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In Vitro Analyses of the Contributions of the Hip Capsule to Joint Biomechanics

Emma Donnelly, *The University of Western Ontario*

Supervisor: Willing, Ryan, *The University of Western Ontario*
Co-Supervisor: Degen, Ryan, *The University of Western Ontario*
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Abstract

Optimal management of the hip capsule during arthroscopic surgery has not been established. The impact of incisions made to the capsule during minimally invasive procedures on joint biomechanics, and whether repair provides any benefit, continue to be debated. The effectiveness of capsular repair to restore native kinematics may be insufficient. Therefore, a better understanding of joint behavior during various capsule conditions is needed.

A new robotic system was used to analyze the effect of progressive capsulotomy incision and repairs on the behavior of a normal hip within range of motion (ROM) limits with respect to the intact joint. Complete repairs increased the torque at end ROM across all tested joint positions compared to their unrepaired counterparts, though equivalent restraint to the intact joint was not always restored. Although repairs did not restore native joint kinematics, total displacement was increased with an interportal or T-capsulotomy, with and without repair.

Keywords

Hip, Capsule, Capsular Ligaments, Arthroscopy, Stability, Laxity, Biomechanics, Kinematics

Summary for Lay Audience

The hip joint is surrounded by a collection of ligaments that make up the capsule: the iliofemoral, ischiofemoral and pubofemoral ligaments. During minimally invasive hip surgery (arthroscopy), the capsule is invasively incised. Advances in the sophistication of surgical instrumentation and training have improved capabilities for arthroscopy, expanding the frequency with which they are performed. Despite this, optimal management of capsular tissues has not yet been established.

Currently, the choice of capsular incision pattern may largely be dictated by the access and visibility required to treat a given pathology. However, the decision on whether to repair capsular incisions is primarily reliant on physician preference. This decision may affect translations of the femur (thigh bone) within the joint socket, and overall joint biomechanics. In recent literature, investigations of the role of the individual capsular ligaments and their contribution to joint laxity (flexibility) have suggested that they each provide stability in different directions. However, changes in joint behavior or the role of the capsule as a whole after arthroscopic incisions have not been sufficiently explored.

In this study, a new joint motion simulator was used to observe the effect of successive capsulotomy incisions and subsequent repairs on hip joint kinematics. Compared to an intact (healthy) capsule, it was found that resistance to rotational laxity was reduced following capsulotomy, most significantly during external rotation (femur rotating from body's midline towards the outside within the joint socket). Resistance was increased with repair but did not fully restore that of the intact joint.

Varying the capsulotomy approach had less of an effect on translation of the femoral head than it did on capsule laxity. Though it was observed that the femur tended to favor a position towards the back of the joint socket compared to intact after undergoing a capsulotomy, the differences were very small. This suggests that repairing a capsulotomy is less important to ensure hip stability than previously thought.

Co-Authorship Statement

This thesis was written by Emma Donnelly.

Dr. Ryan Willing and Dr. Ryan Degen modified or provided comment on all presented chapters.

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Chapter 1

1 Introduction

1.1 Motivation

Advances in the sophistication of surgical tools has increased the volume of both eligible patients and potential indications for arthroscopic hip surgery. Regardless of the pathology being treated, all soft tissue layers that protect and provide joint stability must be penetrated for required access to the joint cavity – the last of these is a collection of ligaments called the capsule. Despite the increasing favor of arthroscopies over open procedures, optimal capsular management strategies have not been established within the field.

Currently, the choice of incision pattern for a performed arthroscopy will be dependent on the logistics of the pathology being treated (i.e. location and required visibility or access), whereas the choice on whether or not to repair the incision(s) will be largely based on the physician's preference and ability [1–3] .

While existing literature primarily explores rotational limits and how these change after surgery, it is unclear what the implications of arthroscopic intervention are on other biomechanical variables that relate to joint stability. The most significant findings where adverse kinematics are observed often occur at the extremes of motion. While the joint may be most susceptible to abnormal behavior potentially leading to damage at the ends of its range of motion, such as dislocation or tissue strain, much of the movements required for normal activity for the general population occur well within the bounds of the hip's range of motion limits. It is therefore paramount to understand the joint's behavior as it moves within its established limits, in addition to vulnerable positions.

The studies presented in the text to follow were designed to present biomechanical information for surgeons to add to their knowledge when selecting surgical approach and repair strategy for the capsule for any given case.

