femoral head by the acetabulum. The Warwick agreement has cleared any ambiguity surrounding the diagnosis of FAI syndrome, providing clarity to healthcare professionals across all disciplines.[59]

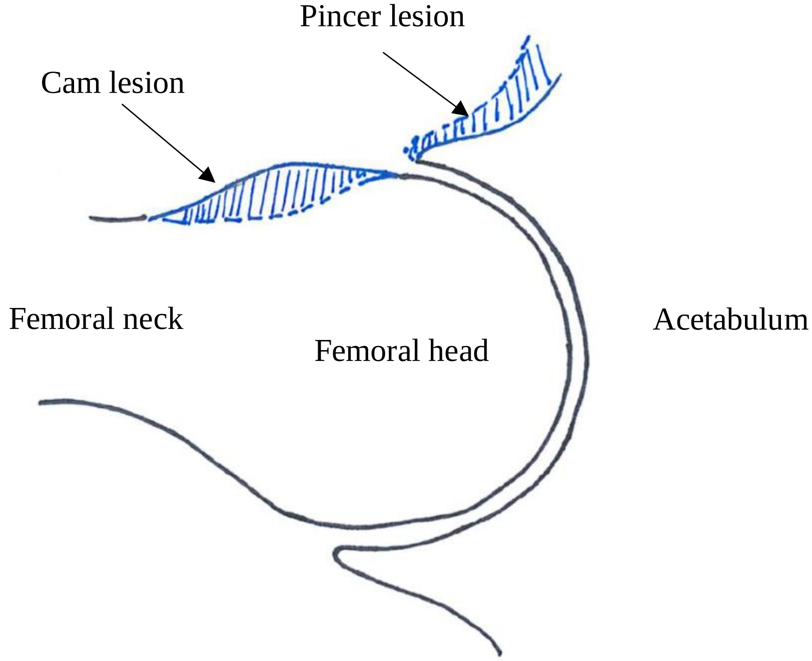

Figure 1-7. Femoroacetabular Impingement Morphology

FAI may consist of both a cam lesion at the proximal femoral head-neck junction and pincer morphology at the anterolateral acetabular rim with associated retroversion. The cam lesion is represented by the blue shaded section of the femur, and the pincer lesion is represented by the blue shaded section of the acetabulum.

The morphologic abnormalities in FAI are theorized to lead to labral tears and through abnormal contact between the femoral head and acetabular rim, specifically in flexion, internal rotation, and adduction, resulting in supra-physiologic stress and injury to the labrum and underlying cartilage.[61,62] Over time, the micro-instability associated with labrum tears and cumulative cartilage damage lead to osteoarthritis. Bony impingement in cam-type FAI syndrome with an alpha angle over 60° has been confirmed in a 4-D dynamic computed tomography study with as little as 41° of hip flexion.[63] Multiple studies have established and strengthened this relationship between FAI syndrome and osteoarthritis.[64–67] Since FAI may be a surgically modifiable risk factor for hip osteoarthritis, early identification is important and further research to assess the long term outcome in hips after surgical correction of FAI is needed.

While non-operative management of FAI with hip-specific physiotherapy can be effective, surgical management to correct a cam or pincer deformity and repair the labrum may result in superior outcomes.[68] Nepple et al. [2022] reported 78% compared to 41% total hip arthroplasty (THA)-free survivorship and superior patient reported outcomes at 15 years after hip arthroscopy when a femoral osteoplasty to remove a cam deformity was completed.[69] Further, good clinical outcomes may also be achieved after hip arthroscopy for the treatment of FAI with concomitant dysplasia. A high rate of return to sport in adolescents and survivorship of 79% at 10 years for conversion to THA in the presence of dysplasia have both been reported.[70,71] Further, a 2019 systematic review and meta-analysis found that 98.7% of allcomers returned to sport after hip arthroscopy for the treatment of FAI and all patient-reported outcomes published improved postoperatively.[72] Despite the growing body of literature supporting hip arthroscopy in the management of FAI, a 2021 systematic review and meta-analysis of 3 randomized control trials including 650 patients that compared hip arthroscopy to physiotherapy in the treatment of FAI found low quality evidence that suggests hip-specific quality of life is similar between the two management strategies at 24 months.[73] The conflicting evidence regarding the optimal management of FAI highlights the need for further investigation on the subject.

FAI may decrease hip stability through multiple mechanisms. Suppauksorn et al. [2020] assessed the effect of partial and complete cam resection in hips with cam-type morphology (alpha angle > 55°) on contact pressure, contact area and peak for between the femoral head and acetabulum.[12] They found a significant decrease in intra-articular contact pressure after a complete cam resection compared to incomplete resection or native cam morphology. Dwyer et al. [2015] assessed the ability of a hip with FAI morphology to maintain the fluid seal in different hip positions compared to normal hip morphology.[10] They found that the peak central compartment fluid pressure was decreased during pivoting movements in hips with FAI, specifically in those with concomitant labral damage. Further, they found lower average central compartment pressures in hips with FAI and an intact labrum compared to those with normal hip morphology.[10] The concomitant effect of the abnormal bony morphology and subsequent soft tissue pathology in FAI on hip stability has not been elucidated.

1.2.1. Cam Over-resection

The most common indication for revision hip arthroscopy is under-resection of the femoral cam lesion or undertreated FAI.[74–76] However, as the emphasis on a complete cam resection has increased, cam over-resection has been identified as an iatrogenic complication with clinical consequences.[77] There are multiple definitions for cam over-resection including resection of over 5% of the femoral head,[77] resection engagement with the acetabulum during dynamic intraoperative examination, and resection resulting in loss of the suction seal.[78] Inferior patient report outcomes, inferior outcomes after revision hip arthroscopy, and higher rates of conversion to THA have been reported after cam over-resection compared to a neutral cam resection.[77,79]

Further, a biomechanical assessment of cam over-resection defined as bone resection 5- and 10-mm proximal to the physeal scar showed a loss of resistance to axial distraction at all flexion angles from 0° to 90° after over-resection.[11] A salvage procedure coined "hip remplissage" with iliotibial band (ITB) allograft, in which a patch of ITB allograft was used to fill the cam over-resection defect has been described with promising short term outcomes in a level IV case series.[80] However, no high quality studies have validated the safety or efficacy of the technique, and currently, no other surgical options with high quality evidence exist to manage cam over-resection.

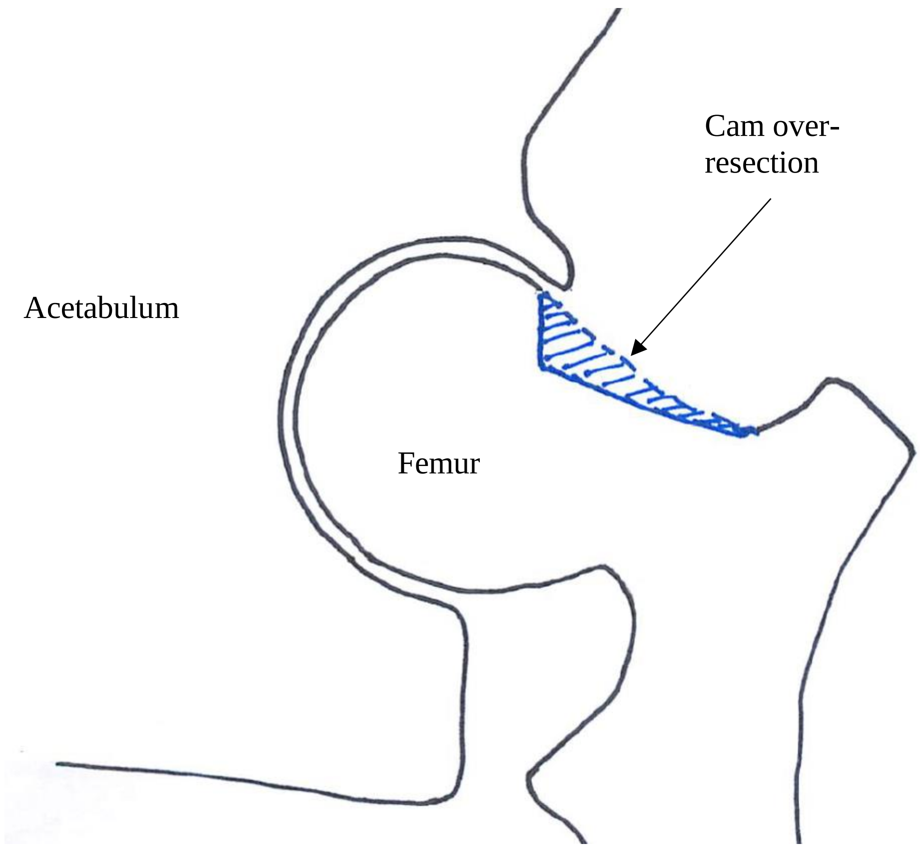

Figure 1-8. Cam Over-resection

Over-resection of a cam lesion leads to inferior clinical outcomes and loss of the suction seal. The blue shaded section represents a cam over-resection, where too much bone is removed. The dashed line represents the correct amount of resection to recreate the normal femoral head-neck junction contour.

1.3. The Hip Seal

The concept of the hip fluid seal was first described in 1837 and has been studied in modern literature since the early 1980's. [81–83] The correlation between labrum tears and arthritis led to the discovery of the labral fluid seal function.[84] The labral fluid seal can maintain a pressurised fluid layer between the femoral head and acetabulum under high compressive loads to prevent contact of the articulating surfaces and distribute loads evenly across the articular surfaces.[84] Since this discovery, there has been an explosion of research dedicated to studying the hip seal, the contributing structures, and objective measures related to the seal. Three common outcome metrics were identified in the systematic review and meta-analysis completed as part of the literature review for this thesis. These outcome metrics include distraction force, intra-articular fluid parameters and contact area and stress between the femoral head and acetabulum.

1.3.1. Distraction

The distraction force required to disrupt the suction seal and the distraction distance between the femoral head and the acetabulum at which the suction seal ruptures are the most utilized metrics to quantify the suction seal in different soft tissue states.[8,11,13,14,21–33,49,50,52,53,56–58] Multiple studies have assessed the isolated contributions of the capsule, labrum, and bone to the suction seal, in intact and altered states. Chapter 2 provides a quantitative analysis of the capsule and labrum in intact compared to abnormal states, respectively.

The contribution of bone to resist distraction is not as clear as the capsule or labrum. No study has assessed the effect of bony congruity alone to the suction seal. It is likely that bone does not contribute to the suction seal, since the bony acetabulum covers less than 50% of the femoral head, and is larger than the femoral head.[4] However, the overlying articular cartilage may play a role in the suction seal in a wet environment such as with surrounding synovial fluid secondary to its expansion properties.[84] Further research to assess the contribution of articular cartilage to the suction seal is warranted.

Distraction of the femoral head away from the acetabulum disrupts the fluid seal and the suction seal simultaneously, and these terms are often used interchangeably. However, the suction seal refers to the resistive force to distraction applied by labrum, capsule, and other factors while the fluid seal refers to the ability of the labrum to maintain a pressurised fluid layer under a compressive load. The suction seal and fluid seal are likely affected differently by many contributing variables such as the force direction, the rate of force, and whether the force is constant or changing. The relationship between the suction seal and fluid seal has been assessed in three studies that measured the intra-articular pressure and distractive strength in a series of labral, capsular, and bony conditions.[14,31,50] Nepple et al. [2014] found a moderate correlation between peak intra-articular pressure and distractive strength for a series of labral conditions but no correlation between peak pressurization and distractive strength ($r = 0.005$, not significant) for intact state specimens.[31] Utsunomiya et al. [2020] found similar decreases in intra-articular pressure and distractive resistance after labral repair and refixation compared to intact conditions.[50] Storaci et al. [2020] found a strong correlation between maximum distraction force and peak negative intra-articular pressure ($r = -0.83$, $p = 0.001$) when comparing the suction seal in hips with different labral height.[50] Based on these findings, while a relationship between the suction seal and fluid seal exists, its relative contributions and characteristics are still relatively unknown.

1.3.2. Fluid Parameters

Fluid parameters within the hip joint include the central compartment pressure and volume during movement and the flow rate between the central and peripheral compartments during compression and distraction. The central compartment pressure during a compressive load describes the fluid seal of the hip. Ten studies have assessed changes in hip stability using fluid parameters.[10,14,19,20,31,41,50,51,54,57] The specific outcome measures vary widely among studies that measure fluid parameters to quantify hip stability. Outcome measures include central compartment pressure during compression,[41,50,57] and distraction,[14,50,69] peripheral compartment pressure during different ROM,[10,19,54] and intra-articular volume measurements.[20,41] Chapter 2 provides further details about these studies and the fluid parameters they used to quantify hip stability.

Fluid parameters have been used to quantify the relative contributions of the capsule and labrum to hip stability. Nepple et al. [2014] measured the force required, and negative intra-articular pressure to distract a hip 5 mm at a constant rate in different capsular and labral conditions.[31] They found that the labrum contributed greater resistance to distraction when the femoral head and acetabulum were 1 to 2 mm apart, and the capsule contributed greater resistance to distraction when the femoral head and acetabulum were further away, over 3 mm apart. Although these findings have not been reproduced elsewhere, the labrum may apply a superior seal when there is maximum contact between its inner surface and the femoral head. Therefore, the labrum may function maximally when the femoral head and acetabulum are close together. On the other hand, the capsule has a high collagen-I content, with similar tensile properties to most ligaments.[86] As strain on the capsule increases, the stress increases proportionally until the yield point is reached, followed by macroscopic failure.[85] At 3 to 5 mm of distraction, the stress-strain relationship may be mid-curve resulting in a large resistance to distraction at that point.

1.3.3. Contact Force and Stress

The contact area, contact stress, and peak force between the femoral head and acetabulum in different soft tissue states during compression of the hip joint have also been used as outcome metrics related to the hip suction seal.[8,9,12,52,53,55] Most studies that use these measures to quantify hip stability insert a pressure sensor between the femoral head and acetabulum.[9,12,52,53,55] These sensors are thin-film, piezoresistive sensors that disrupt the seal between the labrum and femoral head. Therefore, the contact area, stress, and force between the femoral head and acetabulum cannot be identical to a central compartment pressure representing the fluid seal, or even the resistive force to distraction that represents the suction seal. The relationship between these contact measures, the fluid seal, and the suction seal have not been well studied. Chapter 2 provides further details about studies that use contact outcome measures to represent hip stability and the relationship between contact measures, the fluid seal, and the suction seal.

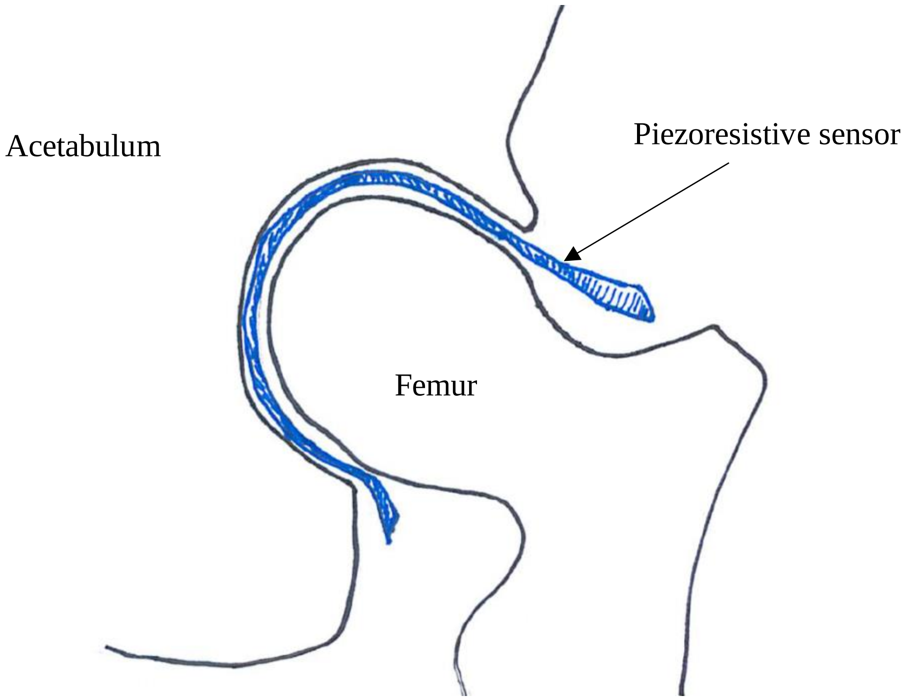

Figure 1-9. Piezoresistive Sensor to Detect Hip Contact Forces

The blue spacer represents a piezoresistive sensor that detects the contact area, contact stress, and peak force between the femoral head and acetabulum. However, the separation of the femoral head, acetabulum and associated labrum also disrupts the hip seal.

1.4. Thesis Rationale

1.4.1. Systematic Review and Meta-Analysis:

Several biomechanical studies have assessed the contributions of the capsule, labrum, and bone to hip stability. However, most studies have used dissimilar methodology and have assessed anatomic structures in isolation, or stability metrics in isolation. A systematic review and meta-analysis was conducted to summarize how the anatomic structures of the hip contribute to the suction seal, their relative contributions to hip stability, and what metrics are used to measure the suction seal and hip stability.

1.4.2. Part I:

Previous research using the suction seal as a representation of hip stability has shown that the capsule, labrum, and bony congruence all contribute to hip stability. However, most biomechanical studies that have quantified the contribution of an anatomic structure of the hip to the suction seal have assessed each component in isolation and few have assessed the relative contributions of the hip capsule, labrum, and bone in both normal and abnormal states. Part I of our biomechanical investigations aimed to quantify the relative contributions of the capsule and labrum to the suction seal by testing multiple combined capsule and labral conditions.

1.4.3. Part II:

Previous research has identified that cam over-resection decreases the hip's resistance to distraction resulting in a decrease in hip stability.[11] However, there is no biomechanical study that provides evidence for a technique to restore hip stability or the suction seal after cam over-resection. Part II of our biomechanical investigations aimed to provide evidence that a labral reconstruction helps restore the suction seal and improve hip stability after cam over-resection.

1.5. Hypotheses

1.5.1. Systematic Review:

We hypothesized that a capsular repair or reconstruction would improve stability compared to a capsulotomy or capsulectomy respectively, that a labral repair or reconstruction would improve stability compared to a labral tear, and that a femoral cam and acetabular rim resection would improve stability compared to the abnormal bone morphology in FAI syndrome.

1.5.2. Part I:

We hypothesized that an intact labrum and capsule would provide the greatest resistance to distraction, that an intact labrum would contribute more to the suction seal than a capsulotomy, and that a repaired capsule would contribute more to the suction seal than a repaired labrum.

1.5.3. Part II:

We hypothesized that a labral reconstruction would at least partially restore the suction seal after a cam over-resection and that a larger (10 mm) labral reconstruction would provide greater resistance to distraction compared to a smaller (6 mm) labral reconstruction.

1.6. Thesis Overview

Chapter 2 provides a systematic review and meta-analysis of the soft tissue and bony stabilizers of the hip and the outcome metrics used to quantify hip stability. Chapter 3 compares the distractive stability of different concurrent labrum and capsular conditions. Chapter 4 assesses the distractive stability after cam over-resection and compares the strength of the suction seal in different labrum states include labrum tear, repair, and 6 mm and 10 mm labral reconstruction. Chapter 5 provides a general discussion, summary of findings and potential areas for future investigation.

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Chapter 2

2. The Contribution of Soft Tissue and Bony Stabilizers to the Hip Suction Seal: A Systematic Review of Biomechanical Studies

Overview:

As introduced earlier, previous biomechanical studies have identified capsular closure, labral repair, or reconstruction, and osteochondroplasty as important surgical interventions to improve hip stability. This chapter investigates the outcome metrics used to quantify hip stability and assess the relative contributions of the labrum, capsule, and bone to hip stability.

(A version of this chapter has been submitted for publication in the American Journal of Sports Medicine and is under review.)

2.1. Introduction

Procedural volumes for hip arthroscopy continue to increase globally as the field advances in both diagnostic and therapeutic capacities.[4,49] Despite recent interest in the biomechanical consequences of soft tissue and bony management in hip arthroscopy, it is unclear how certain aspects of surgical correction of capsular, labral, and bony pathology influence joint mechanics and stability. The bony congruity of the femoral head and acetabulum, the labrum, and the capsule are important contributors to hip stability. Biomechanical evidence suggests normal, intact hip anatomy provides the greatest joint stability, and the introduction of bony or soft tissue pathology decreases stability.[7,22,46,54] The presence of pathology, or treatment thereof, can contribute to microinstability, which is symptomatic excessive motion of the femoral head within the acetabulum leading to altered joint loading and concordant pain, dysfunction, and osteoarthritis.[30,39,48,52] This has led to an increased focus on refining surgical techniques to restore normal joint anatomy and enhance surgical outcomes. Many techniques for capsular closure, labrum preservation or restoration, and femoral cam and acetabular rim resection have been supported by biomechanical studies and are utilized in hip arthroscopy procedures based on patient indications.[10,21,43,47]

Multiple outcome metrics have been used to quantify hip stability in the setting of bone and soft tissue pathology. The hip suction seal has been established as a reproducible measure of hip stability, particularly in the setting of labral pathology.[6,16,51] However, the contributions of the capsule and bone to the suction seal have not been well defined. Other outcome metrics such as hip range of motion, contact forces, joint loading and translations between the femoral head and acetabulum have been used to quantify the capsule and bony contribution to hip stability respectively.[27,44,45,47,58] The relationship between different outcome metrics to quantify hip stability is still largely unknown. The purpose of this review was to investigate the outcome metrics used to quantify hip stability and assess the contributions of the labrum, capsule, and bone in different conditions to hip suction seal mechanics in in-vitro biomechanical studies. We hypothesized that a capsular repair or reconstruction would improve stability compared to a capsulotomy or capsulectomy respectively, that a labral repair or reconstruction would improve stability compared to a labral tear, and that a femoral cam and acetabular rim resection would improve stability compared to the abnormal bone morphology in femoroacetabular impingement syndrome (FAIS).