1.2 Objective

This study aims to adapt a robotic six-degrees-of-freedom joint motion simulator, designed for wear testing of orthopaedic implants, for cadaveric hip experiments and to investigate the effects of various surgical capsulotomy and repair states to hip joint biomechanics. As such, the objectives of this study are to:

1. Establish rotational range of motion limits of the intact joint in response to consistent applied torques using a novel system

2. Investigate how various capsulotomy and repair states affect tissue laxity as it applies to the joint's biomechanics

3. Investigate the displacement pattern of the femoral head through rotational range of motion

Chapter 2

This chapter introduces gross anatomy of the hip joint, and a closer look at the anatomy and physiology of relevant tissues to provide context and familiarize the reader with terminologies used throughout this text. This is followed by an understanding of current approaches to hip arthroscopy and measures under which they might need to be employed. Finally, a review of previous scientific studies that have investigated biomechanics relating to the hip capsule are presented.

2 Background

Anatomical terminology will be used throughout the text to describe hip joint motion and direction. Anatomical planes (Figure 2-1) and axes provide reference for the description of these movements and positioning.

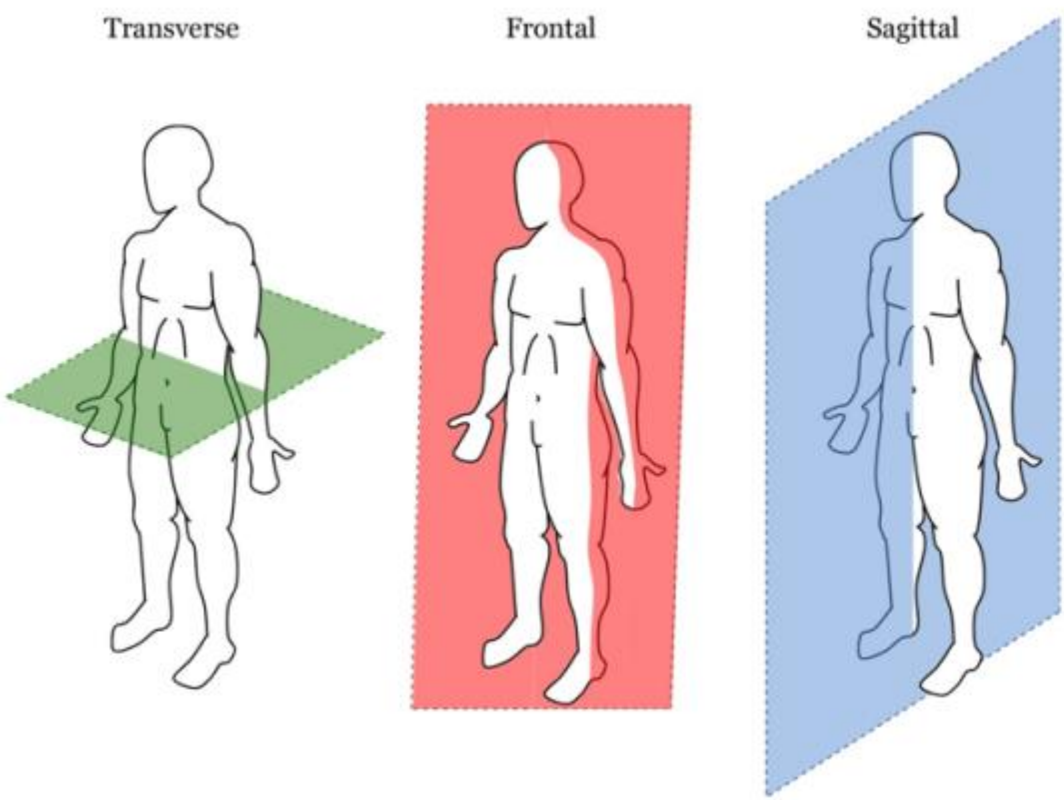


Figure 2-1: Planes used to define anatomical motions

Joint rotation (**Figure 2-1)**, described with respect to the standard anatomical position, may occur in one of three anatomical planes:

- Flexion and extension occur in the **sagittal plane**. Hip flexion is the action of decreasing the angle between the femur and pelvis in this plane. Hip extension increases this angle.

- Adduction and abduction occur in the **frontal** (**coronal) plane**. Hip adduction is the action of decreasing the angle between the femur and pelvis in this plane. Hip abduction increases this angle. Adduction/ adduction (AA) movements or forces are often grouped.

- Internal and external rotation occur in the **transverse (axial) plane**, about the long axis of the femur. Internal rotation of the hip is the action of rotating the femur toward the centre of the body in this plane. External rotation rotates the femur away from the centre of the body. Internal/ external (IE) movements or forces are often grouped.