2.2. Methods

2.2.1. Study Registration

This study was registered in the International prospective register of systematic reviews. No ethics or institutional review board approval was required.

2.2.2. Search Strategy

Two online databases (Embase and PubMed) were searched from database inception until 30 October 2022, for literature that investigated the contribution of the hip labrum, capsule, or bony structure to the suction seal in biomechanical cadaver studies. The search included broad terms such as “hip arthroscopy”, “cadaver” and “labrum” (Table 2-1) and was completed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and checklist.

Search Strategy	
Embase	Pubmed
1. Hip/	1. Hip
2. Hip arthroscopy.mp. or hip arthroscopy/	2. Hip arthroscopy
3. 1 OR 2	3. 1 OR 2
4. Hip instability.mp. or hip microinstability.mp. or hip stability.mp.	4. Hip instability OR hip microinstability OR hip stability
5. (Hip biomechan* or hip biomechanics).mp. or biomechanics/	5. Hip biomechanics
6. Cadaver/	6. Cadaver
7. 4 OR 5 OR 6	7. 4 OR 5 OR 6
8. Hip capsul* or hip capsule.mp.	8. Hip capsule
9. Capsulotomy/	9. Capsulotomy
10. Iliofemoral.mp. or ilioischial.mp. or pubofemoral.mp.	10. Iliofemoral or ilioischial or pubofemoral
11. (Hip labr* or hip labrum or labral tear or labral repair or labral reconstruction).mp.	11. Hip labrum or labral tear or labral repair or labral reconstruction
12. Femoroacetabular impingement.mp. or hip impingement.mp. or cam over-resection.mp.	12. Femoroacetabular impingement or hip impingement or cam over-resection
13. 8 OR 9 OR 10 OR 11 OR 12	13. 8 OR 9 OR 10 OR 11 OR 12
14. 3 AND 7 AND 13	14. 3 AND 7 AND 13
15. Limit 14 to English language	15. 14 AND (english[language])
Total: 481	Total: 1826

Table 2-1. Search Strategy.

2.2.3. Assessment of Study Eligibility

The research question and study eligibility criteria were established a priori. The inclusion criteria were English language studies, the biomechanical evaluation of human cadaveric hip specimens, and an assessment of the contribution of the labrum, capsule, or bone to the hip suction seal and stability metrics. Exclusion criteria were animal studies, reviews, technique reports, editorials, opinion articles, clinical studies, abstracts, studies that concerned open surgery, arthroplasty, reorientation osteotomy or traumatic dislocations and studies that focused on patient reported outcome scores.

2.2.4. Study Screening

All titles, relevant abstracts and full-text articles were screened by two Orthopaedic Surgeon reviewers independently. Any disagreements were deliberated between the two reviewers and a senior author was consulted if a consensus could not be obtained. The references of the included studies were manually screened for any articles that were not included in the initial search strategy.

2.2.5. Data Abstraction

Data was collected and recorded in an Excel spreadsheet (Version 16.66, 2022, Microsoft Corp). Abstracted data included the manuscript title, author(s), year of publication, study design, number of cadaveric specimens, cadaver age, cadaver handling, hip structures assessed and stability metric outcomes. The data was extracted by one reviewer and checked by a second reviewer. Disagreements were deliberated between the two reviewers and a senior author was consulted if a consensus could not be obtained. Missing data was excluded from the analysis. Study investigators were contacted for additional details and raw data as necessary.

2.2.6. Data Synthesis

The biomechanical cadaveric studies were assessed for several hip stability metrics including the distractive force and distance required to rupture the suction seal, the peak negative pressure and change in volume in the central compartment associated with disruption of the suction seal and the change in contact area, force and pressure between the femoral head and acetabulum in different soft tissue and bony structural states.

2.2.7. Statistical Analysis

Weighted means and standard deviations were calculated for continuous variables using IBM SPSS Statistics version 23, Chicago, IL. Standardized mean differences (SMD) were calculated between the capsulotomy or capsulectomy and capsular repair or reconstruction groups in the native capsule studies. SMD were calculated between the labrum tear or labrectomy and labrum repair or reconstruction groups in the native labrum studies. Review Manager Version 5.4.1, The Cochrane Collaboration, 2020 (RevMan) was used for data analysis. Forest plots were created for the distractive force and distance comparing the capsulotomy or capsulectomy and capsular repair or reconstruction states and for comparing the labrum tear or labrectomy and labrum repair or reconstruction states. The I^2 index was used to measure the heterogeneity of the included studies.[23] Effect sizes were calculated using a random effects model with the DerSimonian-Laird estimator, because high heterogeneity precluded the use of a fixed effect model.[11] An SMD score of 0.2 to 0.49 was considered weak, a score of 0.5 to 0.79 was moderate, and a score of 0.8 or greater was considered large.[9]

2.3. Results

2.3.1. Search Strategy

The initial search of online databases identified 2307 studies. A systemic screening and assessment of eligibility identified 33 articles that satisfied the inclusion criteria (Fig. 2-1).

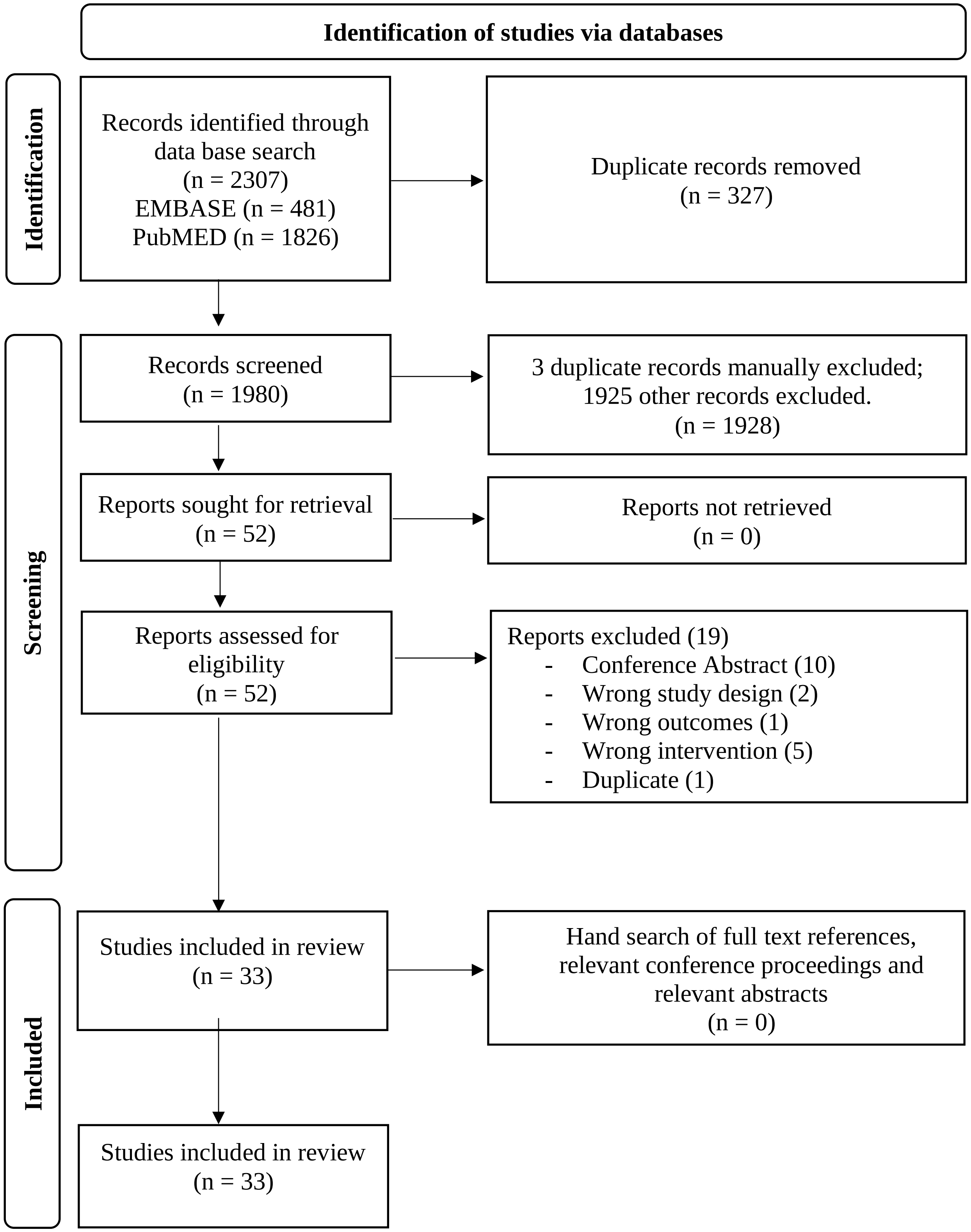


Figure 2-1. Preferred Reporting Items for Systematic Reviews and Meta-analysis flow diagram.

2.3.2. Study Characteristics

The studies comprised of 259 specimens (322 hips) with an average age of 51.5 years (range 18 to 85 years). Twenty-four studies evaluated distraction force or distance to quantify the suction seal. [8,10,15,19,24–26,28,29,31,33,36,37,40,42,53,55,56,58,60,62–65] Ten studies evaluated fluid parameters[6,13,14,16,42,51,55,60,61,63] and six studies evaluated contact forces. [3,8,35,56,57,65] A summary of the characteristics of each study is shown in Table 2-2 and 2-3.

Author, year	Number of specimens (hips)	Mean age (range)	Structures assessed	Outcome metrics included
Zaffagnini et al. 2016	16 (24)	NR (NR)	Labrum, bone	Distraction, contact forces
Wingstrand, Wingstrand and Krantz, 1990	NR (6)	NR (19-77)	Capsule	Distraction, fluid measures
Storaci et al. 2020	23 (12)	57.2 (46-65)	Labrum	Distraction, fluid measures
Waterman et al. 2019	6 (12)	63 (46-65)	Capsule	Fluid measures
Murata et al. 2022	10 (10)	58.1 (51-62)	Capsule	Distraction
Bhatia et al. 2015	6 (6)	57.5 (46-62)	Bone	Contact forces
Cadet et al. 2012	6 (6)	78.3 (NR)	Labrum	Fluid measures
Capurro et al. 2022	5 (10)	NR (NR)	Labrum	Distraction, contact forces
Suppauksorn et al. 2020	8 (8)	62.5 (NR)	Labrum	Distraction, contact forces
De Giacomo et al. 2021	4 (8)	55.7 (42-73)	Capsule	Distraction
Dwyer et al. 2014	8 (8)	48 (25-63)	Labrum	Fluid measures
Dwyer et al. 2015	10 (10)	50 (42-63)	Labrum, bone	Fluid measures
Fagotti et al. 2018	8 (8)	53.4 (42-59)	Capsule	Distraction
Ferguson et al. 2003	4 (6)	50 (40-64)	Labrum	Fluid measures
Ito et al. 2009	7 (7)	68.5 (59-85)	Labrum, capsule	Distraction
Jackson et al. 2015	4 (8)	58.5 (48-71)	Capsule	Distraction
Jacobsen et al. 2019	9 (9)	61 (NR)	Capsule	Distraction
Johannsen et al. 2019	6 (12)	29 (18-41)	Labrum, capsule	Distraction
Johannsen et al. 2019	7 (8)	31 (18-46)	Capsule	Distraction
Khair et al. 2017	12 (12)	65.67 (NR)	Capsule	Distraction
Lazaro et al. 2021	6 (6)	42 (23-47)	Capsule, bone	Distraction
Lee et al. 2015	10 (10)	59.2 (29-64)	Labrum	Contact forces
Lertwanich et al. 2016	5 (10)	NR (43-49)	Labrum, capsule	Distraction
Maldonado et al. 2022	6 (12)	54.4 (37-68)	Labrum	Distraction
Philippon et al. 2014	5 (8)	47.8 (41-51)	Labrum	Fluid measures
Nepple et al. 2014	5 (8)	47.8 (41-51)	Labrum, capsule	Distraction, fluid measures
Signorelli et al. 2017	6 (8)	87 (NR)	Labrum	Distraction
Suppauksorn et al. 2020	8 (8)	62.6 (NR)	Bone	Contact forces
Suppauksorn et al. 2022	8 (8)	53.1 (NR)	Labrum, bone	Distraction
Utsunomiya et al. 2020	12 (12)	57.2 (46-65)	Labrum, bone	Distraction, fluid measures
Weber et al. 2018	8 (8)	63.3 (NR)	Capsule	Distraction
Crawford et al. 2007	6 (6)	NR (NR)	Labrum, capsule	Distraction
Wydra et al. 2021	8 (16)	54.1 (29-62)	Capsule	Distraction

Table 2-2. Summary of Included Studies

NR, Not Reported.

Title	Author	Year	Purpose, Results and Conclusions	Limitations
Soft tissues contribution to hip joint kinematics and biomechanics	Zaffagnini et al.	2016	Part A assessed the periarticular soft tissues and capsule contribution to ROM and joint centre translation in 36 positions. Part B assessed the hip suction seal strength in different labrum states. Part C assessed the contact area between femoral head and acetabulum during three provocative clinical examinations for FAI. Part A found an inverse relationship between the amount of periarticular tissue present and the hip ROM and joint centre translation. Part B found no difference in the mean distraction distance between an intact labrum (1.8 mm) and labral tear (1.9 mm), and statistical differences among all other states including vertical mattress repair (3.3 mm), cerclage repair (4.4 mm), and partial labrectomy (5.7 mm). Part C found that a hyperextended and externally rotated position localizes the contact area to the posterior-superior acetabulum. The main conclusion was that the hip stability is highly reliant on the surrounding soft tissues.	Separate specimens used for each part resulting in small sample size; advanced mean age of specimens; no specimen screening for bony changes; capsule management in part B was not reported; time-zero collection of data.
Intracapsular and atmospheric pressure in the dynamics and stability of the hip: A biomechanical study	Wingstrand, Wingstrand and Krantz	1990	Part A assessed changes in the intracapsular pressure in different hip positions and with a simulated hip effusion. Part B assessed the distraction distance with an intact capsule and capsulotomy as a surrogate for the effect of atmospheric pressure. Part A found an increase in intracapsular pressure at extremes of motion and when volume was added. Part B found that the stabilizing effect of atmospheric pressure represented by an intact capsule is 200 N. The main conclusions were that extremes of motion and an effusion contribute to increased intracapsular pressure and capsular injury may be associated with instability.	Small sample size; limited methodology; multiple comparisons and reduced power; specimens not screened for soft tissue or bony pathology; time-zero collection of data.
The Hip Suction Seal, Part I The Role of Acetabular Labral Height on Hip Distractive Stability	Storaci et al.	2020	Storaci et al. investigated the effect of labral height on the suction seal. A labral height greater than 6 mm was associated with a greater maximum distraction force, greater distance to rupture of the suction seal and greater intra-articular negative pressure. Labral height is positively associated with the strength of the suction seal.	Not randomized; one hip position tested; all other soft tissues removed; time-zero collection of data.
Intra-articular Volume Reduction With Arthroscopic Plication for Capsular Laxity of the Hip: A Cadaveric	Waterman et al.	2019	Waterman et al. compared the decrease in intracapsular volume after an interportal capsular shift and T-capsulotomy plication. They found that both capsular closures decreased the capsular volume compared to baseline (35.9% and 24.5% respectively) and there was no difference in the volumetric reduction between the two closure techniques. Both	Small sample size, advanced mean age of specimens; method of specimen preparation not detailed; specimens not screened for soft tissue or bony

Comparison of Two Surgical Techniques			closure techniques decrease the intra-articular volume similar amounts.	pathology; time-zero collection of data.
Biomechanical Evaluation of 4 Suture Techniques for Hip Capsular Closure	Murata et al.	2022	Murata et al. compared the ROM and distraction distance in multiple hip positions for 7 capsular states to assess which suture technique best restored native stability after a 5 cm IPC. They found that compared to a 5 cm IPC a standard suture technique did not limit ROM or distraction while the shoelace, double shoelace, and Quebec City slider (QCS) repair limited external rotation (-8.1°, -7.8°, and -10.2°), extension (-6.3°, -7.3°, and -8.1°) and femoral head distraction (-1.8, -2.2 and -1.9 mm). They conclude that when closing the hip capsule, a shoelace, double shoelace or QCS repair technique should be used to restore hip stability.	Advanced mean age of specimens; time-zero collection of data; did not assess other capsulotomy configurations; free-hand repair technique introduces variability.
Effects of Acetabular Rim Trimming on Hip Joint Contact Pressures How Much is Too Much?	Bhatia et al.	2015	Bhatia et al. compared the changes in contact area, pressure, and peak forces at the acetabular base and rim after sequential rim trimming up to 8 mm. At the base they found an increased contact area after 4 mm of resection (169.12% of normal) and increased contact pressure and peak force after 6 mm of resection (292.76% and 166% of normal respectively). At the rim they found a decreased contact area, contact pressure, and peak force after 6 mm of resection (66.32%, 65.47% and 50.77% of normal respectively). They concluded that resecting more than 4 to 6 mm of rim may increase contact pressures at the base contributing to joint degeneration.	Advanced mean age of specimens; time-zero collection of data; non-randomized conditions; no absolute data reported; multiple comparisons and reduced power.
Investigation of the Preservation of the Fluid Seal Effect in the Repaired, Partially Resected, and Reconstructed Acetabular Labrum in a Cadaveric Hip Model	Cadet et al.	2012	Cadet et al. compared the fluid seal after labral tear, repair, partial resection, and reconstruction. They found a decrease in fluid efflux with a labral repair (0.21 mL/s) compared to labral tear (0.54 mL/s), partial resection (0.6 mL/s) and reconstruction (0.3 mL/s). However, the labral repair did not restore the normal fluid seal of an intact labrum (0.006 mL/s). They concluded a labral repair improves the fluid seal but does not restore it completely.	Small sample size; advanced mean age of specimens; non-randomized conditions; time-zero collection of data; no loading or rotational torque conditions.
Hip Labral Reconstruction with a	Capurro et al.	2022	Capurro et al. compared the biomechanical effects of segmental labral reconstruction with synthetic polyurethane scaffold (PS) compared to	No descriptive statistics of specimens; qualitative