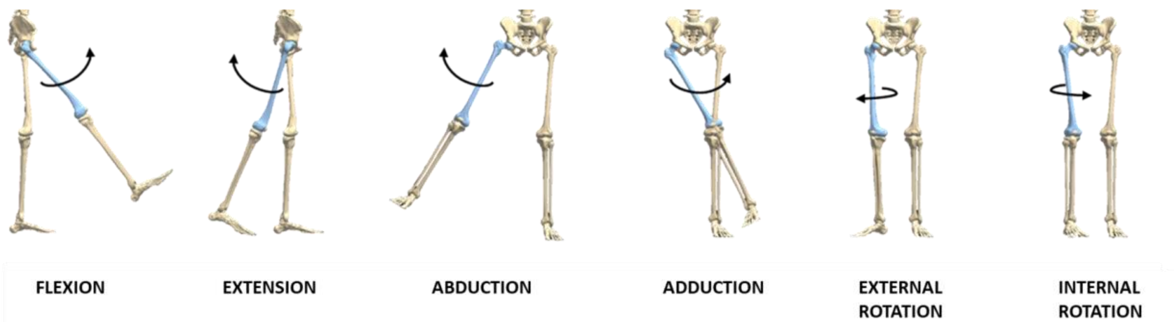


Figure 2-2: Depiction of anatomical rotations of the hip

Additional common terms used to describe direction (Figure 2-3) can also be described with respect to anatomical planes.

- Anterior-posterior: towards the front-back of the body respectively - in the axial plane
- Superior-inferior: describe a position that is respectively above or below – in the coronal or sagittal plane.
- Medial-lateral: describe a position that is respectively, towards or away from the midline of the body – in the coronal plane.

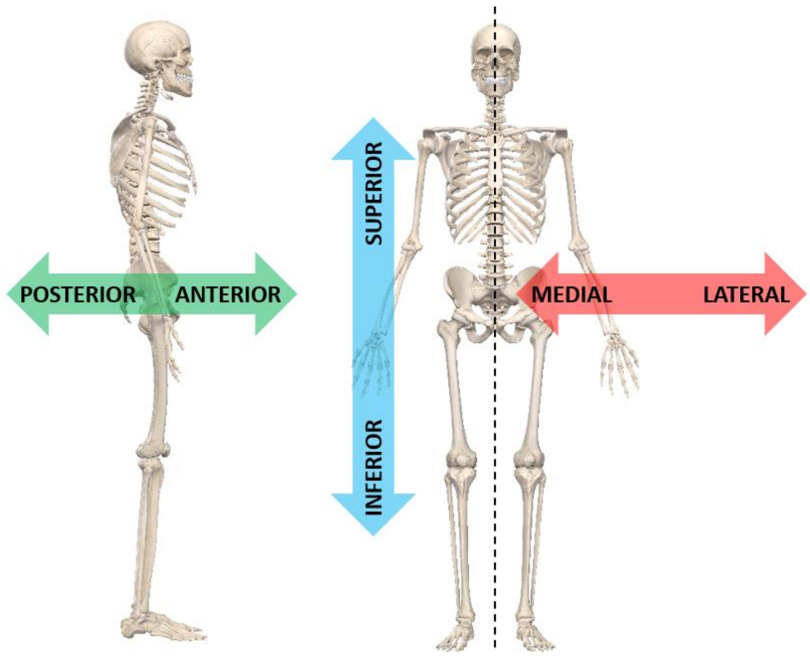


Figure 2-3: Anatomical terms to describe direction

Proximal/ distal and superficial/ deep are terms used to describe relative anatomic position. Proximal describes a position closer to the torso, and distal specifies a relative position closer to an extremity. Superficial describes a position closer to the surface of the body, whereas deep indicates a position further internal.

2.1 Hip anatomy

Bony Anatomy

The hip anatomy presented in the following paragraphs are the bony structures, structures contained within the joint, and hip ligaments. All tissues and structures that are superficial to the hip ligaments are *extracapsular* and removed prior to testing, thereby making them inconsequential in the context of this research.

The hip is the human body's largest weight bearing joint. During gait, it is estimated the hip supports the equivalent of 3 times a person's body with every step [4–6]. The hip is described as a diarthrodial ball and socket joint formed by two osseous bodies. The head of the femur fits inside a concave cavity of the pelvis called the acetabulum, respectively making up the ball and socket components. A ball and socket joint allows for three rotational degrees of freedom (DOF): flexion-extension, internal-external rotation, and abduction-adduction, with the ability to perform combined movements by rotating in multiple DOFs at once.