Polyurethane Scaffold Restoration of Femoroacetabular Contact Biomechanics			segmental labrectomy. They found that a PS reconstruction improved all outcome metrics compared to labrectomy and restored the contact area and peak force to normal values. Additionally, the labral seal was lost in all specimens after labrectomy but was restored in 80% of specimens after PS reconstruction. They concluded that a PS reconstruction improves the hip contact biomechanics compared to a segmental labrectomy.	assessment of suction seal; non-randomized conditions; time-zero collection of data.
Comparison of Suction Seal and Contact Pressures Between 270° Labral Reconstruction, Labral Repair, and the Intact Labrum	Suppauksorn et al.	2020	Suppauksorn et al. compared the biomechanical properties of an intact labrum, labral tear, repair and 270° reconstruction. They found a larger hip contact area after labral repair compared to reconstruction and a qualitative restoration of the suction seal after labral repair but not labral reconstruction. They concluded that a labral repair is biomechanically superior to a reconstruction regarding restoration of contact area and a qualitative suction seal.	Advanced mean age of specimens; no absolute data reported; specimens not screened for soft tissue pathology; time-zero collection of data.
Biomechanical Comparison of Capsular Repair, Capsular Shift and Capsular Plication for Hip Capsular Closure Is a Single Repair Technique Best for All?	De Giacomo et al.	2021	De Giacomo et al. compared the biomechanical effects of a capsular repair, capsular shift, and a combination capsular shift with plication after an IPC by assessing changes ROM and distraction distance under a constant load. They found that all closure techniques restored near normal ROM and resulted in similar distraction distances, but a combined capsular shift and plication restricted ROM further than other repair techniques. They concluded that while all capsular closure techniques are effective in restoring stability, a combined capsular shift and plication may be necessary in patients in hip laxity and microinstability.	Only part of the protocol was randomized; time-zero collection of data; multiple comparisons and reduced power.
The Acetabular Labrum Regulates Fluid Circulation of the Hip Joint During Functional Activities	Dwyer et al.	2014	Dwyer et al. evaluated the sealing function of the labrum by assessing the fluid transport between the peripheral and central compartments during fluid infusion and in different hip positions. They found that the labrum was directly responsible for resistance to fluid transport during loading and that hip position, specifically flexion and internal rotation resulted in less resistance of fluid transport from the central to peripheral compartments.	Advanced mean age of specimens; fluid infusion into the central compartment does not represent normal fluid mechanics; time-zero collection of data.
Femoroacetabular Impingement Negates	Dwyer et al.	2015	Dwyer et al. assessed the effect of FAI-induced labral damage, as opposed to in vitro, iatrogenic labral damage, to the suction seal. In	Small sample size; fluid infusion into the central

the Acetabular Labral Seal During Pivoting Maneuvers but Not Gait			pivoting positions, they found decreased peak central compartment fluid pressures in hips with FAI morphology and associated labral pathology (15 kPa) compared to normal hips (42 kPa). The concluded that the suction function of the labrum was reduced in pivoting positions when the labrum had been damaged by FAI morphology.	compartment does not represent normal fluid mechanics; time-zero collection of data.
Effects of Capsular Reconstruction With an Iliotibial Band Allograft on Distractive Stability of the Hip Joint A Biomechanical Study	Fagotti et al.	2018	Fagotti et al. evaluated the biomechanical effects of capsular reconstruction with ITB allograft on the distractive stability of the hip joint. They found that while a capsular reconstruction increased the force required to rupture the suction seal (median 156 N) compared to a capsular defect (89 N), it did not recreate the normal resistance to distraction of an intact capsule (218 N). They concluded that a capsular reconstruction with ITB allograft at least partially restores the distractive stability of the hip.	Time-zero collection of data; initial positioning of 15° static flexion may have influenced capsular resistance to distraction; repeated distraction of capsule.
An in vitro investigation of the acetabular labral seal in hip joint mechanics	Ferguson, Bryant, Ganz & Ito	2003	Ferguson, Bryant, Ganz, and Ito assessed the change in intra-articular fluid pressure and cartilage consolidation after labrum resection. They found a significant decrease in average intra-articular pressure under constant load after labrum resection (216 kPa) compared to an intact labrum (541 kPa). Similarly, the initial consolidation rate was 22% greater after labrum resection. They concluded cartilage consolidates more quickly after labrum resection and the labrum contributes to intra-articular fluid pressurization.	Small sample size; specimens not screened for soft tissue pathology; time-zero collection of data; single hip position tested.
The Proximal Hip Joint Capsule and the Zona Orbicularis Contribute to Hip Joint Stability in Distraction	Ito et al.	2009	Ito et al. assessed the contribution of the zona orbicularis to hip stability in distraction. They found the greatest reduction in distraction force needed to distract the hip joint 1, 3 and 5 mm between a partially resected capsule and completely resected capsule. They concluded that the proximal to middle part of the capsule including the zona orbicularis acts as a locking ring around the neck of the femur.	Small sample size; only male comparisons; multiple comparisons and reduced power; time-zero collection of data.
Biomechanical Effects of Capsular Shift in the Treatment of Hip Microinstability Creation and Testing	Jackson et al.	2015	Jackson et al. evaluated the biomechanical effects of a capsular shift. They found that after stretching the capsule in extension there was greater internal rotation at all flexion angles and increased distraction compared to the intact state. Further they found that both the capsular repair and capsular shift restored normal internal rotation in flexion and the capsular shift state alone restored internal rotation in	Small sample size; no radiographic data of specimens; time-zero collection of data; no consideration of possible

of a Novel Hip Instability Model			extension. They concluded that the capsular shift most closely restores normal range of motion after a capsulotomy.	overtightening with capsular shift.
Biomechanical Response to Distraction of Hip Capsular Reconstruction with Human Acellular Dermal Patch Graft	Jacobsen et al.	2020	Jacobsen et al. quantified the biomechanical properties of a human dermal allograft capsular reconstruction and assessed whether it restored the capsular distractive stability. They found no significant difference in the distractive force required to distract the hip joint 5 mm between dermal allograft reconstruction and the intact capsule. They concluded that the dermal allograft reconstruction restores the distractive strength of the hip capsule.	Advanced mean age of specimens; all other soft tissues removed from the specimens, no screening of specimens for arthritic changes; time-zero collection of data.
Contributions of the Capsule and Labrum to Hip Mechanics in the Context of Hip Microinstability	Johannsen et al.	2019	Johannsen et al. assessed the biomechanical role of anterior capsular laxity and labral insufficiency in atraumatic hip microinstability. With a fixed ER force, labral insufficiency in the setting of an intact capsule increased femoral head translation by 0.3 mm and 0.5 mm in the ML and AP planes respectively. Labral insufficiency in the setting of capsular laxity increased femoral head translation by 0.7 mm, 0.7 mm and 0.5 mm in the ML, AP, and SI planes respectively. Compared to an intact capsule, labral insufficiency in the setting of capsular laxity resulted in increased femoral head translation by1.8 mm, 1 mm and 1.1 mm in the ML, AP, and SI planes respectively. They concluded that the anterior hip capsule was the primary stabilizer to femoral head translation, but labral insufficiency in the setting of capsular laxity produced the most significant increases in femoral head translation.	The effect of venting was not reported; testing was only performed in 0° and maximum extension; capsulotomy was performed in labral insufficiency state with associated repair; time-zero collection of data.
The Role of Anterior Capsular Laxity in Hip Microinstability: A Novel Biomechanical Model	Johannsen et al.	2019	Johanssen et al. assessed the role of capsular laxity in atraumatic hip microinstability. Compared to a vented state, femoral head translation increased by 0.6 mm, 1.2 mm and 0.5 mm in ML, AP, and SI planes respectively in a capsular laxity state with a fixed ER displacement force. They concluded that the anterior capsule functions in controlling hip rotation and femoral head displacement.	Small sample size; did not address conditions that may alter pelvic tilt and hip biomechanics; cumulative forces of weightbearing, muscle contraction and gravity may be different than force applied in study.
The Effect of Capsulotomy and Capsular Repair on	Khair et al.	2017	Khair et al. quantified the changes in force required to distract a hip after increasing IPC length and compared the strength of side-to-side and acetabular-based suture anchor (SA) capsular repair techniques.	Advanced mean age of specimens; pure axial distraction used; did not test

Hip Distraction: A Cadaveric Investigation			They found an inverse relationship between IPC length and force required to distract a hip and no difference in distraction force required after side-to-side repair or SA capsular repair. They concluded that the larger an IPC, the weaker the suction seal and that both side-to-side and SA capsular repair techniques restore the suction seal after IPC.	the repair groups to failure; acetabular version not considered; possible exhaustion of capsular tissue after multiple trials.
Proximal Overresection During Femoral Osteochondroplasty Negatively Affects the Distractive Stability of the Hip Joint: A Cadaver Study	Lazaro et al.	2021	Lazaro et al. determined whether cam proximal over-resection decreases the rotational and distractive stability of the hip joint. They found a significant increase in distraction distance for a constant force after both 5 mm and 10 mm proximal over-resection at all hip flexion angles, but no increase in ER when an ER torque was applied. They concluded that cam over-resection compromises the distractive stability of the hip joint but does not affect rotational stability.	Small sample size; potential for accumulative wear and joint laxity with repeated specimen testing; no radiographic assessment of the acetabular morphology; large variation in degree of FAI.
Labral Reconstruction With Iliotibial Band Autografts and Semitendinosus Allografts Improves Hip Joint Contact Area and Contact Pressure: An In Vitro Analysis	Lee et al.	2015	Lee et al. characterized the joint biomechanics including the contact area, contact pressure and peak force within a hip in intact, deficient, and reconstructed labrum conditions. They found a decrease in contact area and increase in contact pressure after segmental anterosuperior labral resection. Further, they found a restoration of both the contact area and contact pressure after both ITB and ST labral reconstruction to near normal levels. There was no difference in the results between ITB and ST labral reconstructions. They concluded that labral reconstruction may improve hip joint biomechanics compared to a labrum-resected state.	Open technique for labrum reconstruction; results affected by possible sensor saturation; small sample size; only two hip positions tested; time-zero collection of data.
Biomechanical evaluation contribution of the acetabular labrum to hip stability	Lertwanich et al.	2016	Lertwanich et al. evaluated the effect of a 1.5 cm capsulotomy and 1 cm anterosuperior labral resection on hip stability with axial and combined axial and anterior, posterior, or lateral loading. They found that at 30° flexion and axial loading, a combined capsulotomy and labral resection resulted in more displacement (9.6 mm) compared to a capsulotomy alone (5.6 mm) or intact hip (5.2 mm). Similar results were found under combined axial and anterior or posterior loading. They concluded that the labrum was vital to hip stability and 1 cm resection contributes to a “wobbling” effect.	Few hip positions tested; time-zero collection of data; no preoperative radiographic assessment for bony abnormalities; no repair conditions tested.

An Increased Allograft Width for Circumferential Labral Reconstruction Better Restores Distractive Stability of the Hip: A Cadaveric Biomechanical Analysis	Maldonado et al.	2022	Maldonado et al. assessed the distractive stability after circumferential labral reconstruction (CLR) with a ITB allograft < 6.5 mm in height and > 6.5 mm in height. They found a CLR with ITB allograft < 6.5 mm in height did not restore the distractive force necessary to rupture the suction seal (63 N compared to 148.4 N in the intact state). However, a CLR with ITB allograft > 6.5 mm restored the distractive stability to near normal levels (135.8 N to disrupt the suction seal). They concluded that wide allografts should be used to perform CLR.	Labral reconstruction was performed open rather than arthroscopically; supraphysiologic distractive forces were applied; arbitrary cut-off for labrum reconstruction height; time-zero collection and analysis of data.
The hip fluid seal - Part I: the effect of an acetabular labral tear, repair, resection, and reconstruction on hip fluid pressurization	Philippon et al.	2014	Philippon et al. characterized intra-articular fluid pressurization in six labral conditions: intact, tear, repair (looped and through sutures), partial resection, reconstruction with ITB and complete resection. The labral tear, partial resection, complete resection, and reconstruction average pressurizations were 75%, 53%, 24% and 110 % of the intact state. The through sutures repair improved the average pressurization compared to a labral tear by 46% while the looped repair did not improve pressurization. They concluded that labral pathology results in decreases in intra-articular fluid pressurization, which can be restored by a through type labral repair or labral reconstruction.	The model used simulated loading only under single leg stance phase of gait; time-zero collection and analysis of data; several hips failed to demonstrate intra-articular fluid pressurization, often with mild degenerative changes.
The hip fluid seal - Part II: The effect of an acetabular labral tear, repair, resection, and reconstruction on hip stability to distraction	Nepple et al.	2014	Nepple et al. characterized the relative contributions of the capsule and labrum to hip distractive stability. They found that the relative labrum contribution was greatest at 1 and 2 mm of displacement, accounting for 77% and 70% of the distractive stability respectively. The capsule contribution increased with displacement, providing 41% and 52% of distractive stability at 3 mm and 5 mm respectively. They concluded that the labrum is the primary hip stabilizer at small displacements while the capsule plays a greater role as displacement increases.	Small sample size; time-zero collection and analysis of data; few hip positions tested.
Evaluation of the sealing function of the acetabular labrum: an in vitro biomechanical study	Signorelli et al.	2017	Signorelli et al. evaluated the biomechanical sealing function of an intact labrum and the effect of labral–chondral separation, vertical mattress repair, cerclage labral repair, and partial labrectomy on distraction load and hip joint centre (HJC) displacement. They found that under constant distraction forces, there was a significant increase in the distraction distance for each sequential condition, in the order	Open technique utilized; only considered chondro-labral separation pattern of labral pathology; non-randomized order of condition testing; tissue

			above, apart from an intact labrum compared to labral-chondral separation. They concluded that a partial labrectomy results in the greatest decrease in distractive stability and that a vertical mattress labral repair may be favourable to a cerclage repair.	exhaustion with repetitive testing; time-zero collection and analysis of data.
A Cadaveric Study of Cam-Type Femoroacetabular Impingement: Biomechanical Comparison of Contact Pressures Between Cam Morphology, Partial Femoral Osteoplasty and Complete Femoral Osteoplasty	Suppauksorn et al.	2020	Suppauksorn et al. compared the biomechanical properties, specifically the contact pressure, contact force and peak force between the femoral head and acetabulum of a hip joint with an intact femoral cam lesion, partial cam resection and complete cam resection. Compared to an intact cam lesion, they found a 6.4% and 17.4% decrease in contact pressure in the incomplete resection and complete resection conditions respectively. There was no difference in contact force and peak force between groups. They concluded a complete cam resection results in lower intra-articular hip contact pressure, highlighting the importance of this surgical procedure.	Small sample size; underpowered based on post-hoc analysis; only one position tested; time-zero collection and analysis of data.
The Effect of Rim Preparation, Labral Augmentation, and Labral Reconstruction on the Suction Seal of the Hip	Suppauksorn et al.	2022	Suppauksorn et al. evaluated the biomechanical properties, specifically the peak resistant force and distraction distance of the labral suction seal in the native labrum and after rim preparation, labral augmentation, and labral reconstruction. Compared to the intact condition they found decreased peak distractive force and displacement at peak distractive force in all conditions as follows: rim preparation, 91.1% and 94.4%; augmentation, 66.1% and 78.2%; reconstruction, 55.6% and 64.7% of normal. They concluded that the suction seal is not significantly changed following rim preparation, and that labral augmentation may recreate the suction seal better than labral reconstruction.	Small sample size; advanced mean age of specimens; constant distraction force used to assess structures with viscoelastic properties; non-randomized conditions; time-zero collection and analysis of data.
The hip suction seal, Part II: The Effect of Rim Trimming, Chondrolabral Junction Separation, and Labral	Utsunomiya et al.	2020	Utsunomiya et al. assessed the force, displacement, and intra-articular pressure during distraction after acetabular rim resection, chondrolabral junction (CLJ) separation, CLJ repair and CLJ refixation. Compared to the intact condition, they found no difference in any parameters after rim resection, a shorter distance to rupture of the suction seal in the labral refixation state (1.8 mm vs. 5.6 mm intact	Results of acetabular resection may be different in vivo as specimens had normal centre-edge angles; labral motion was not directly measured; no

Repair/Refixation on Hip Distractive Stability			state) and decreased maximum distraction force and negative pressure in the labral refixation and repair states compared to the intact state. They concluded that rim trimming does not change the biomechanical properties of the labral suction seal and labral refixation reduces labral motility, which may improve postoperative pain relief and healing	randomization of conditions, labral heigh was not matched between the two groups.
Vertical Extension of the T-Capsulotomy Incision in Hip Arthroscopic Surgery Does Not Affect the Force Required for Hip Distraction: Effect of Capsulotomy Size, Type and Subsequent Repair	Weber et al.	2018	Weber et al. quantified how increasing IPC size, conversion to T-capsulotomy, and subsequent repair affect the force required to distract the hip. The force required to distract the hip was 274.6 N in the intact state, 209.7 N with a 2 cm IPC, 160.4 N with a 4 cm IPC, 140.7 N with a half-T capsulotomy, 112 N with a full T capsulotomy, 177.3 N after isolated T-limb repair and 331.7 N after complete repair. They concluded that a larger IPC decreases the force needed to distract a hip but conversion of an IPC to T-capsulotomy did not affect the force required the distract a hip. Further, complete capsular repair restores the native hip stability.	Advanced mean age of specimens; axial distraction represents a “worst case scenario” unlikely to be replicated in vivo; repair groups were not tested to failure; acetabular version was not assessed; possible exhaustion of capsular tissue after multiple trials.
The Biomechanics of the Hip Labrum and the Stability of the Hip	Crawford et al.	2007	Crawford et al. evaluated the mechanical factors leading to the formation of labral tears and the effect of labral tears on hip kinematics at extremes of hip motion. They found that compared to an intact hip labrum, 43% and 60% less force was required to distract the femoral head by 3 mm after venting the capsule and introducing a labral tear respectively. They concluded that a labral tear decreases hip stability at extremes of motion.	Small sample size; no specimen demographics supplied; time-zero collection and analysis of data.
Pie-Crusting Capsulotomy Provides Similar Visualization With Increased Repair Stiffness Compared With a T-Capsulotomy: A Biomechanical Study	Wydra et al.	2021	Wydra et al. compared the area of visualization, capsular stiffness, and strength between pie-crusting the capsule and a T-capsulotomy. The force required to distract each condition 6 mm was: 250.1 N for the intact condition, 114.3 N after a T-capsulotomy, 170.1 N after a pie-capsulotomy, 165.04 N for T-capsulotomy repair, 204.43 N after pie-capsulotomy repair and improved visualization after both capsulotomies. They concluded that both capsulotomies and repairs provided similar strength and visualization adequate for hip arthroscopy.	Small sample size; advanced mean age of specimens; open technique for capsulotomies and repairs; visualization analysis was completed on an open specimen; time-zero collection and analysis of data.

Table 2-3. Detailed Summary of Included Studies

ROM, range of motion; FAI, femoroacetabular impingement; IPC, interportal capsulotomy; ITB, iliotibial tract; ER, external rotation; ML, medial-lateral; AP, anterior-posterior; SI, superior-inferior.

2.3.3. Capsule

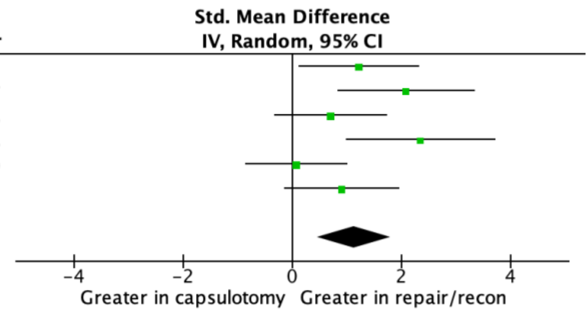
The capsular contribution to hip stability was quantified using both distraction and fluid outcome metrics in 17 biomechanical cadaveric studies.[10,15,19,24–26,28,29,31,33,36,40,42,61–64] Multiple capsular states were investigated including intact, iatrogenic laxity, capsulotomy, repair, reconstruction and capsulectomy conditions. Four studies created a capsular laxity model to assess microinstability.[25,28,29,40] Two studies simulated iliofemoral ligament (IFL) laxity by stretching the capsule in extension under 35 N·m of extension torque for one hour.[25,40] Two studies created capsular laxity by first administering 30 N·m of external rotation torque in a maximally extended hip for 100 cycles at 0.5 Hz followed by a second-round of 1000 cycles of repeated external rotation to the position achieved at the end of the first 100 cycles.[28,29] All four studies measured the distraction distance under a load control condition from 40 to 200 N to quantify hip stability and all demonstrated increased femoral head translation in the laxity state compared to an intact capsular state suggesting decreased stability.

Three studies quantified the capsular contribution to stability through fluid outcome metrics.[42,61,63] Two studies measured the negative intra-articular pressure within the central compartment while distracting or rotating the hip joint with an intact capsule.[42,63] Waterman et al. [2019] compared the reduction in central compartment volume after interportal capsular shift or T capsulotomy plication.[61] Wingstrand et al. [1990] found no change in intracapsular pressure while rotating the hip about the femoral neck axis.[63] Nepple et al [2014] found no correlation between peak intra-articular fluid pressurization and maximal distraction force with an intact capsule, and concluded these two functions of the fluid seal may be independent.[42,51] Waterman et al. [2019] found similar decreases in intra-capsular volume after interportal capsular shift and T-capsular plication compared to baseline.[61] They concluded that both repair strategies result in a decreased capsular volume.

Six biomechanical studies that compared a capsular repair or reconstruction to capsulotomy or capsulectomy were included in a quantitative analysis.[15,25,26,31,62,64] All of these used similar experimental conditions including an interportal capsulotomy or small capsulectomy with subsequent repair or reconstruction. Two studies added a T capsulotomy and subsequent repair in addition to the interportal capsulotomy and repair. [62,64] Fresh frozen cadaveric hips were dissected down to the capsule, mounted onto custom testing systems, and assessed for their distractive stability of the hip joint. One study assessed the distraction distance under load control conditions of 40 and 80 N, [19,25,40] while the other five studies assessed the force required to rupture the suction seal or to distract the hip joint a predetermined distance.[15,26,31,62,64] The standardized effect size for distraction between experimental (capsular repair or reconstruction) and control (capsulotomy or capsulectomy) was 1.13 (95% CI 0.46, 1.80, $p = 0.0009$, $I^2 = 55\%$). The forest plot for distraction in the capsular repair or reconstruction and capsulotomy or capsulectomy settings are demonstrated in Figure 2-2.

Study or Subgroup	Repair/Reconstruction Mean	SD	Total	Capsulotomy Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
Jackson 2015	−4.3	2.83	8	−7.6	2.26	8	16.8%	1.22 [0.12, 2.31]	2015
Khair 2017	257	82.2	6	119.2	52	12	14.8%	2.08 [0.84, 3.33]	2017
Fagotti 2018 (1)	168.1	76.3	8	112.06	75.56	8	17.9%	0.70 [−0.32, 1.72]	2018
Weber 2018	331.7	103.7	8	112	70.2	8	13.5%	2.35 [0.99, 3.70]	2018
Jacobsen 2019 (2)	217	129	9	208	89	9	19.3%	0.08 [−0.85, 1.00]	2019
Wydra 2021	165.04	40.43	8	114.3	63.4	8	17.5%	0.90 [−0.14, 1.95]	2021
Total (95% CI)			**47**			**53**	**100.0%**	**1.13 [0.46, 1.80]**	

Heterogeneity: $Tau^2 = 0.38$; $Chi^2 = 11.02$, df = 5 (P = 0.05); $I^2 = 55\%$
Test for overall effect: Z = 3.32 (P = 0.0009)



Footnotes
(1) Capsular Reconstruction
(2) Capsular Reconstruction

Figure 2-2. Capsular Repair or Reconstruction vs. Capsulotomy or Capsulectomy

Std, standard; SD, standard deviation; IV, inverse variance; CI, confidence interval.

2.3.4. Labrum

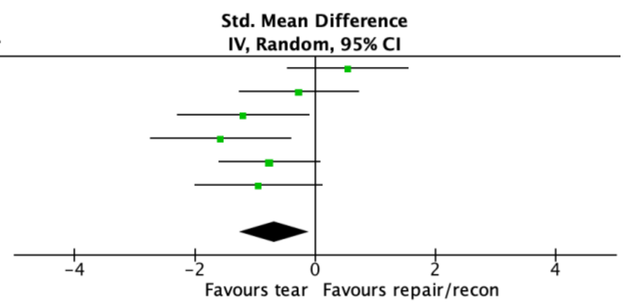
The labral contribution to hip stability was quantified using distraction, contact forces and fluid outcome metrics in 19 biomechanical cadaveric studies.[6,8,10,13,14,16,24,29,35–37,42,51,53,55,56,58,60,65] Multiple labral states were investigated including intact, tear, repair, augmentation, partial and complete labrectomy, and reconstruction conditions. Five studies quantified the labrum contribution to stability through fluid outcome metrics only.[6,13,14,16,51] Three studies quantified the fluid seal by measuring the fluid efflux from the central compartment during fluid infusion in several conditions and hip positions.[6,13,14] Two studies quantified the fluid seal by measuring the fluid pressure within the central compartment in different labral conditions.[16,51] Additionally, Ferguson et al. [2003] also measured the cartilage creep consolidation in intact and labrectomy states to quantify the contribution of the central compartment hydrostatic fluid pressure to cartilage health.[16] All five studies confirmed the importance of an intact labrum to the resistance of fluid transport between the central and peripheral compartments. These studies also reproduced an increase in fluid efflux in labrum pathology states and pivoting positions involving terminal flexion and internal rotation. [6,13,14,16,51]

Three studies quantified the labrum contribution to stability through contact forces by inserting a Tekscan pressure sensor between the femoral head and acetabulum to compare the contact pressure, area, and peak force after a labrectomy and labral reconstruction.[8,35,56] Capurro et al. [2022] used a Model 4400 hip specific Tekscan pressure sensor[8] while Lee et al. [2015] and Suppauksorn et al. [2020] used Model 5101 large Tekscan pressor sensors.[35,56] Two studies compared a partial labrectomy to a segmental labral reconstruction using a polyurethane scaffold,[8] iliotibial band (ITB) autograft or semitendinosus allograft.[8,35] Suppauksorn et al. [2020] compared labral tear and repair conditions to a 270° labral reconstruction using ITB allograft.[56] Two studies also made a qualitative assessment of the suction seal during distraction for each tested condition.[8,56] Two studies found increased contact pressure and decreased contact area after partial labrectomy with at least partial restoration of normal acetabular contact areas and pressures after segmental labral reconstruction with a polyurethane scaffold, ITB or semitendinosus allograft. [8,35] Suppauksorn et al. [2020] reported decreased contact area and increased contact force after a labral reconstruction compared to a labral repair.[56] While Capurro et al. [2022] reported reestablishment of the suction seal after segmental labral reconstruction in 80% of specimens, Suppauksorn et al. [2020] reported restoration of the suction seal after 270° labral reconstruction in only 12.5% of specimens. These studies concluded that while a labral reconstruction improves hip stability compared to a labrum-deficient state, it may not restore normal contact forces, areas, and pressures in the hip joint as well as a labral repair.

Six of the 19 biomechanical studies that assessed the contribution of the labrum to hip stability were included in quantitative analyses.[37,42,53,58,60,65] Five studies that compared a labral repair or reconstruction to a labral tear made up the primary quantitative analysis.[42,53,58,60,65] All of these studies used similar experimental conditions including the creation of a labral tear with subsequent repair or reconstruction. Two studies additionally removed abnormal bone morphology via a femoral cam resection or acetabular osteochondroplasty.[58,60] Fresh frozen cadaveric hips were dissected down to the capsule, mounted onto custom testing systems, and assessed for their distractive stability of the hip joint. Two studies assessed the distraction distance under a load control condition,[42,53] while the other three studies assessed the force required to rupture the suction seal or to distract the hip joint a predetermined distance.[58,60,65] The standardized effect size for distraction between experimental (labral repair or reconstruction) and control (labrum tear) was -0.67 (95% CI -1.25, -0.09, p = 0.02, I^2 = 49%). The forest plot for distraction in the labral repair or reconstruction and labral tear settings are demonstrated in Figure 2-3.

	Labrum repair/Recon			Labrum tear				Std. Mean Difference	
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI	Year
Nepple 2014 (1)	126.04	46.58	8	104.12	27.4	8	16.9%	0.54 [−0.46, 1.55]	2014
Nepple 2014 (2)	90.42	47.95	8	104.12	46.58	8	17.2%	−0.27 [−1.26, 0.71]	2014
Zaffagnini 2016	−3.3	1.4	8	−1.9	0.7	8	15.5%	−1.20 [−2.29, −0.11]	2016
Signorelli 2017	−8.3	0.3	8	−6.5	1.5	8	14.3%	−1.57 [−2.74, −0.41]	2017
Utsunomiya 2020	77.2	37.1	12	100.6	19.3	12	20.0%	−0.76 [−1.60, 0.07]	2020
Suppauksorn 2022 (3)	78.9	51.2	8	126.3	43.5	8	16.1%	−0.94 [−1.99, 0.11]	2022
Total (95% CI)			**52**			**52**	**100.0%**	**−0.67 [−1.25, −0.09]**	

Heterogeneity: $Tau^2 = 0.25$; $Chi^2 = 9.73$, df = 5 (P = 0.08); $I^2 = 49\%$
Test for overall effect: Z = 2.28 (P = 0.02)



Footnotes
(1) Labrum Repair
(2) Labrum Reconstruction
(3) Labrum Reconstruction

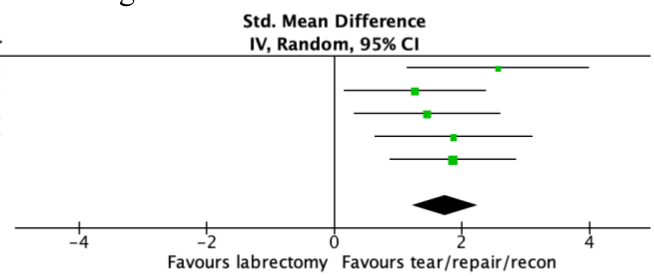
Figure 2-3. Labrum Repair or Reconstruction vs. Labral Tear.

Std, standard; SD, standard deviation; IV, inverse variance; CI, confidence interval.

A secondary analysis included four studies that compared a labral repair or reconstruction to a labrectomy.[37,42,53,65] All of these studies used similar experimental conditions. Three studies included partial labrectomy and labral repair conditions,[42,53,65] and two studies included labral reconstruction and complete labrectomy condition.[37,42] Fresh frozen cadaveric hips were dissected down to the capsule, mounted onto custom testing systems, and assessed for their distractive stability of the hip joint. Two studies assessed the distraction distance under a load control condition,[53,65] while the other two studies assessed the force required to rupture the suction seal or to distract the hip joint a predetermined distance.[37,41] The standardized effect size for distraction between experimental (labral repair or reconstruction) and control (labrectomy) was 1.74 (95% CI 1.23, 2.26, $p = 0.00001$, $I^2 = 0\%$). The forest plot for distraction in the labral repair or reconstruction and labral tear settings are demonstrated in Figure 2-4.

	tear, repair, reconstruct			Labrectomy				Std. Mean Difference	
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI	Year
Nepple 2014 (1)	126.04	27.4	8	39.73	35.62	8	13.2%	2.57 [1.15, 3.99]	2014
Nepple 2014 (2)	90.42	47.95	8	36.99	30.14	8	21.8%	1.26 [0.16, 2.36]	2014
Zaffagnini 2016	−3.3	1.4	8	−5.7	1.7	8	20.4%	1.46 [0.32, 2.60]	2016
Signorelli 2017	−7.7	0.8	8	−9.6	1.1	8	17.4%	1.87 [0.64, 3.10]	2017
Maldonado 2022	135.8	44.6	12	44.3	50.3	12	27.2%	1.86 [0.87, 2.84]	2022
Total (95% CI)			**44**			**44**	**100.0%**	**1.74 [1.23, 2.26]**	

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 2.37$, df = 4 (P = 0.67); $I^2 = 0\%$
Test for overall effect: Z = 6.64 (P < 0.00001)



Footnotes
(1) Through-repair vs. partial labrectomy
(2) Recon vs. complete labrectomy

Figure 2-4. Labral Repair or Reconstruction vs. Labrectomy.

Std, standard; SD, standard deviation; IV, inverse variance; CI, confidence interval.

2.3.5. Bone

The bony contribution to hip stability was quantified using distraction, contact forces and fluid outcome metrics in seven biomechanical cadaveric studies.[3,13,33,57,58,60,65] Multiple bony states were investigated including normal hip congruency, femoral cam morphology with and without acetabular pincer morphology, partial cam resection, complete cam resection, cam over-resection, and various degrees of acetabular osteochondroplasty. Two studies assessed native FAIS morphology specifically. [13,57]Four studies quantified the contribution of different bony states to hip stability using distraction outcome metrics.[33,58,60,65] Both the purpose and conditions tested in these studies varied broadly. Two studies quantified the contribution of different bony states to hip stability using fluid outcome metrics.[13,60] Dwyer et al. [2015] assessed the effect of FAI-induced labral pathology on hip central compartment pressure, and Utsunomiya et al. [2020] assessed the central compartment pressure in different combined acetabular osteochondroplasty and labral conditions. [13,60] Three studies considered the contribution of different bony states to hip stability using contact stress, contact area, and peak force between the femoral head and acetabulum.[3,57,65] Zaffagnini et al. [2016] found that a hyperextended, externally rotated hip position localizes the contact area to the posterior-superior acetabulum.[65] Bhatia et al. [2015] reported increased contact area after 4 mm of acetabular rim resection and increased contact pressure and peak force after 6 mm of resection.[3] Suppauksorn et al. [2020] found a 6.4% and 17.4% decrease in contact pressure after incomplete and complete femoral cam resections respectively.[57] No quantitative analysis was completed to assess the bony contribution to hip stability secondary to the large variability in the methodology and reporting between included studies.

2.3.6. Outcome Metric Comparison

Four studies assessed both distraction and fluid measures to quantify hip stability.[42,55,60,63] Three studies measured the intra-articular pressure and distractive strength in a series of labral, capsular and bony conditions.[42,55,60] Nepple et al. [2014] found a moderate correlation between peak intra-articular pressure and distractive strength for a series of labral conditions but no correlation between peak pressurization and distractive strength (*r* = 0.005, not significant) for intact state specimens.[60] Utsunomiya et al. [2020] found similar decreases in intra-articular pressure and distractive resistance after labral repair and refixation compared to intact conditions.[60] Storaci et al. [2020] found a strong correlation between maximum distraction force and peak negative intra-articular pressure ($r = -0.83$, $p = 0.001$) when comparing the suction seal in hips with different labral height. Wingstrand et al. [1990] measured changes in intra-articular pressure in different hip positions and completed a separate analysis that measured the maximum distraction force in different capsular conditions.[63]

Three studies assessed both distraction and contact forces to quantify hip stability.[8,56,65] Two studies compared the contact stress, contact area, and peak force between the femoral head and acetabulum in different labrum states in addition to completing a dichotomous analysis of the suction seal for each state. Capurro et al. [2022] found lower contact areas, higher contact forces, higher peak forces, and loss of the suction seal with the segmental labrectomy state, while greater contact areas, lower contact forces, lower peak forces, and restoration of the suction seal occurred after segmental labral reconstruction.[8] Suppauksorn et al. [2020] found greater contact areas and restoration of the suction seal after labral repair compared to lower contact areas and restoration of the suction seal in only 12.5% of specimens after labral reconstruction.[56] Zaffagnini et al. [2016] compared the distractive distance between multiple labral states and in a separate analysis assessed the contact area between the femoral head and acetabulum during 3 clinical examination maneuvers.[65]

2.4. Discussion

There were two main findings in this study. First, a capsular repair or reconstruction improved hip stability compared to a capsulotomy or capsulectomy state, respectively. Second, a labral repair or reconstruction did not improve hip stability compared to a labral tear state but did improve stability compared to a labrectomy state. Notably, no quantitative analysis was feasible from studies evaluating the effect of osseous resection on hip stability due to the heterogeneity in methodology and outcome metrics assessed.

Two of the six studies included in the capsular quantitative analysis assessed capsulectomy and capsular reconstruction conditions.[15,26] It was appropriate to combine the capsular repair and reconstruction states and compare them to the capsulotomy and capsulectomy states for two reasons. First, there are similar structural changes between repair and reconstruction, as well as capsulotomy and capsulectomy. An interportal capsulotomy violates the IFL, one of the primary stabilizing structures of the hip capsule, by cutting it perpendicular to its fibres. [50] Both studies that investigated a capsulectomy state created a capsular defect by removing approximately a 20 mm by 30 mm portion of capsule at the proximal and anterior aspect of the capsule, effectively producing a defect in the IFL.[15,26] Second, the relationship between a capsulotomy and capsular repair exhibited the same pattern as a capsulectomy and capsular reconstruction respectively. The improved stability identified in this biomechanical systematic review, paired with supportive clinical evidence suggesting improved clinical outcomes with complete capsular closure emphasize the importance of capsular closure in routine hip arthroscopy cases.[2]

Labral tear management has been a highly debated topic in hip arthroscopy over the last twenty years. A labral tear may occasionally be an incidental finding, but more commonly it is associated with underlying pathology such as FAIS and contributes to the clinical presentation with groin pain and mechanical symptoms.[20,34] The labrum is an important contributor to the suction seal and hip stability, and great focus has been directed towards restoring its function when injured or damaged, with an emphasis on repair, or reconstruction when repair is not feasible.[5] This review suggests that repairing a labral tear does not always restore its normal suction seal function. In fact, in the presence of cam morphology, an isolated labral repair may increase strain in the cartilage at the chondrolabral junction.[59] The labrum repair strategy also has a biomechanical effect on the suction seal. A vertical mattress repair fixes the base of the labrum back to the acetabular rim while leaving the outer edge free to potentially contribute to the suction seal during distraction. In contrast, a simple suture repair strategy cinches the labrum circumferentially resulting in less contact area between the labrum and femoral head. Signorelli et al. [2017] and Zaffagnini et al [2016] both showed greater resistance to distraction after a vertical mattress labral repair compared to simple suture repair.[53,65]Last, labrectomy significantly decreases the distractive strength of the hip compared to either labral tear or repair. If a labrum tear is symptomatic and must be addressed, our findings suggest that it is most important to avoid excision of the torn labrum, and that either a labral repair or reconstruction would be a better option to maintain at least partial hip stability. Whether a vertical mattress repair technique results in different clinical outcomes than a simple suture technique could be an area of future clinical investigation.

A third finding of this study was that there may be a correlation between distraction, intra-articular pressure, and contact forces as outcome metrics for hip stability, but further investigation is needed. The correlation between distractive strength and intra-capsular pressure may be hypothesized based on Boyle's law, $P \propto 1/V$ where P is the pressure and V is the volume.[17] If it is assumed an intact hip capsule is fluid-tight and maintains a constant temperature, then when the intra-capsular volume increases during hip distraction, the pressure must decrease. This finding was replicated in all three studies that reported both intra-articular pressure and distractive strength. [42,55,60] Nepple et al. [2014] found a moderate correlation between peak intra-articular pressure and distractive strength for a series of labral conditions but no correlation between peak pressurization and distractive strength ($r = 0.005$, not significant) for intact state specimens.[60] They concluded that the distractive stability and fluid pressurization functions of the labrum may be independent due to the lack of correlation. Fluid pressurization (intra-articular fluid and interstitial fluid within articular cartilage during compressive loads)[51] is not equivalent to intra-articular pressure. An inverse relationship between intra-articular pressure and distraction strength likely exists and deserves further study.

A relationship between contact area, contact force, peak contact pressures and distraction strength may also exist. Capurro et al. [2022] reported restoration of the suction seal, higher contact areas, lower contact forces, and lower peak forces after a labral reconstruction compared to a partial labrectomy. [8] Similarly, Suppauksorn et al. [2020] reported restoration of the suction seal and greater contact areas after a labral repair compared to a labral reconstruction. [56] It may be that soft tissue and bony conditions that increase contact areas and decrease contact forces between the femoral head and acetabulum also contribute to greater distractive strength. However, no study in this review compared these two outcome measures on continuous scales. Further investigation is warranted to identify this potential relationship.

2.4.1. Strengths

This review considered the contribution of several anatomic structures through multiple outcome metrics to add to our current understanding of hip stability, how it differs in pathologic states, and how it changes with surgical intervention. We used rigorous methods with predetermined objectives, strict inclusion and exclusion criteria and a standardized method of assessment a priori to carry out a reproducible search and report relevant results. This review also strengthens the biomechanical evidence underlying current trends in the management of FAIS and other hip pathology. Gupta et al. [2015] reported 100% of hip arthroscopy surgeons perform a labral repair when a labral tear is present and 88.9% perform a capsular closure at the end of surgery in most cases.[21] Five-year patient reported outcomes, patient satisfaction, rate or revision surgery and conversion to hip arthroplasty after hip arthroscopy favor complete capsular repair.[12,18] Additionally, patients who undergo labral repair are less likely to be converted to THA within 10 years compared to those who undergo labral debridement.[32] This review supports avoiding labral debridement when managing symptomatic labral tears and performing IPC repair to restore stability during hip arthroscopy.

2.4.2. Limitations

The heterogeneity among included studies in this systematic review limited the ability to complete large comparative analyses. The variability in methodology including biomechanical set-up, surgical technique, and outcome measures assessed made it difficult to use many of the studies included in the review in any meta-analyses. Second, the average age of the cadavers was 51.5 years, and most studies only included hips with normal morphology. This demographic does not accurately reflect the young hip with FAIS that most commonly undergoes hip arthroscopy. Third, the in vitro setting of the included studies introduced multiple limitations. In most studies, the surrounding soft tissues were dissected down to the level of the capsule, so any synergistic stability normally afforded by those tissues was removed. Further, the instability states created were iatrogenic in nature, dissimilar to the clinical pathology generally seen in patients.

Additionally, the in vitro surgical correction was mostly completed in an open fashion, as opposed to an in vivo setting where surgery is done arthroscopically. Last, changes in range of motion secondary to applied rotational forces was not included as an outcome measure in our review. This decision was made in the context of a previous systematic review completed by Jimenez et al. [2021], which assessed predominantly the rotational differences after capsular repair compared to capsular release.[27]

2.4.3. Future Directions

A comparison of different outcome metrics used to assess hip stability will help define new soft tissue and bony stabilizer functions. Understanding the relationship between these outcome metrics will also help make further conclusions about previously completed biomechanical research. Second, a comparison of the relative contributions of the labrum, capsule, and bone to hip stability would help clinicians understand what the most important aspects of the hip are and how to address them to maximize stability and patient function. It may be that the native conchoidal shape of the femoral head is essential to maintain the labral seal and distribute load and the optimal degree of cam resection should be individualized based on underlying femoral head and labral anatomy.[38,46] Last, the effective management of loss of the suction seal and instability secondary to iatrogenic cam over-resection is a relatively understudied area. The hip remplissage is a suggested solution but does not have the same underlying biomechanical principles as a remplissage for anterior shoulder instability, and current evidence is limited to level IV, small sample case series.[1] Future investigation using multiple outcome metrics regarding techniques to restore hip stability after cam over-resection is warranted.

2.5. Conclusion

Biomechanical evidence supports capsulotomy repair or reconstruction to improve hip distractive stability at the end of hip arthroscopic surgery. While the repair of a torn labrum does not improve distractive resistance, it is superior to removal of the torn portion.

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Chapter 3

3. The Shared Contributions of the Capsule, Labrum, and Bone to the Suction Seal of the Hip: Part I

Overview:

Previous studies have quantified the change in hip stability associated with isolated capsulotomy and repair, and labral tear and repair. The purpose of this chapter is to evaluate the change in hip distractive stability after a capsulotomy, labral tear, and simultaneous repair of both structures. The hypothesis was that a complete capsular repair and labral repair would restore the hip distractive stability to near normal levels.

3.1. Introduction

Capsular management remains a controversial topic in hip arthroscopy, balancing the risks of exposure and iatrogenic injury. An interportal capsulotomy is often made at the beginning of the procedure to improve access to bony deformity and associated labral pathology.[8,29] There is ongoing interest in the biomechanical effects of a capsulotomy and capsular repair, weighing the importance of exposure with iatrogenic injury. Although the hip is an inherently stable joint due to the high degree of congruity between the femoral head and acetabulum, microinstability and post-operative dislocation are ongoing issues that have not been resolved.[33,42]

Numerous studies have assessed the effects of interportal capsulotomy (IPC) size, T extension and subsequent repair strategies and techniques.[16,30] As the length of the IPC increases, hip range of motion (ROM) increases and distractive stability decreases.[18,39,40] A T extension is useful to gain access to the femoral head-neck junction and may increase rotational ROM, but does not seem to affect distractive stability.[1,4,39] Some studies have shown complete restoration of capsular function with a capsular closure,[3,18,27,39] while others have not.[15,32,18,43]

Multiple studies have also assessed the effect of the location and size of labral tears and subsequent management.[22,37] It is still unclear whether a labral repair improves hip stability compared to a labral tear. Some studies have found improved stability after a labral repair[26] while other studies have found the opposite.[34,36,38,43] Regardless of the tear pattern, labral debridement results in suboptimal hip stability compared to a labral tear, repair, or reconstruction.[21,26,34,43]

While many studies have assessed the capsule and labrum contribution to hip stability in isolation, few have considered their relative contributions together.[7,14,17,20,25] No study has assessed the relative contributions of the capsule and labrum to the distractive stability of the hip after simultaneous repair. The purpose of this study was to evaluate the change in hip distractive stability after a capsulotomy, labral tear, and simultaneous repair of both structures. We hypothesized that a complete capsular repair and labral repair would restore the hip distractive stability to near normal levels.