Articular Soft Tissues

The ability of the joint to successfully carry the required body loads depends greatly on its stability. There are four supporting soft tissue structures that each play their role in maintaining joint stability [3,7–10]. Three of these structures – the ligamentum teres, labrum, and zona orbicularis – are contained within the joint. The ligamentum teres attaches the head of the femur to the inferior acetabular rim. The labrum is attached to the outer rim of the acetabulum, effectively increasing the depth of the socket resulting in greater femoral head coverage. The circular fibers of the zona orbicularis for a collar around the neck of the femur.

Superficial to all is the final stabilizing structure; an entity called the capsule. It is comprised of the iliofemoral, pubofemoral, and ischiofemoral ligaments. Their longitudinal fibers are nearly indistinguishable from one another in such a way that they form a single structure that completely encompasses the ball and socket joint of the hip as well as the deep stabilizing structures. The capsule attaches inferiorly around the neck of the femur and superiorly to the perimeter of the acetabulum. The ischiofemoral ligament originates from the posterior surface of the acetabular rim and wraps around the lateral side of the joint to insert on the anterior aspect of the femur (Figure 2-4b). It is the sole capsular structure that provides posterior coverage of the joint. The iliofemoral ligament originates from the anterior inferior iliac spine and fans in a y-shape to attached along the intertrochanteric line of the femur (Figure 2-4a). The pubofemoral ligament provides anterior joint coverage, originating from the anterior aspect of the pubic ramus to attach to the anterior surface of the intertrochanteric fossa (Figure 2-4a).

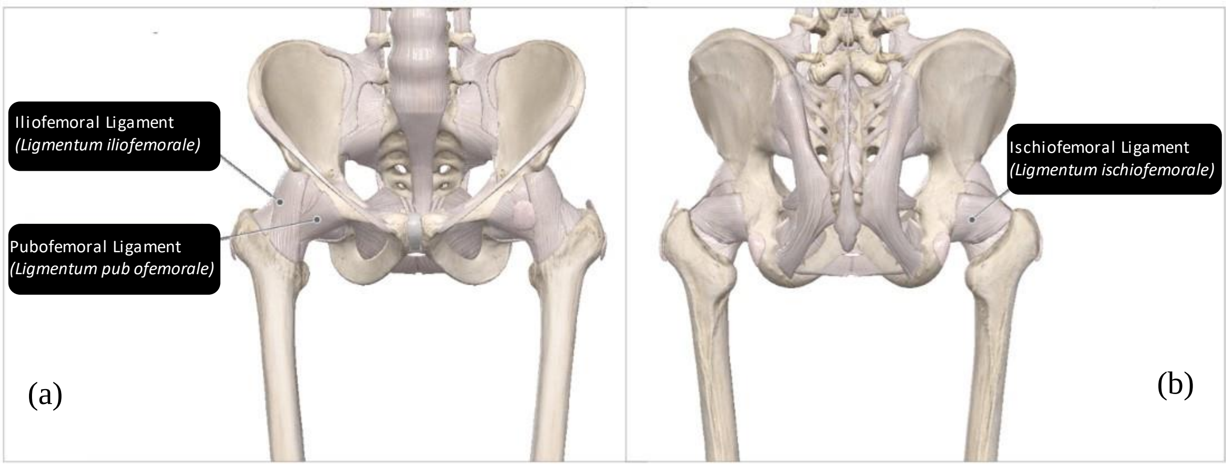


Figure 2-4: Capsular ligaments

Anterior (a) and posterior (b) view of the capsular ligaments and their attachment sites (Image generated courtesy of Complete Anatomy)

2.1.1 Accepted average position and limits

Variability in joint anatomy resulting from a person's stature, sex, or miscellaneous abnormality all contribute to what is considered normal for each person. "Normal" dictates neutral position. Somewhat counterintuitively, neutral does not inherently mean a position in which all relative translations and rotations of the femur with respect to the pelvis are zero. A neutral hip has some natural bias in three directions: adduction, internal rotation, and flexion. Natural flexion of the hip is fundamentally accepted to be 0°. The anatomical axis of the femur is, on average, at a seven (7) degree angle [11] with respect to the mechanical axis of the joint (Figure 2-5). From this position, movement in any direction may be truncated by either soft tissue constraint or encountering bone structures. In a healthy adult joint, these limits are expected to be reached in the range of 125° flexion, 15° extension, ± 45° rotation, 55° abduction, and 35° adduction [6, 12–14].