3.2. Methods

Specimens were acquired from an accredited tissue bank (Science Care, USA) for the purpose of medical research. Initially, fourteen fresh-frozen cadaveric hip specimens, seven matched pairs, were used for testing of the hip suction seal in Parts I and II of the current study. The first four hips were used to pilot the materials testing system, software, custom fixtures, and condition formation. Each specimen consisted of the pelvis and bilateral femurs. Specimens were screened with computed tomography by two orthopaedic surgeons to ensure the absence of previous surgery, injury or bony pathology including acetabular dysplasia defined as a lateral center-edge angle of less than 25° or advanced osteoarthritis defined as a Tonnis grade greater than 1. Specimens were stored at -20°C and thawed at room temperature for 24 hours before testing. If soft tissue abnormalities such as a labral tear were encountered during testing, the specimen was excluded from our analysis. Institutional ethics review board approval was obtained required for the laboratory investigation of deidentified cadaveric specimens (HSREB #121404).

3.2.1. Demographics

Ten hip specimens from five cadavers, three females, were included in the final analysis. The average age was 65.4 years (standard deviation, SD: 7.4 years). No specimens had osteoarthritis or dysplasia (mean lateral centre-edge angle 35.6°, SD: 5.6°) one cadaver (two specimens) had evidence of femoroacetabular impingement (mean alpha angle 51.6°, SD: 10.9°).

3.2.2. Specimen Preparation

After screening, specimens were divided in the midline with a reciprocating saw to separate left and right sides. Each hemipelvis was denuded to the hip capsule, preserving the capsular insertions on both the pelvis and femur. The ilium, ischium and pubis were osteotomized with an oscillating saw to isolate the acetabulum and surrounding bone from the rest of the hemipelvis while preserving the hip capsule. The acetabulum and proximal femur were each potted in custom-designed fixtures with adjustable metal screws with blunt ends to maximize the surface area, fixation points, and stability (Fig. 3-1A, 3-1B). The screws were placed with care to avoid violating the hip capsule and were reinforced with quick-setting, expansive foam between fixture, screws, and bone (Sika Boom AS-PRO, USA). The acetabular concavity was positioned facing directly superior, parallel to the fixture face. The femoral neck was oriented parallel to the cylindrical portion of the fixture and the proximal femoral shaft exited the slit designed to minimize damage to the proximal femoral bone. The first four hips were tested to failure as part of our pilot testing. The potted hips remained firmly fixed at over 500 N of distractive force and the hip completely dislocated before the hip-foam interface failed.

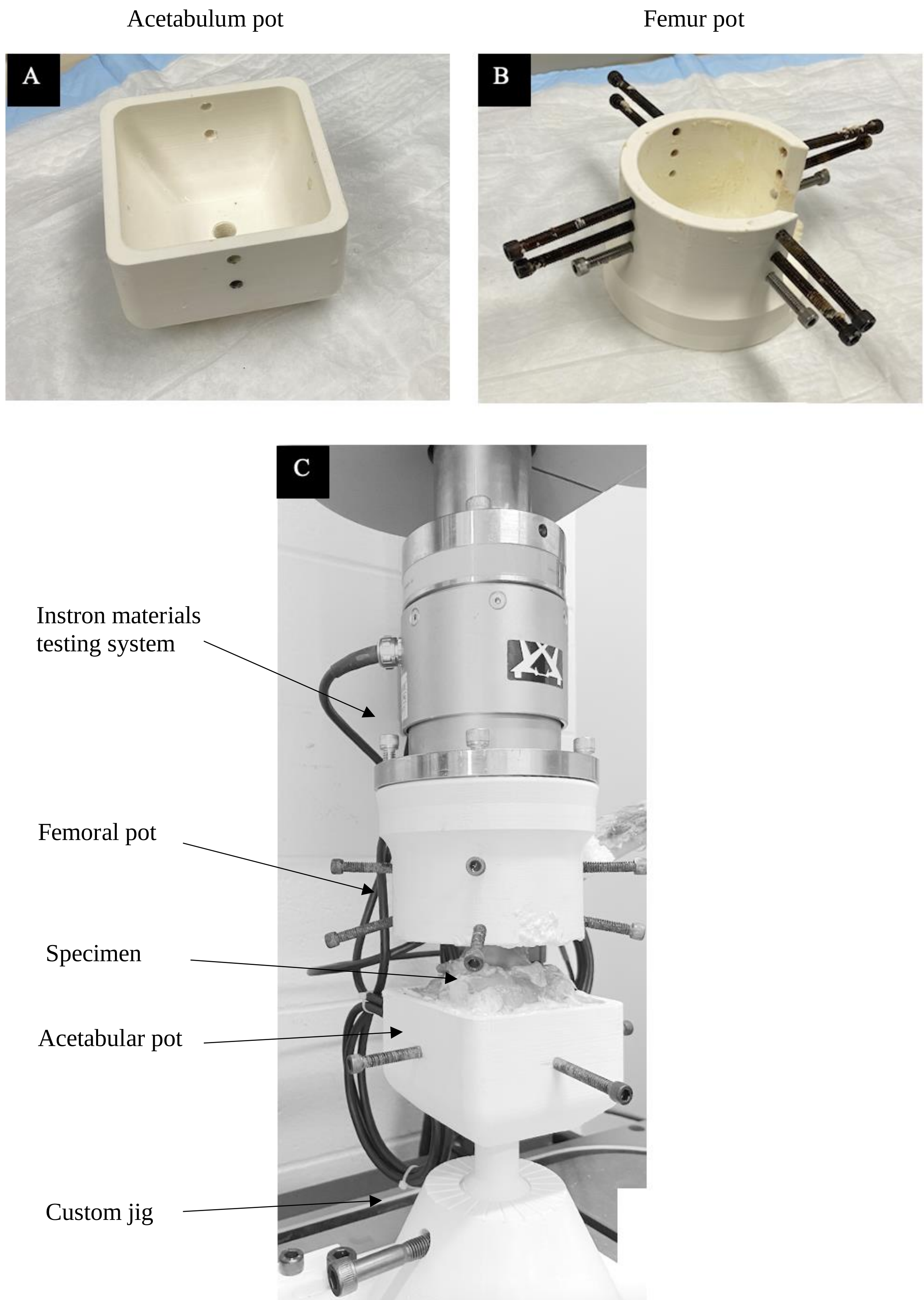


Figure 3-1. Fixtures and Testing Set-up

Acetabular custom fixture without screws (A), femoral custom fixture with screws (B), Materials Testing System with hip and pilot fixtures in-situ (C).

3.2.3. Biomechanical Testing

After potting, the acetabular and femoral fixtures were mounted on a materials testing system (Instron ElectroPuls E10000, Norwood, MA, USA) using custom jigs that together with the materials testing system provided 6 degrees of freedom for hip positioning (Fig. 3-1C). Calibration and three test repetitions were completed for each condition and hip position. Calibration consisted of a compressive force of 50 N along the axis of the femoral neck for 30 seconds to ensure bony contact between the femoral head and acetabulum and the presence of the hip suction seal. The displacement was zeroed during the calibration. The testing trials followed the calibration and consisted of distraction at a rate of 0.5 mm/s along the axis of the femoral neck while the distraction force and displacement were recorded at a minimum of 100 Hz using a data acquisition conditioner. Distraction was stopped when the hip suction seal was ruptured, indicated by a drop in distraction force of greater than 20% or when distractive forces or distance over 500 N or 15 mm respectively were encountered to prevent soft tissue injury. [21,26] All ten specimens underwent baseline testing with an intact capsule. Five hips (one hip from each matched pair) were randomized to protocol A which involved a 2 cm IPC; while five hips (other hip from each matched pair) underwent protocol B which involved a 4 cm IPC, using a web-based randomizer (Fig 3-2).[37] The neutral testing position was defined with the femoral neck perpendicular to the acetabular concavity to maximize the congruence between the femoral head and the acetabulum. Each specimen was tested at the neutral testing position, neutral rotation with 45° of flexion, and 45° of flexion with 15° internal rotation in random order for all 7 soft-tissue conditions, 6 of them surgical. The flexion angles were measured with an electronic goniometer compared to the vertical axis and internal rotation was considered neutral when the linea aspera of the proximal femur was directed posterior. The internal rotation angle was measured with a goniometer measuring the direction of the linea aspera compared to directly posterior. Internal rotation was added to assess for any impingement in the neutral condition that may have altered the observed forces. The conditions were (1) intact, (2) 2 cm or 4 cm IPC, (3) IPC and labral tear, (4) IPC, labral tear, T extension (5) IPC, labral repair, T extension, (6) IPC, labral repair, T extension repair, and (7) complete capsulotomy repair and labral repair (Fig 3-3A-G).

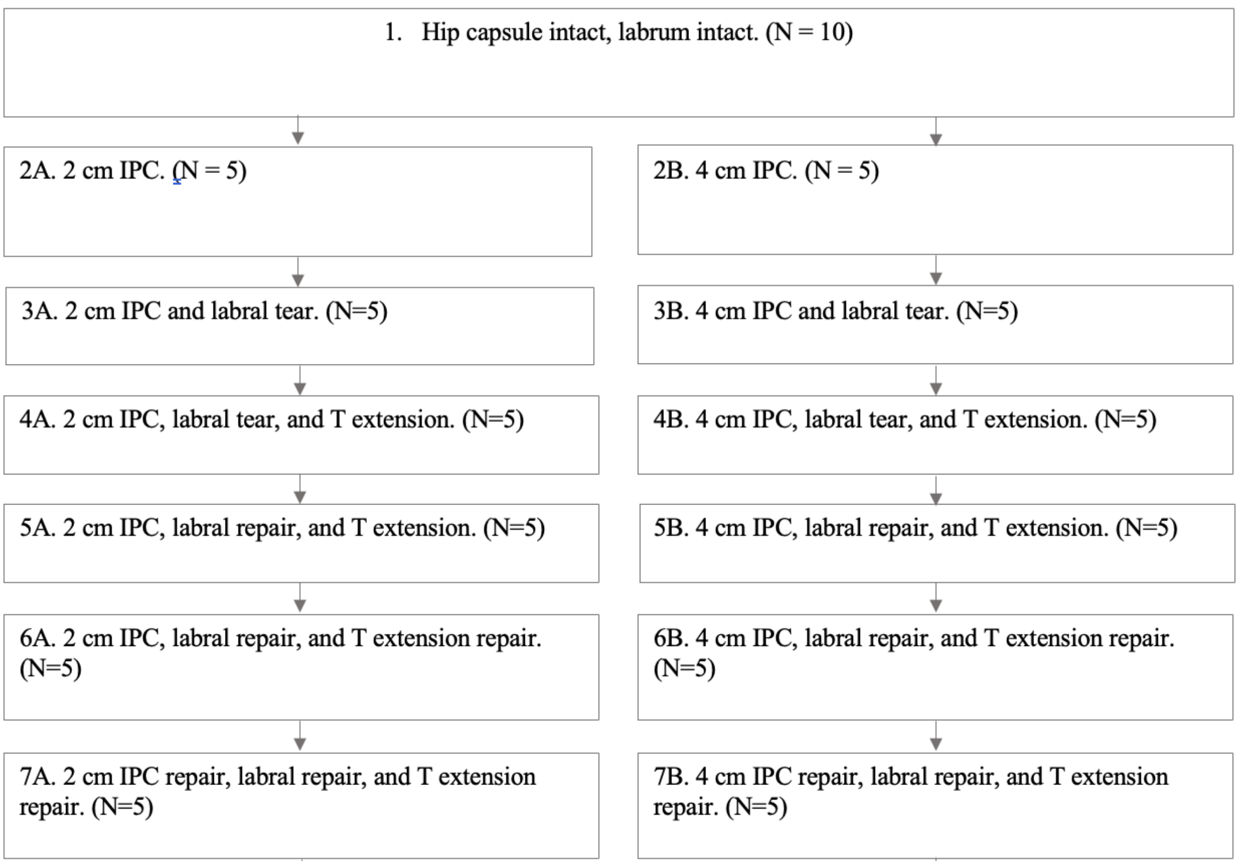


Figure 3-2. Part I Specimen Protocol.

Protocol A consisted of a 2 cm IPC (left column) and protocol B consisted of a 4 cm IPC (right column). IPC, interportal capsulotomy; cm, centimeters.

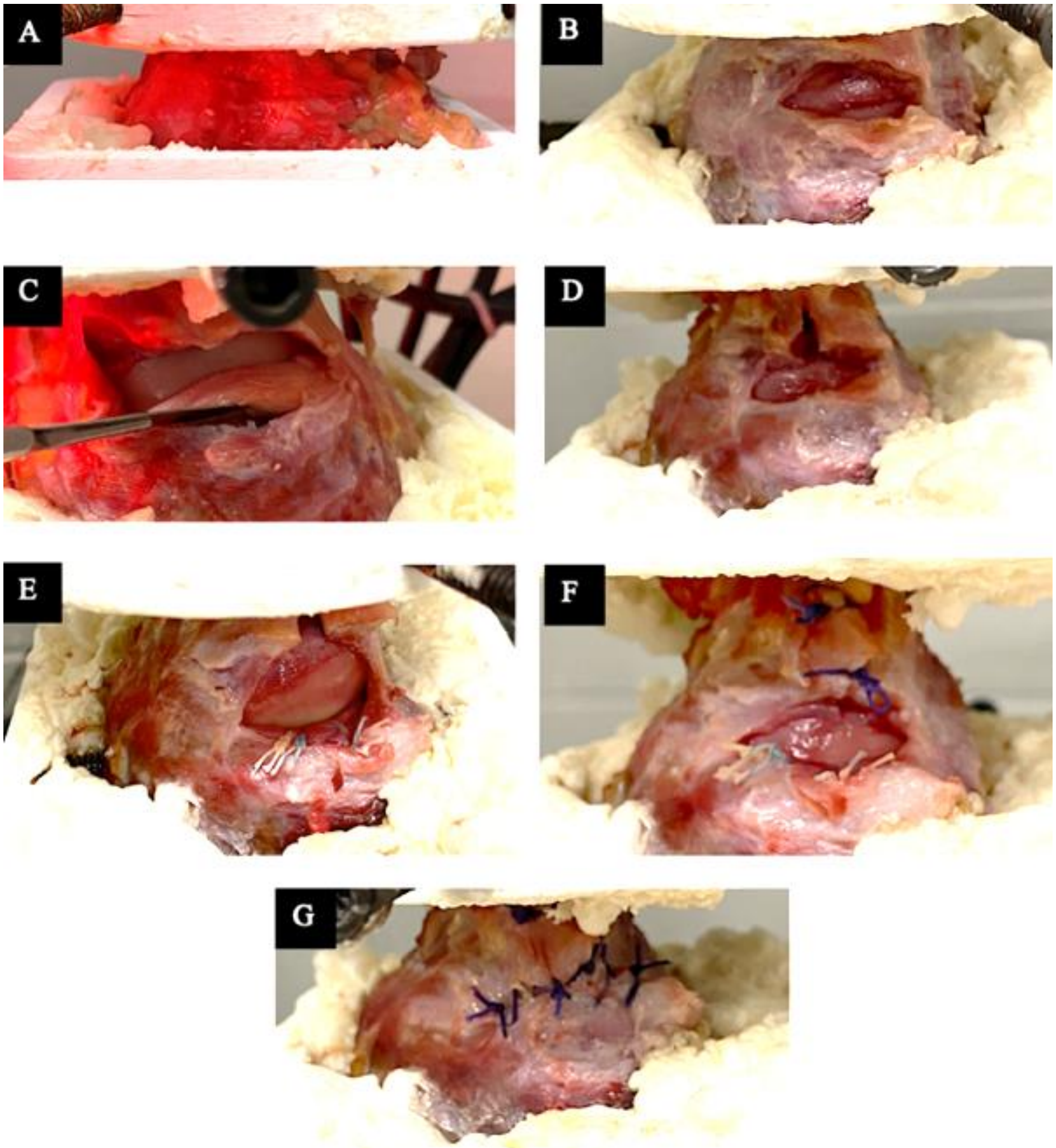


Figure 3-3. Soft Tissue Conditions Tested.

(A) intact capsule and labrum, (B) 2 or 4 cm IPC, (C) 2 or 4 cm IPC and labral tear, (D) 2 or 4 cm IPC, labral tear, T extension, (E) 2 or 4 cm IPC, labral repair, T extension, (F) 2 or 4 cm IPC, labral repair, T extension repair, (G) 2 or 4 cm IPC repair, labral repair, T extension repair.

3.2.4. Testing Conditions

All procedures were performed by an orthopaedic surgeon. Distraction testing was completed consecutively after each condition was prepared. After the intact condition was tested (1), a full-thickness incision was made in the anterior capsule to replicate an IPC (2A, 2B). The capsulotomy was located between the 12:00- and 3:00-o'clock positions on the acetabular clock face, a commonly described IPC location and preferred location of the senior author's IPC. [18] The IPC was 2 cm long in protocol A, and 4 cm long in protocol B. A full-thickness, 20 mm long labral tear was then made under direct visualization through the IPC from 12:30- to 2:30-o'clock on the acetabular clock face at the chondrolabral junction using a No. 11 blade (3A, 3B). This tear pattern is typically associated with FAI and is where most tears occur clinically.[5,23] A T extension was then made by making a perpendicular incision to the IPC along the femoral neck without damaging the zona orbicularis (4A, 4B). A labral repair was performed using loop labrum repair technique.[31] Two double-loaded 2.9 mm suture anchors (Osteoraptor, Smith and Nephew, Andover, MA) were placed 1 to 1.5 cm apart, adjacent to the subchondral bone of the acetabular rim without violating the articular surface. Two suture limbs from each anchor were passed through the labral tear and tied to each corresponding limb on the capsular side of the labrum to complete the repair (5A, 5B). The T extension was closed with two interrupted figure-of-eight, high-tensile strength sutures spaced evenly apart over the length of the T portion (6A, 6B). Finally, the IPC was closed with figure-of-eight, high-tensile strength sutures spaced evenly apart over its length (7A, 7B). In protocol A, two sutures were placed to repair the 2 cm IPC while in protocol B, 4 sutures were placed to repair 4 cm IPC.

3.2.5. Statistical Analysis

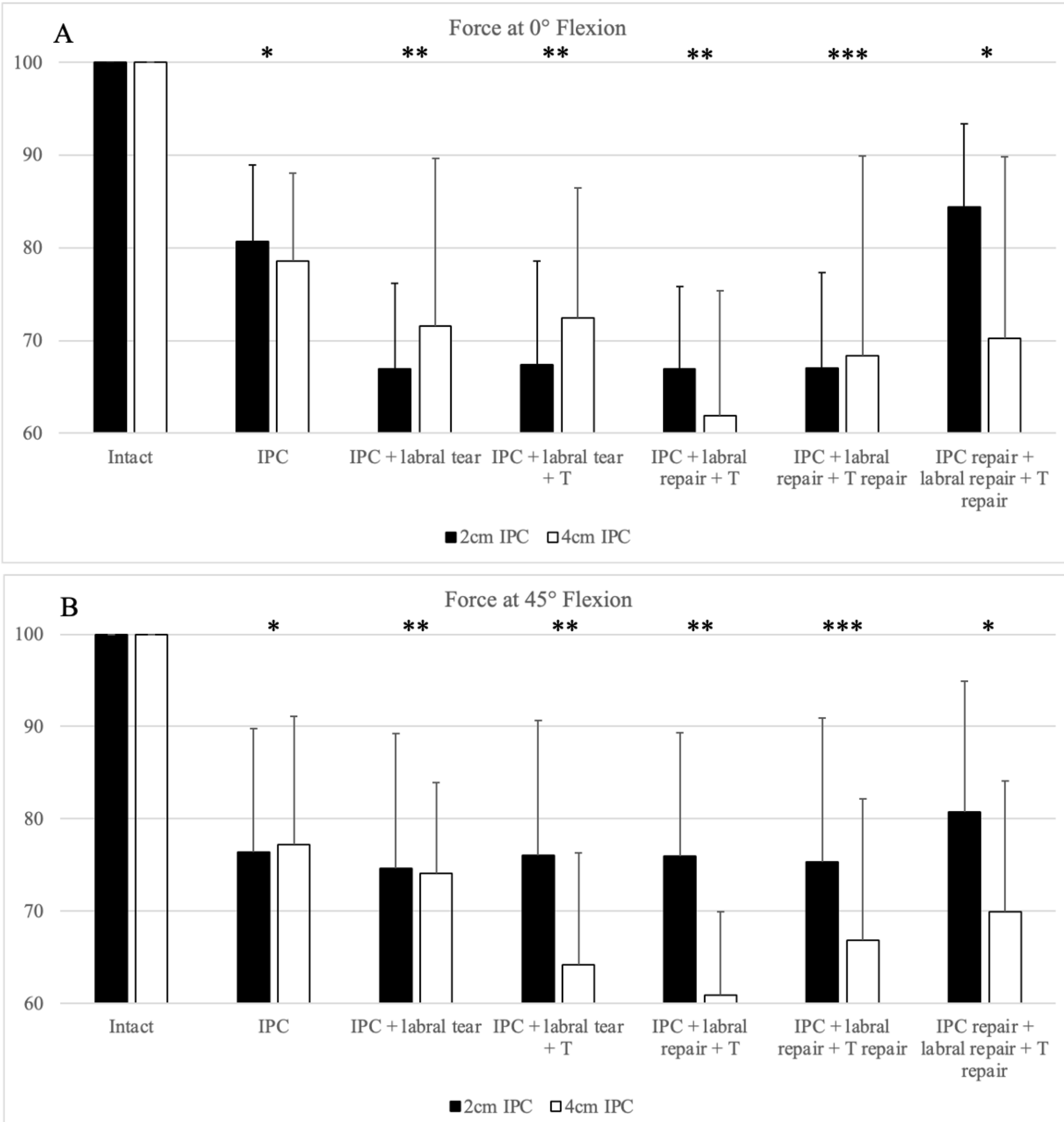
Statistical analysis was performed with computation software (IBM SPSS Statistics version 23, Chicago, IL, USA). A power analysis was conducted using a sample size calculator (G*Power, version 3.1; Universität Düsseldorf). Statistical power was considered a priori. Assuming a repeated measures, within-between interaction ANOVA design including one within-subjects factor with 21 levels, one between-subjects factor with 2 groups, ten specimens were sufficient to detect an effect size, $f = 0.25$ for the distraction force needed to disrupt the suction seal with 87% statistical power.

Cadaver demographics and hip morphology were recorded. A two-way mixed repeated measures model, adjusted for multiple comparisons with the Bonferroni correction, was completed to determine the effect of the soft tissue condition, hip position and length of IPC on the distraction force required to disrupt the suction seal. Significance was set at $P < 0.05$, and all data are presented as mean and standard deviation.

3.3. Results

3.3.1. Distractive Stability

Compared to the intact condition, the relative force required to disrupt the suction seal for each soft tissue condition is graphed for each hip position in figure 3-4 (Fig 3-4).


A
Force at 0° Flexion
100
90
80
70
60
*
**
**
**
***
*
Intact
IPC
IPC + labral tear
IPC + labral tear + T
IPC + labral repair + T
IPC + labral repair + T repair
IPC repair + labral repair + T repair
2cm IPC
4cm IPC
B
Force at 45° Flexion
100
90
80
70
60
*
**
**
**
***
*
Intact
IPC
IPC + labral tear
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IPC + labral repair + T
IPC + labral repair + T repair
IPC repair + labral repair + T repair
2cm IPC
4cm IPC

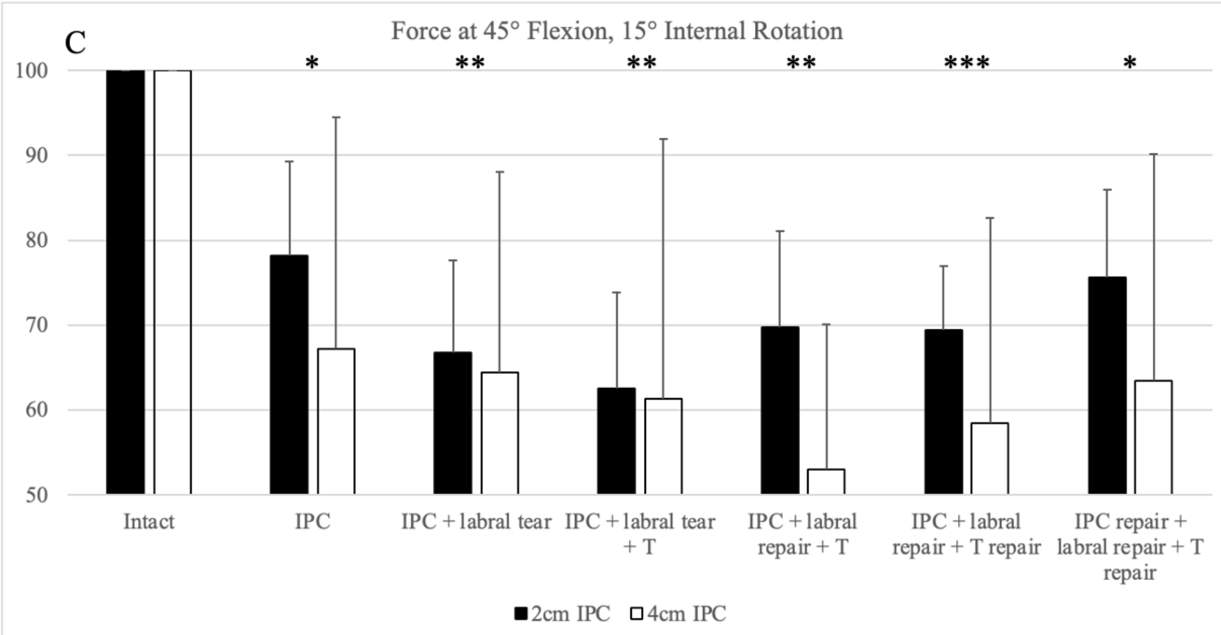
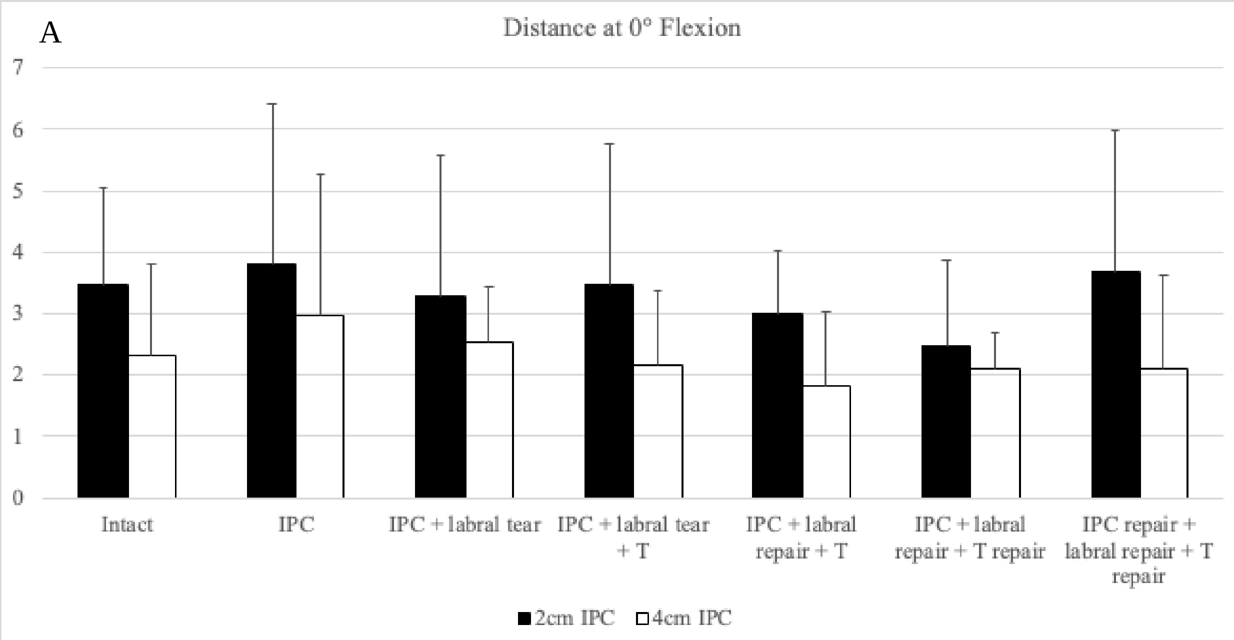


Figure 3-4. Distractive Force Required to Disrupt the Suction Seal

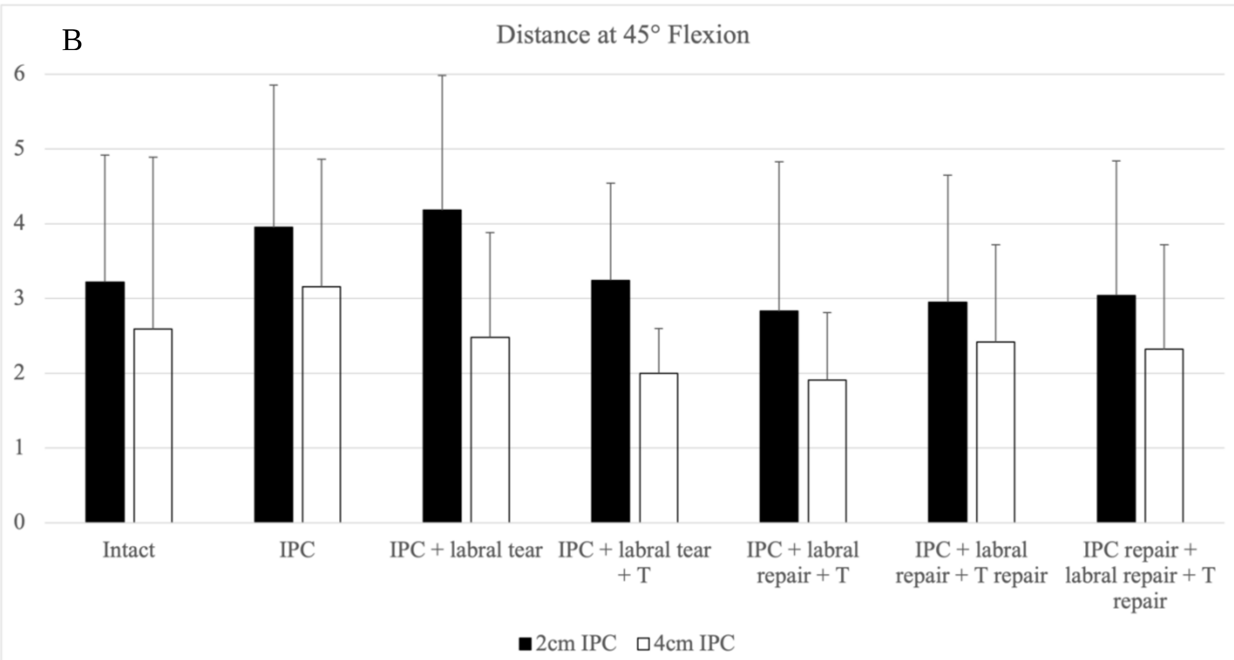
The distractive force required to rupture the suction seal at 0° (A), 45° flexion (B), and 45° flexion with 15° internal rotation (C). IPC, interportal capsulotomy; T, T extension; cm, centimeters; *, significant $P < .05$ compared to intact condition; **, significant $P < .01$ compared to intact condition and significant $P < .05$ compared to IPC condition; *** significant $P < .01$ compared to intact condition.

Less force was required to disrupt the suction seal after a capsulotomy and labral tear were made, with partial restoration after capsulotomy and labral repair. The distance at which the suction seal was disrupted for each condition is graphed in figure 3-5 (Fig 3-5)

A


Distance at 0° Flexion
7
6
5
4
3
2
1
0
Intact
IPC
IPC + labral tear
IPC + labral tear + T
IPC + labral repair + T
IPC + labral repair + T repair
IPC repair + labral repair + T repair
2cm IPC
4cm IPC

B


Distance at 45° Flexion
6
5
4
3
2
1
0
Intact
IPC
IPC + labral tear
IPC + labral tear + T
IPC + labral repair + T
IPC + labral repair + T repair
IPC repair + labral repair + T repair
2cm IPC
4cm IPC

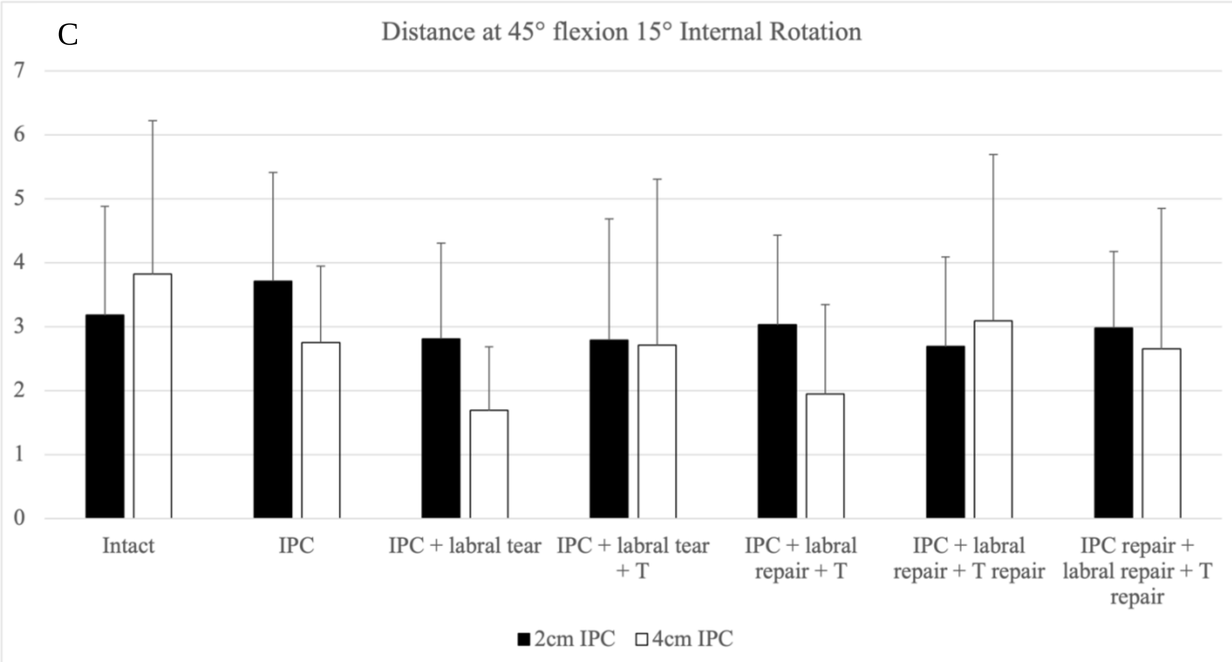


Figure 3-5. The Distractive Distance at Which the Suction Seal Ruptured

The distractive distance at which the suction seal ruptured at 0° (A), 45° flexion (B), and 45° flexion with 15° internal rotation (C). IPC, interportal capsulotomy; T, T extension; cm, centimeters.

The labrum appeared to play a larger role at neutral flexion compared to a flexed position. While a 4 cm IPC did not initially weaken the suction seal compared to a 2 cm IPC, it resulted in less restoration of distractive resistance after IPC repair, although this did not meet statistical significance. The distractive distance did not demonstrate a clear pattern between soft tissue condition or hip positions. There was no significant main effect of hip position, ($P = .159$) or length of IPC ($P = .465$). There was a significant main effect of soft tissue condition on hip distractive stability ($P = .001$). Fixed pairwise comparisons revealed a significantly higher distractive force required to rupture the suction seal in the intact condition compared to all other conditions. The IPC condition required significantly higher distractive force in isolation compared to when combined with a labral tear, T extension, or labral repair, as seen in Table 3-1.

	Intact	IPC	IPC, labral tear	IPC, labral tear, T	IPC, labral repair, T	IPC, labral repair, T repair	IPC repair, labral repair, T repair
Intact		MD: 23.6 ***p* = 0.012*** CI: 4.9, 42.4	MD: 30.3 ***p* = 0.002*** CI: 11.3, 49.4	MD: 32.7 ***p* = 0.001*** CI: 13.9, 51.5	MD: 35.3 ***p* < 0.001*** CI: 20.8, 49.7	MD: 32.3 ***p* = 0.002*** CI: 12.5, 52.4	MD: 25.9 ***p* = 0.01*** CI: 5.8, 46.1
IPC			MD: 6.6 ***p* = 0.014*** CI: 1.2, 12.0	MD: 9.0 ***p* = 0.005*** CI: 2.8, 15.3	MD: 11.6 ***p* = 0.002*** CI: 4.4, 18.8	MD: 2.25 *p* = 0.095 CI: -1.1, 18.6	MD: 2.3 *p* = 1.000 CI: -12.8, 17.4
IPC, labral tear				MD: 2.4 *p* = 1.000 CI: -2.6, 7.5	MD: 5.0 *p* = 0.41 CI: -2.5, 12.5	MD: 2.2 *p* = 1.000 CI: -8.6, 12.9	MD: -4.3 *p* = 1.000 CI: -19.7, 11.1
IPC, labral tear, T					MD: 2.6 *p* = 1.000 CI: -3.1, 8.3	MD: -0.3 *p* = 1.000 CI: -8.1, 7.6	MD: -6.7 *p* = 1.000 CI: -19.9, 6.4
IPC, labral repair, T						MD: -2.8 *p* = 1.000 CI: -10.2, 4.6	MD: -9.3 *p* = 0.117 CI: -20.2, 1.5
IPC, labral repair, T repair							MD: -6.5 *p* = 0.438 CI: -16.4, 3.4
IPC repair, labral repair, T repair							

Table 3-1: Soft Tissue Condition Pairwise Comparisons for Distractive Force.

IPC, Interportal capsulotomy; T, T-capsulotomy; MD, mean difference; CI, 95% confidence interval; *, significant.

3.4. Discussion

The main finding of this study was that the distractive stability of an intact hip capsule and labrum could not be completely restored once the soft tissues were violated, despite complete repair. Previous biomechanical studies assessed distractive hip stability after both a capsular repair and a labral repair in isolation. However, no biomechanical study has assessed the restoration of the hip suction seal after a simultaneous capsular and labral repair. Among studies that assessed hip stability after a capsular repair compared to an intact capsule, most used rotational ROM and resistance to distraction to report a complete restoration of normal stability after repair.[1,3,11,15,18,24,27,39–41] Philippon et al. [2017] was the only group to report incomplete reduction of the increased ROM after capsulotomy during hip arthroscopy.[32] Murata et al. [2022] interestingly showed an incomplete reestablishment of distractive stability after a simple capsular repair, which improved after a shoelace, double-shoelace or Quebec-city slider repair.[24] The inability to completely restore normal distractive stability after combined capsular and labral repair may help explain why post-operative restrictions after hip arthroscopy remain effective and important.[9]

Studies that assessed hip stability after a labral repair compared to an intact labrum used a variety of outcome metrics to report an inability to restore a normal seal after repair, including the distractive force and distance at which the suction seal ruptured, the contact pressure, force, and area between the femoral head and acetabulum, and the intra-articular fluid pressure and fluid transfer before and after labral repair.[5,19,34–36,38,43] Capurro et al. [2022] was the only group to show a complete restoration of contact force and area between the femoral head and acetabulum. However, this was after segmental labral reconstruction with synthetic polyurethane scaffold, and they did not compare this to a labral repair.[6]

Among studies that assessed hip stability after addressing both the capsule and labrum, only Myers et al. [2011] evaluated the restoration of rotational ROM after repair of the capsule and labrum.[25] They found a significant increase in external rotation after sectioning the IFL, and after sectioning both the IFL and labrum compared to an intact condition. However, they found no increase in external rotation after sectioning the labrum alone. They reported a reduction in ROM after repair of both the IFL and labrum, equivalent to the ROM of a hip with intact soft tissues.[25]

Other studies that considered both the capsule and labrum simultaneously only looked at a capsulotomy and labral tear setting compared to intact tissues, without evaluating repair of these structures.[7,14,17,20] These studies all found a decrease in stability in the capsulotomy and labral tear setting compared to intact structures.[7,14,17,20]

Although a 2 cm IPC may not completely transect the IFL, we found no difference in the distractive stability between a 2 cm and 4 cm IPC.[13] Khair et al. [2017] reported a decrease in distractive stability with increasing capsulotomy size, and complete restoration after capsular repair.[18] However, Wuerz et al. [2016] found no difference between rotational ROM after a 4 cm and 6 cm capsulotomy, with the hip in neutral flexion.[40] In our study, we found a slight decrease in distractive stability due to IPC length in hip flexion. The IFL limits external rotation in hip flexion, and it is possible that it contributes more to distractive stability when the hip is in a flexed position too.[28] We also found a decrease in distractive stability due to a labral tear in a neutral hip position, that was not replicated in hip flexion. This finding did not reach statistical significance but aligns with previous research that demonstrates greater labral fluid seal function in extension and external rotation, and decreased fluid seal function in flexion and internal rotation.[10] The capsular and labral contribution to the suction seal in different hip positions is an area that deserves further study.

3.4.1. Strengths

This study implemented a standardized, reproducible methodology with an a priori hypothesis. We adapted our protocol and outcome measures from previously published studies that also assessed the soft tissue effect on the hip suction seal.[11,18,26] We conducted a power analysis and were adequately powered to show a difference in our primary comparison. We also addressed multiple ongoing clinical controversies by assessing IPC size, simultaneous capsular and labral fixation, and repair techniques. Our results align with the concept that the capsulotomy size should be minimized, or avoided all together in cases where capsular stability is essential for hip stability, such as hip dysplasia.[2] If a capsulotomy is mandatory in these cases, then capsular plication may be best to restore hip stability, as our study shows incomplete restoration of distractive strength with a figure-of-eight suture technique. Our results also align with previous findings that a T extension does not further destabilize a hip[3,39] and that a labral repair may not improve hip stability compared to a labral tear setting.[34,36,38,43]

3.4.2. Limitations

This study has limitations common to all biomechanical cadaveric studies. The axial distraction used to measure the hip suction seal is unlikely to occur commonly in vivo and therefore only provides a quantifiable representation of hip stability. Cadaveric specimens have no healing potential, which likely strengthens both capsular and labral repairs resulting in improved long-term stability in vivo. This may have resulted in underestimation of the hip distractive stability after soft tissue repair. The average age of the cadavers in this study was 65 years and only 20% of hips exhibited FAI morphology, which is not representative of the demographic that most commonly undergoes hip arthroscopy. The labral pathology in this study was iatrogenic, and likely differs from in vivo labral tears seen in clinical patients. The capsulotomies, labral repairs and capsular repairs were completed in an open fashion, compared to arthroscopic fixation in a clinical setting. The figure-of-eight repair technique that we employed for our IPC and T extension repair may have contributed to an incomplete restoration of the suction seal after capsular repair.[24] Last, this study applied a non-randomized order of condition testing, which could theoretically confound the results due to tissue fatigue. However, this strategy was purposefully used to maximize the conditions compared without re-repairing any tissues, which in the opinion of the authors has a far greater effect on tissue strength compared to the number of trials completed.

3.4.3. Future Directions

Few studies have assessed the relative contributions of the capsule and labrum to the suction seal and hip stability.[25,26] Future research will assess how the repair strategy affects the relationship between the capsule and labrum; as well as the effect of combined capsular plication and labral repair. Additionally, the relative contributions of the capsule and labrum in different hip pathologies will be important as the technical considerations for hip arthroscopy in hip dysplasia and FAI continue to evolve. Finally, further research to ascertain how differences in biomechanical hip stability affects clinical function and patient reported outcomes after hip arthroscopy will be an important step to direct future management of the capsule and labrum in hip arthroscopy.

3.5. Conclusion

In the biomechanical cadaveric model, the distractive resistance of an intact hip capsule and labrum was not restored once the soft tissues were violated, despite complete repair.

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Chapter 4

4. The Shared Contributions of the Capsule, Labrum, and Bone to the Suction Seal of the Hip: Part II

Overview: *Previous studies have quantified the change in hip stability associated with a cam over-resection, labral repair, and labral reconstruction in isolation. The purpose of this chapter is to evaluate the change in hip distractive stability after a cam over-resection and labral repair, or labral reconstruction. The hypothesis was that a labral reconstruction would partially restore hip stability and that a 10-mm labral reconstruction would restore the distractive stability to a greater extent than a 6-mm labral reconstruction or a labral repair.*

4.1. Introduction

Hip arthroscopy has become the gold standard to treat femoroacetabular impingement (FAI).[10] In treating FAI, procedural elements include a capsulotomy, labral repair of any associated labral tear, cam and pincer osteochondroplasty, and capsular closure.[5,11,22] Several recent studies have highlighted the importance of performing an adequate femoral osteochondroplasty, resulting in improved survivorship and lower re-operation rates.[2,19]

The goal of femoral osteochondroplasty is to completely resect the abnormal cam and achieve femoral head sphericity.[5,9,11] The most documented reason for revision hip arthroscopy is under-resection of the cam lesion.[22] A greater emphasis on complete cam resection has likely contributed to an increased incidence of cam over-resection, a recently recognized surgical complication.[17,32] However, cam over-resection has been associated with worse clinical outcomes, revision hip arthroscopy and decreased biomechanical hip stability.[14,17] Current treatment options to improve patient function after cam over-resection are limited. Hip remplissage, filling of the over-resection defect, and a large labral reconstruction have both been suggested as treatment options, but there is little to no supportive data for either option.[1]

A labral reconstruction recreates a deficient labrum with autograft or allograft.[12] While there are good short term clinical outcomes after labral reconstruction, long term outcomes are lacking.[3,28] Similar to a labral repair, a labral reconstruction may partially restore the suction seal, but has not completely restored hip stability to that of an intact labrum in biomechanical models.[16] In the context of cam over-resection, it is theorized that a labral reconstruction with a larger graft than the native labrum may be able to restore the suction seal. However, there is no supportive evidence in this regard.

While the biomechanical consequences of cam over-resection, labral repair and labral reconstruction have been studied in isolation, no biomechanical study has assessed the effect of a labral repair or reconstruction after cam over-resection. The purpose of this study was to evaluate the change in hip distractive stability after a combined cam over-resection and labral repair, or labral reconstruction. We hypothesized that after a cam over-resection (1) a labral reconstruction would at least partially restore the suction seal and (2) a 10-mm labral reconstruction would restore the suction seal to a greater extent than a 6-mm labral reconstruction or a labral repair.

4.2. Methods

Specimens were acquired from an accredited tissue bank (Science Care, USA) for the purpose of medical research. Initially, fourteen fresh-frozen cadaveric hip specimens, seven matched pairs, were used for testing of the hip suction seal in Parts I and II of the current study. The first four hips were used to pilot the materials testing system, software, custom fixtures, and condition formation. Each specimen consisted of a pelvis and bilateral femurs. As described in Part I, specimens were imaged to exclude hips with acetabular dysplasia or advanced degeneration. (Part I, unpublished). Specimens were stored at -20°C and thawed at room temperature for 24 hours before testing. If soft tissue abnormalities such as a labral tear were encountered during testing, the specimen was excluded from our analysis. For a full description of specimen preparation, please see the Specimen Preparation Subsection of Part I (Part I, unpublished). Institutional ethics review board approval was obtained for the laboratory investigation of deidentified cadaveric specimens (HSREB #121404).

4.2.1. Demographics

Ten hip specimens from five cadavers, three females, were included in the final analysis. The average age was 65.4 years (standard deviation, SD: 7.4 years). No specimens had osteoarthritis or dysplasia (mean lateral centre-edge angle 35.6°, SD: 5.6°) one cadaver (two specimens) had evidence of femoroacetabular impingement (mean alpha angle 51.6°, SD: 10.9°).

4.2.2. Biomechanical Testing

After potting, the acetabular and femoral fixtures were mounted on a materials testing system (Instron ElectroPuls E10000, Norwood, MA, USA) using custom jigs that together with the materials testing system provided 6 degrees of freedom for hip positioning (Fig. 4-1). The same distraction protocol and hip positions were used for both Parts I and II (Part I, unpublished).[24]

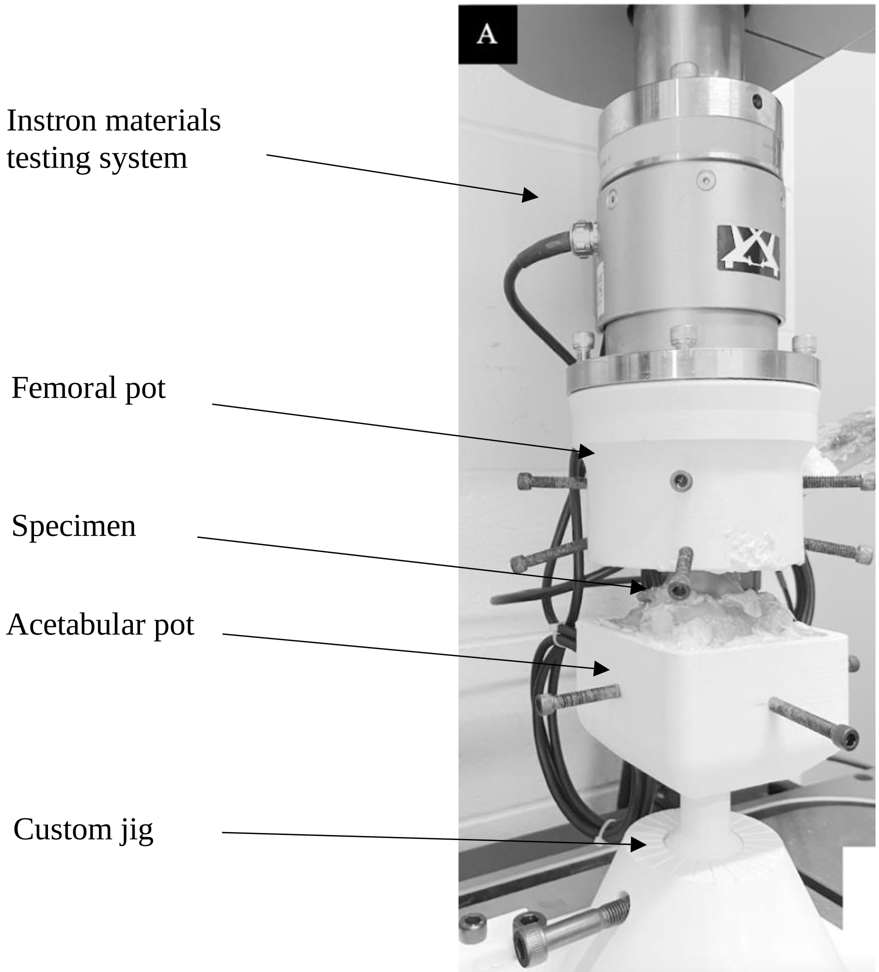

Figure 4-1. Testing Set-up

Materials Testing System with hip and pilot fixtures in-situ

All ten specimens underwent baseline testing with an intact capsule. Five hips, one hip from each matched pair, were randomized to protocol A while the other hip from each matched pair underwent protocol B using a web-based randomizer.[33] The neutral testing position was maintained from Part I, defined by positioning the femoral neck perpendicular to the acetabular concavity to maximize the congruence between the femoral head and the acetabulum (Part I, unpublished). Each specimen was tested at the neutral testing position, 45° of flexion, and at 45° of flexion and 15° internal rotation in random order for all 6 bony and soft tissue conditions, 5 of them surgical. The flexion and internal rotation angles were measured in the same method as Part I (Part I, unpublished). The conditions were (1) intact, (2) capsulectomy and pre-existing labral repair, (3) capsulectomy, 5-mm cam over-resection and labral repair, (4) capsulectomy, 5-mm cam over-resection and labral tear, (5) capsulectomy, 5-mm cam over-resection and labrectomy, and (6A, 6B) capsulectomy, 5-mm cam over-resection with 6- or 10-mm iliotibial band (ITB) labral reconstruction (Fig 4-2A-F). The difference between protocol A and B was the width of the labral reconstruction. In protocol A, the labral reconstruction was 6-mm and in protocol B the Labral reconstruction was 10-mm (Fig 4-3). Specimens underwent initial baseline testing with all structures intact and completed Part I protocol. After completion of Part I, the capsule was excised, and Part II of the protocol commenced.

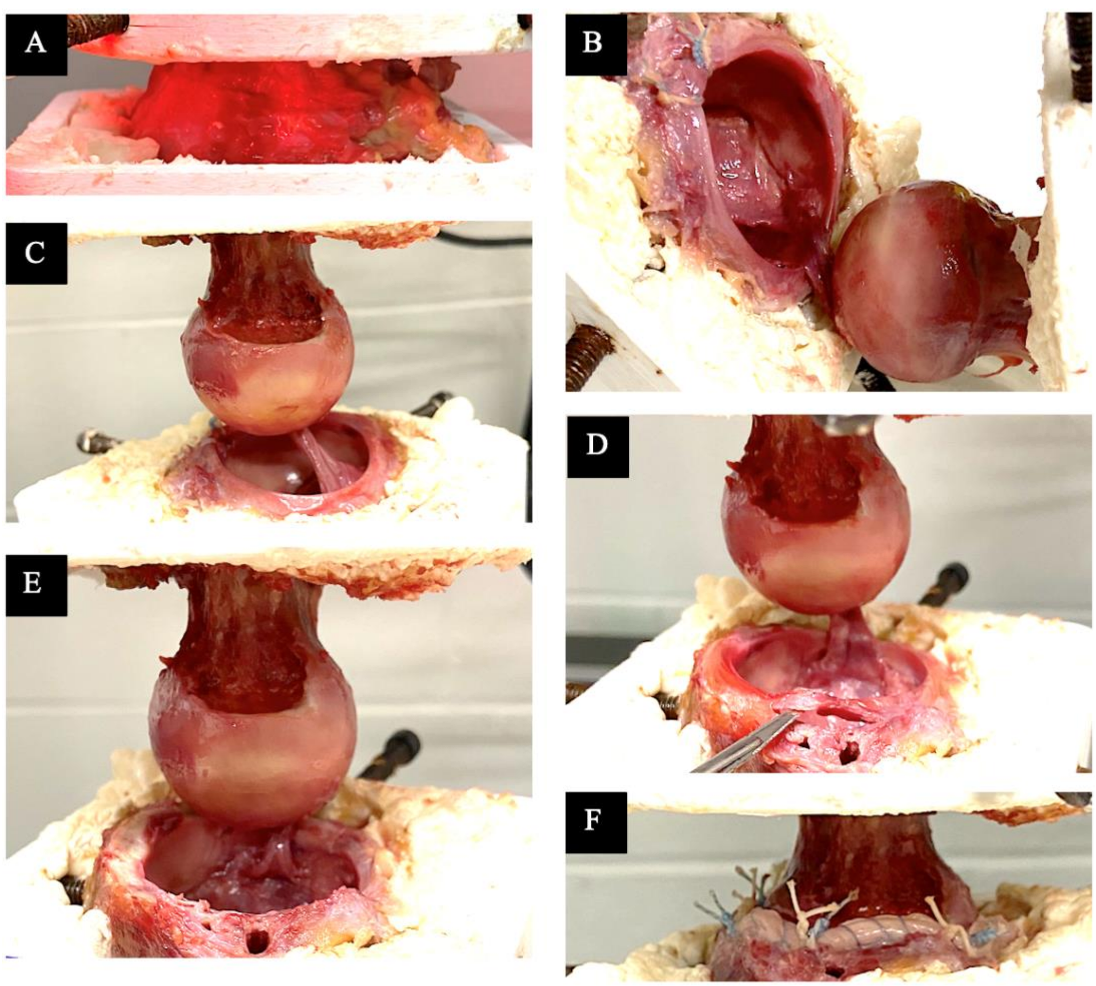

Figure 4-2. Soft Tissue Conditions Tested.

(A) intact capsule and labrum, (B) capsulectomy with pre-existing labral repair, (C) capsulectomy, 5-mm cam over-resection and labral repair, (D) capsulectomy, 5-mm cam over-resection and labral tear, (E) capsulectomy, 5-mm cam over-resection and labrectomy, and (F) capsulectomy, 5-mm cam over-resection with 6- or 10-mm ITB labral reconstruction.

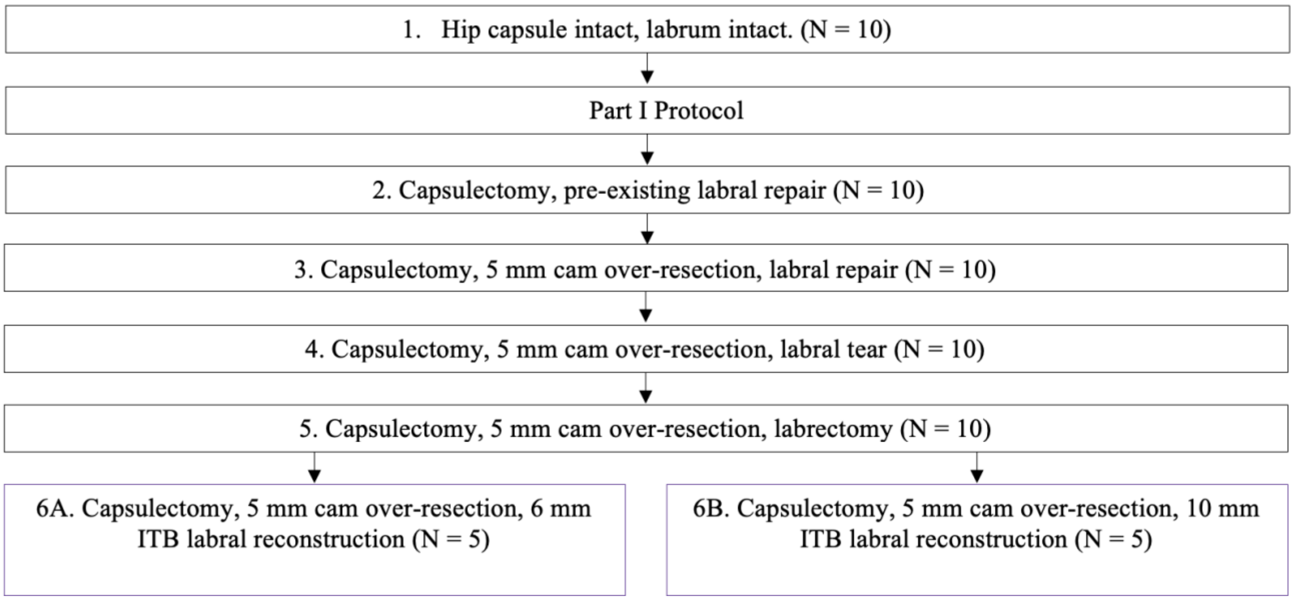

Figure 4-3. Part II Specimen Protocol.

Protocol A consisted of a 6-mm labral reconstruction (left column) and protocol B consisted of a 10-mm labral reconstruction (right column). N, number; mm, millimeters; ITB, iliotibial band.

Testing Conditions

All procedures were performed by a trained orthopaedic surgeon. Distraction testing was completed consecutively after each condition was prepared. After the intact condition was tested (1), the Part I protocol was completed (Part I, unpublished). The capsule was sharply excised leaving the repaired labrum and ligamentum teres intact (2). The femoral head physeal scar, a commonly used landmark for the proximal limit of a femoral osteochondroplasty, was identified and the osteochondroplasty was started at this level using a handheld motorized burr under direct visualization.[14] The resection was extended 5-mm proximal and 5-mm deep into the articular surface of the femoral head under direct visualization from 12:00-o'clock to 3:00-o'clock on the acetabular clock face (3). The sutures that were previously placed in the labrum were cut to create a cam over-resection combined with a labral tear (4). The entire labrum was sharply resected from its insertion on the acetabulum using the anterior and posterior ends of the transverse acetabular ligament (TAL) as anatomic landmarks for complete resection (5). A labral reconstruction with a width of 6- or 10-mm was completed using a front-to-back fixation technique adapted from Maldonado et al. [2022] with ITB, previously harvested from the cadaver specimen (6A, 6B).[15] The ITB was cut to a length of 100 mm, folded lengthwise into thirds and tubularized using No. 2-0 absorbable sutures in a running fashion (Vicryl; Ethicon, Somerville, NJ).[23] Pilot drill holes were made approximately 15-mm apart from anteromedial to posterolateral circumferentially around the acetabular rim (2.9-mm diameter drill, Osteoraptor suture anchor, Smith and Nephew, Andover, MA). Care was taken to place the drill holes as close to the rim as possible without violating the chondral surface. Additionally, drill holes were carefully placed immediately adjacent to the TAL both anteriorly and posteriorly. ITB graft fixation was completed from anterior to posterior using 5 double loaded 2.9-mm all-suture anchors in a simple looped fashion (2.9-mm Osteoraptor suture anchor, Smith and Nephew, Andover, MA).

4.2.3. Statistical Analysis

Statistical analysis was performed with computation software (IBM SPSS Statistics version 23, Chicago, IL). A power analysis was conducted using a sample size calculator (G*Power, version 3.1; Universität Düsseldorf). Statistical power was considered a priori. Assuming a repeated measures, within-between interaction ANOVA design including one within-subjects factor with 18 levels, one between-subjects factor with 2 groups, ten specimens were sufficient to detect an effect size, $f = 0.25$ for the distraction force needed to disrupt the suction seal with 83% statistical power.

Initially, A two-way mixed repeated measures model was planned to test for a difference in the distraction force required to disrupt the suction seal in the neutral hip testing position where the within-subjects factor was the hip structural condition, with six levels described in protocol A and B, and the dependent variable was the distraction force required to disrupt the suction seal. However, due to the non-normal distribution of the data, a Friedman test of differences among structural conditions and hip positions was conducted. Post hoc Wilcoxon Signed-Rank Tests were competed to compare the repeated measures structural conditions for each hip position. Mann-Whitney-U tests were completed to compare the 6- and 10-mm ITB labral reconstruction conditions.

4.3. Results

4.3.1. Distractive Stability

The median and interquartile range of the force and displacement for each structural condition at each hip position are detailed in Table 4-1. A Friedman test of differences among soft tissue and bony conditions and all hip positions was significant (P = .001). Post hoc Wilcoxon Signed-Ranks Tests were completed to compare the repeated measures soft tissue and bony conditions for each hip position. Mann-Whitney-U tests were completed to compare the 6-mm and 10-mm labral reconstruction conditions. For all hip positions, the resistive force that opposed the disruption of the suction seal was significantly greater for the intact condition compared to all other conditions. The resistive force for the capsulectomy, 5-mm cam over-resection, labrectomy condition was significantly less compared to all other conditions. (Tables 4-1, 4-2, 4-3). During testing, no qualitative suction seal was observed in any specimen after the labrum was excised. At 45° of flexion, the 10-mm labral reconstruction resistive force was significantly lower than the capsulectomy, 5-mm cam over-resection, labral repair condition, and the capsulectomy, 5-mm cam over-resection, labral tear condition (Table 4-2). At 45° of flexion and 15° of internal rotation, the resistive force for the capsulectomy, labral repair condition was significantly greater than the capsulectomy, 5-mm cam over-resection, labral repair condition, and the capsulectomy, 5-mm cam over-resection and labral tear condition (Table 4-3). There was no difference at any hip position in the distractive force between the 6- and 10-mm labral reconstruction conditions but the resistive force trended towards being significantly greater with the 10-mm graft. Interestingly, during testing a qualitative suction seal was achieved in 20% of hip specimens with a 6-mm labral reconstruction while a seal was in achieved 60% of specimens with a 10-mm labral reconstruction.

Outcome Measure	Position	Intact (N=10)	Caps, LR (N=10)	Caps, LR, cam (N=10)	Caps, LT, cam (N=10)	Caps, Labrect, cam (N=10)	Caps, Labrect, cam, 6-recon (N=5)	Caps, Labrect, cam, 10-recon (N=5)
Force (%) median, IQR	0° F	100, (100-100)[c]	59.1 (40.5-73.1)[ac]	51.2 (31.9, 55.4)[ac]	49.7 (45.6, 61.4)[ac]	0 (0, 0)[a]	0 (0, 28.2)[b]	44.1 (0, 65.5)[b]
	45° F	100, (100-100)[c]	53.2 (48.4, 74.5)[ac]	56.2 (38.5, 74.1)[acd]	52.3 (42.0, 72.3)[acd]	0 (0, 17.8)[ad]	0 (0, 54.4)[b]	42.4 (0, 66.3)[b]
	45° F, 15° IR	100, (100-100)[c]	56.2 (12.3, 72.2)[ac]	41.5 (0, 49.3)[ac]	44.2 (0, 55.9)[ace]	0 (0, 38.1)[ae]	34.3 (0, 46.8)[b]	38.5 (18.2, 54.7)[b]
Disp. (mm) median, IQR	0° F	2.6 (1.5, 4.7)	1.5 (1.1, 3.3)	1.5 (1.1, 4.3)	1.6 (0.6, 4.1)	0.8 (0.8, 0.8)	1.1 (1.1, 1.1)	0.6 (0.5, NA)
	45° F	2.2 (1.5, 4.8)	1.7 (0.9, 3.2)	2.5 (0.9, 4.3)	1.8 (0.8, 2.5)	0.6 (0.1, NR)	0.8 (0.4, NR)	0.6 (0.4, NR)
	45° F, 15° IR	2.9 (2.2, 4.9)	2.4 (0.9, 3.2)	3.3 (0.6, 9.1)	2.0 (0.7, 12.7)	6.8 (1.4, 9.4)	5.9 (1.1, NR)	7.1 (0.2, 8.6)

Table 4-1. Mean Distractive Force and Distance.

%, relative force compared to intact state; Caps, capsulectomy; LR, labral repair; cam, 5-mm cam over-resection; LT, labral tear; Labrect, labrectomy; 6-recon, 6-mm labral reconstruction; 10-recon, 10-mm labral reconstruction; N, number; IQR, interquartile range; F, flexion; IR, internal rotation; Disp, displacement; mm, millimeters; NR, no result; a, $P < .01$ significantly different compared to the intact condition; b, $P < .05$ significantly different compared to the intact condition; c, $P < .05$ significantly different compared to the labrectomy condition; d, $P < .05$ significantly different compared to Caps, LR condition; e, $P < .05$ significantly different compared to the 10-mm labral reconstruction condition.

Intact (N=10)	Intact (N=10)	Caps, LR (N=10)	Caps, LR, cam (N=10)	Caps, LT, cam (N=10)	Caps, Labrect, cam (N=10)	Caps, Labrect, cam, 6-recon (N=5)	Caps, Labrect, cam, 10-recon (N=5)
Intact		**0.005**	**0.005**	**0.005**	**0.002**	**0.034**	**0.042**
Caps, LR			0.173	0.139	**0.008**	0.144	0.138
Caps, LR, cam				0.515	**0.012**	0.144	0.686
Caps, LT, cam					**0.008**	0.273	0.225
Caps, Labrect, cam						0.317	0.109
Caps, Labrect, cam, 6-recon							0.196
Caps, Labrect, cam, 10-recon (N=5)							

Table 4-2. Structural Conditions at 0° Flexion Pairwise Wilcoxon and Mann-Whitney-U P-value Comparisons for Distractive Force.

N, number; Caps, capsulectomy; LR, labral repair; cam, 5-mm cam over-resection; LT, labral tear; Labrect, labrectomy; 6-recon, 6-mm labral reconstruction; 10-recon, 10-mm labral reconstruction; IR, internal rotation; mm, millimeters; **bold**, statistically significant.

Intact (N=10)	Intact (N=10)	Caps, LR (N=10)	Caps, LR, cam (N=10)	Caps, LT, cam (N=10)	Caps, Labrect, cam (N=10)	Caps, Labrect, cam, 6-recon (N=5)	Caps, Labrect, cam, 10-recon (N=5)
Intact		**0.005**	**0.005**	**0.005**	**0.004**	**0.042**	**0.043**
Caps, LR			**0.025**	**0.036**	**0.012**	0.465	0.08
Caps, LR, cam				0.499	**0.063**	0.715	0.144
Caps, LT, cam					**0.018**	1	0.068
Caps, Labrect, cam						0.285	0.273
Caps, Labrect, cam, 6-recon							0.459
Caps, Labrect, cam, 10-recon (N=5)							

Table 4-3. 45° Flexion Pairwise Wilcoxon and Mann-Whitney-U P-value Comparisons for Distractive Force.

N, number; Caps, capsulectomy; LR, labral repair; cam, 5-mm cam over-resection; LT, labral tear; Labrect, labrectomy; 6-recon, 6-mm labral reconstruction; 10-recon, 10-mm labral reconstruction; IR, internal rotation; mm, millimeters; **bold**, statistically significant.

Intact (N=10)	Intact (N=10)	Caps, LR (N=10)	Caps, LR, cam (N=10)	Caps, LT, cam (N=10)	Caps, Labrect, cam (N=10)	Caps, Labrect, cam, 6-recon (N=5)	Caps, Labrect, cam, 10-recon (N=5)
Intact		**0.005**	**0.005**	**0.005**	**0.004**	**0.039**	**0.042**
Caps, LR			0.314	0.953	**0.008**	0.068	0.08
Caps, LR, cam				0.374	**0.008**	0.273	**0.043**
Caps, LT, cam					**0.008**	0.273	**0.043**
Caps, Labrect, cam						0.18	0.109
Caps, Labrect, cam, 6-recon							0.577
Caps, Labrect, cam, 10-recon(N=5)							

Table 4-4. 45° Flexion, 15° Internal Rotation Pairwise Wilcoxon and Mann-Whitney-U P-value Comparisons for Distractive Force.

N, number; Caps, capsulectomy; LR, labral repair; cam, 5-mm cam over-resection; LT, labral tear; Labrect, labrectomy; 6-recon, 6-mm labral reconstruction; 10-recon, 10-mm labral reconstruction; IR, internal rotation; mm, millimeters; **bold**, statistically significant.

4.4. Discussion

The main finding of this study was that after a cam over-resection, hip distractive stability was improved following labral reconstruction, although neither reconstruction group was significantly different compared to labral repair. Comparing between reconstruction groups, a 10-mm wide ITB labral reconstruction graft trended towards an improved distractive stability compared to a 6-mm wide graft, but the difference did not reach statistical significance. This study objectively affirms that labral reconstruction is a viable treatment option for cam over-resection, supporting a commonly held belief among hip arthroscopy surgeons.

Cam over-resection has been identified as a challenging complication of hip arthroscopy to manage, associated with poor patient reported outcomes and a high conversion rate to total hip arthroplasty (THA).[17,32] There are few suggested treatment options to improve clinical outcome after cam over-resection. Revision hip arthroscopy to treat cam over-resection has worse outcomes and a lower patient acceptable symptomatic state compared to revision hip arthroscopy for a neutral cam resection or under resection.[17] A hip remplissage, filling of the cam over-resection defect with ITB allograft has been proposed, and Arner et al. [2021] reported promising results in a small case series of 13 patients who underwent remplissage after cam over-resection.[1] They found improved patient reported outcomes including the modified Harris Hip Score, Western Ontario and McMaster Universities Osteoarthritis Index and Hip Outcome Score in 12 out of 13 patients after hip remplissage with an average follow up of 3.1 years.[1] However, unlike in the shoulder, where a Hill Sachs lesion is filled with infraspinatus tendon and capsule, which converts an intra-articular defect into an extra-articular defect, the hip remplissage fills the cam over-resection with ITB allograft but does not change the relationship of the defect to the acetabular articulating surface.[6,31] Further, in the shoulder a remplissage contributes to a decrease in post-operative range of motion, which limits the shoulder to a stable arc of movement. The range of motion limitation after a shoulder remplissage also likely contributes considerably to improved shoulder stability.[8] For the hip remplissage, the presumed mechanism of action is to improve the suction seal, however this has also not been demonstrated biomechanically, and further follow-up is required to ensure tissue graft healing. Finally, in Arner's 2021 study, 7 of the 13 patients underwent concomitant labral reconstruction or augmentation, and 7 underwent concomitant capsular reconstruction in addition to the hip remplissage procedure.[1] One or both procedures may have also contributed to improved hip stability and clinical outcome after surgery, which could have confounded the results.

Biomechanical hip stability is affected by both the extent of the cam resection and labral status. Lazaro et al. [2021] found that a 5- and 10-mm proximal extension of a femoral osteochondroplasty past the physeal scar increased the femoral head displacement from the acetabulum under a constant distractive force.[14] A cam over-resection may decrease distractive stability through decreased contact area between the femoral head and acetabular labrum, in turn compromising the suction seal.[14,17] Interestingly, we found no significant difference in the distractive stability after a 5-mm cam over-resection and labral repair compared to a labral repair alone. Multiple studies have documented the inability of a labral repair to restore the normal distractive stability of the hip compared to an intact labrum in isolation.[24,27,30,33] However, no study has looked at the combined effect of cam resection and labral pathology together. A labral repair may already compromise the hip suction seal, so the addition of a cam over-resection may not significantly decrease the stability in this setting. A direct comparison of the hip distractive stability after a cam over-resection with an intact labrum compared to after labral repair is lacking and could be an area of future study.

Our study also showed that in the presence of a cam over-resection, a labrectomy results in complete elimination of the suction seal. Multiple biomechanical studies showed that a labral debridement is less stable than an intact labrum, labral repair, or labral reconstruction[15,20,24,33] Therefore, it is not surprising that in the presence of a cam over-resection, a labrectomy also worsens hip stability. However, this is the first study that examined the effect of a labrectomy in the presence of a cam resection and has reported this novel finding.

After a 5-mm cam over-resection, we found a trend towards improved distractive stability with a 10-mm wide ITB graft used for labral reconstruction compared to a 6-mm wide graft. Our findings align with previous biomechanical assessments of the contribution of labral width to hip stability. Storaci et al. [2020] compared the maximum distraction force, distance to suction seal rupture and peak negative pressure in 5 cadaveric hips with a labral height less than 6-mm and 7 hips with a labral heigh greater than 6-mm.[25] They found a significantly shorter distance to suction seal rupture and significantly lower peak negative pressure in hips with smaller labra.[25] Similarly, Maldonado et al. [2022] measured the force and displacement at which the suction seal ruptured with an intact labrum, after an ITB labral reconstruction with a graft less than 6.5-mm wide, and a graft greater than 6.5-mm wide. They found a similar required force to disrupt the suction seal after a wide labral reconstruction compared to intact labrum, but not after a narrow labral reconstruction.[15] Both studies concluded that a wider labrum improves the suction seal, consistent with the findings in our study.

4.4.1. Strengths

Like Part I of this study, Part II employed a standardized, reproducible methodology with an a priori hypothesis. The protocol and outcome measures were adapted from previously published studies that also assessed the hip suction seal.[7,13,20] A power analysis was conducted prior to the study and the statistical methods were modified based on the distribution of the data to satisfy the non-normal nature. We also introduced a novel management strategy for an ongoing iatrogenic clinical issue. We applied pre-existing evidence that a labral reconstruction improves hip stability by at least partially re-establishing the suction seal after a labral debridement and applied it to the new clinical context of a cam over-resection.[4,15,21,26,27]

4.4.2. Limitations

This study has limitations common to all biomechanical cadaveric studies. The axial distraction used to measure the hip suction seal is unlikely to occur commonly in vivo and therefore only provides a quantifiable representation of hip stability. Cadaveric specimens have no healing potential, which likely strengthens labral repairs and may partially fill in a cam over-resection with bone and fibrocartilage resulting in improved long-term stability in vivo. This may have resulted in an underestimation of the hip distractive stability in the labral repair, cam over-resection and labral reconstruction conditions. The average age of the cadavers in this study was 65 years and only 20% of hips exhibited FAI morphology, which is not representative of the demographic that most commonly undergoes hip arthroscopy. The labral pathology in this study was iatrogenic, and likely differs from in vivo labral tears seen in clinical patients. The cam over-resection and labral reconstructions were completed in an open fashion, compared to arthroscopic fixation in a clinical setting. Last, this study applied a non-randomized order of condition testing, which could theoretically confound the results due to tissue fatigue. However, this strategy was purposefully used to maximize the conditions compared without re-repairing any tissues, which in the opinion of the authors has a far greater effect on tissue strength compared to the number of trials completed.

4.4.3. Future directions

This is the first study to assess the change in hip stability associated with a labral reconstruction after a cam over-resection. Future research may include a similar assessment of the suction seal after a cam over-resection with an intact labrum condition, to compare how a labral reconstruction changes hip stability against the gold standard. An assessment of a labral reconstruction in the presence of a larger cam over-resection may also provide information on how much contact the labrum must have with the articular surface to recreate the suction seal. Finally, a subject that deserves further investigation is the effect of the cam resection shape on the suction seal. The native femoral head is not a perfect sphere, but rather a conchoid.[18] The pursuit of femoral head sphericity does not recreate an anatomic scenario and may introduce microinstability. Further study of the effect of cam resection shape on hip stability is warranted.

4.5. Conclusion

After a cam over-resection, a labral reconstruction improves the distractive stability of the hip, comparable to a labral repair or debridement, making it a viable treatment option for patients with ongoing symptoms after hip arthroscopy for FAI with evidence of an osseous over-resection.

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Chapter 5

5. General Discussion and Conclusions

Hip stability has multiple constituents, and maximizing clinical stability and hip function continues to pose a challenging problem. Multiple biomechanical cadaveric studies have identified the capsule, labrum and congruence between the femoral head and acetabulum as important contributing factors.[1–3] However, the complex interplay between them, and the optimal management for recently described clinical scenarios such as cam over-resection still lack clarity.[4,5] The goals of this thesis were to gain a better understanding of the relative contributions of the capsule, labrum and bone to the hip suction seal, and identify possible treatments for cam over-resection..

Specific objectives were established to achieve the goals of this thesis. Chapters 2 through 4 discuss the completion of these objectives. Our conclusions will be briefly summarized and contextualized in the treatment of FAI and hip microinstability. To review, the objectives were: (1) to assess the current understanding in the literature of the relative contributions of the capsule, labrum and bone to the hip suction seal, (2) to measure the simultaneous contribution of the capsule and labrum in normal and abnormal states to the suction seal, and (3) to assess the effect of a labral repair compared to a labral reconstruction with different graft width after a cam over-resection.

Our corresponding hypotheses were: (1) A capsular repair or reconstruction would improve stability compared to a capsulotomy or capsulectomy respectively. A labral repair or reconstruction would improve stability compared to a labral tear. A femoral cam and acetabular rim resection improve stability compared to the abnormal bone morphology in FAI syndrome. (2) A complete capsular repair and labral repair would restore the hip distractive stability to that of an intact capsule and labrum. (3) After a cam over-resection, a labral reconstruction partially restores hip stability and a 10-mm labral reconstruction restores the distractive stability to a greater extent than a 6-mm labral reconstruction or a labral repair.

5.1. Systematic Review and Meta-analysis (Chapter 2)

This study evaluated the current understanding in the literature of the relative contributions of the capsule, labrum, and bone to the hip suction seal. The hypothesis that a capsular repair or reconstruction would improve stability compared to a capsulotomy or capsulectomy respectively was strongly supported in a quantitative analysis of six biomechanical studies with a standardized effect size of 1.13.[6–11] The hypothesis that a labral repair or reconstruction improves stability compared to a labral tear was not supported in a quantitative analysis of six biomechanical studies with a standardized effect size of -0.67.[12–17] No quantitative analysis was completed to assess the hypothesis that a femoral cam and acetabular rim resection improves stability compared to the abnormal bone morphology in FAI syndrome secondary to large heterogeneity between studies.

Perhaps the most important finding of this study was that a labral repair or reconstruction did not improve hip stability compared to a labral tear. A secondary quantitative analysis compared the hip stability after a labral repair or reconstruction to a labral debridement and found clear superiority of a labral repair or reconstruction, with a standardized effect size of 1.74.[12–14,17] The repair of labral tears has been widely adopted secondary to improved patient reported outcomes and 10-year conversion to THA compared to labral debridement.[18] However, no clinical study has ever assessed patient outcomes after a labral repair compared to not repairing a labral tear. There are ethical barriers to performing a randomized controlled trial comparing repair to no repair for a labral tear as multiple studies have documented clinical improvement after labral repair.[19–21] Further, the anterior-superior labrum is densely innervated by nociceptors and mechanoreceptors, which provides a physiological rationale for labral tears being painful.[22] Nonetheless, citing the biomechanical equivalence of a labral tear and repair, a randomized controlled trial comparing the two labral states would provide valuable information to the orthopaedic surgeon.

5.2. Part I (Chapter 3)

After reporting the current understanding of the hip capsule, labrum, and bone contributions to the suction seal, Part I furthered our understanding by testing multiple capsular and labral conditions simultaneously to better understand the relative contribution of each. The hypothesis that a complete capsular repair and labral repair restores hip distractive stability to that of an intact capsule and labrum was refuted in this study. This finding while initially surprising, is supported by previous literature that has found an incomplete restoration of the suction seal after a labral repair in isolation. [12–17] A capsular repair completely restores the distractive stability of a hip in isolation,[7,9,23,24] but there is no reason to suggest it would also restore the distractive stability lost after a labral repair. This study also supports the suction seal-dominant function of the labrum, compared to dual distractive and rotational stability functions of the capsule. Myers et al. [2011] showed no difference in rotational stability after labrum sectioning alone, but complete restoration of rotational stability after capsular repair and labral repair simultaneously.[4] Our study shows a clear loss of distractive stability after a labral tear or repair, compared to an intact labrum, and similarly an incomplete restoration of the suction seal after simultaneous capsular repair and labral repair.

Previous reports suggest capsular plication results in increased capsular strength and decreased volume to supra-physiologic levels.[6,25] To ameliorate the loss of distractive stability associated with a labral repair, perhaps capsular plication should be included in cases of hip labral repair. The assessment of the suction seal after simultaneous labral repair and capsular plication is an area that deserves future study. The clinical implications of routine capsular plication are also unknown, although short to midterm outcomes after plication in patients with borderline hip dysplasia are promising.[26,27]

5.3. Part II (Chapter 4)

The objective of this final study was to apply an established hip arthroscopic technique to a new clinical indication that has been understudied and lacks a reliable solution. The hypothesis that a labral reconstruction partially restores hip stability after a cam over-resection was supported by our study. In the presence of a 5-mm cam over-resection, we showed no difference in the distractive stability after a labral repair compared to a labral reconstruction. Further, both a labral repair and labral reconstruction required significantly more distractive force to rupture the suction seal compared to a labrectomy condition. Second, the hypothesis that a 10-mm labral reconstruction restores the distractive stability to a greater extent than a 6-mm labral reconstruction or a labral repair was not statistically supported by our study. However, our data trended towards improved distractive stability after a 10-mm labral reconstruction compared to a 6-mm graft width. It is possible that with a larger sample size statistical significance may have been met. However, we performed a preliminary power analysis and were initially powered to show a difference with the sample size chosen. The decision to deviate from our initially chosen statistical analysis was appropriate in the context of a non-parametric data distribution. A larger secondary study including an intact labral condition to provide a direct comparison of an intact labrum and labral reconstruction deserves consideration.

This study affirms the ability of a labral reconstruction to partially restore hip stability after a cam over-resection. Few treatments have been described for iatrogenic cam over-resection. A labral reconstruction has been used in a clinical scenario in combination with other procedures to treat cam over-resection, but prior to this biomechanical study, none has tested the efficacy of a labral reconstruction in restoring the suction seal.[5] This study provides the biomechanical basis to assess the clinical efficacy of an isolated labral reconstruction to treat iatrogenic cam over-resection.

5.4. Cadaveric Testing

The limitations of cadaveric testing were discussed in their respective sections of both parts I and II. Such limitations include the results representing time-zero biomechanics, the average specimen age being over 65 years old, and only 20% of the specimens presenting with FAI initially. However, cadaveric testing also provides advantages compared to other biomechanical models. The main advantage is the replication of accurate human anatomy and tissue function, creating an environment that closely resembles an *in vivo* scenario.[28]

Cadaveric testing is an important platform to conduct orthopaedic research. While clinical conclusions cannot be made based on cadaveric studies, it provides the biomechanical rationalization for anatomic function and orthopaedic intervention. Further, it provides an opportunity to introduce novel techniques to treat clinical problems that lack definitive solutions. Biomechanical cadaveric studies should aim to generate hypotheses for clinical trials. This thesis has initially established a thorough understanding of the current literature landscape and used that information to produce *in vitro* results that can be used to test hypotheses *in vivo*.

5.5. Conclusion

Results from this work will contribute to the understanding and management of FAI and hip arthroscopy. The inability for a simultaneous capsular and labral repair to restore a normal suction seal should trigger further study to assess alternative methods to restore a normal suction seal through hip arthroscopy. A labral reconstruction may be an appropriate treatment for iatrogenic cam over-resection.

These results represent *in vitro* kinematics. Further study may complement the current biomechanical understanding with additional *in vitro* assessments or focus on the hypotheses formulated through though these studies with *in vivo* clinical trials.

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