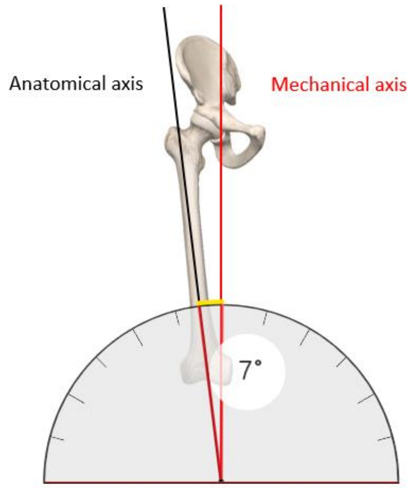


Figure 2-5: Anatomical axis of the femur

The anatomical axis of the femur runs the length of the joint from the greater trochanter to the fossa, and forms on average a seven (7) degree angle with the mechanical axis

2.2 Hip arthroscopy

2.2.1 Indications

Ailments appropriate for treatment via hip arthroscopy commonly result from either a trauma during vehicular accidents, during athletic activity, or anatomic abnormality. Of the latter, femoroacetabular impingement (FAI) is the primary indication. This condition is described as bony overgrowth on either the neck of the femur, the acetabular rim or both, and is the most common indication for arthroscopic intervention in North America [15] Common and long-standing indications resulting from trauma include labral tears, loose or foreign body removal, treatment of synovial diseases and chondral defects [2, 3, 15, 16]. As the prevalence of use of arthroscopy continues to grow, so does the list of indications.

2.2.2 Approaches and Repairs

While arthroscopy allows joint access via minimally invasive means, wider capsular incisions are often required for treatment of intra-articular injuries. As it pertains to the presented research in this text, the choice of cut pattern of these widening incisions is of interest. All capsulotomy approaches begin with the creation of two portals (Figure 2-6a), that are expanded upon sequentially as needed. Rarely do portals alone allow for adequate mobility of instruments and joint visibility. As such, interportal and T-capsulotomies are the two most used approaches [2, 3]. A lateral incision connecting the two portals forms an interportal capsulotomy (Figure 2-6b), which tends to satisfy required access to the acetabulum and labrum as needed. If additional joint access is required, particularly to address femoral pathologies, a T-capsulotomy is created by creating a perpendicular incision at the mid-point of the portals (Figure 2-6c). Complimentary to the capsulotomy approaches are variations of post-procedural capsule management. Choices include leaving the incisions unrepaired, total interportal or T-capsulotomy closure, or partial T-capsulotomy repair. Each has its own implications towards joint stability, laxity, and the patient's healing process.

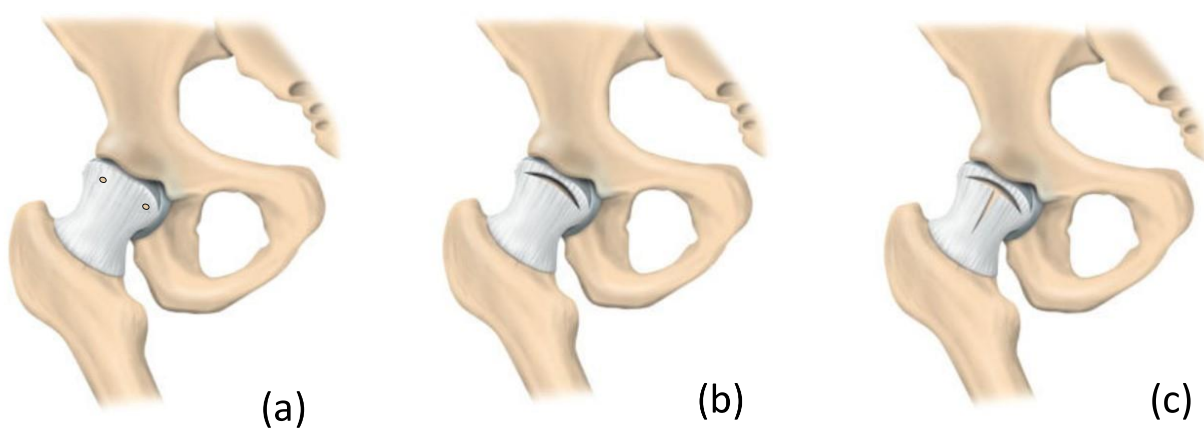


Figure 2-6: Common capsulotomies.

All capsulotomies begin with portals (a) and can be expanded upon horizontally to create an interportal incision (b), and laterally for T-capsulotomy (c). (Adapted image. Use permitted by SAGE publishing)

2.3 Directional Stability

Despite their overlapping anatomy, differences in physical properties of the individual capsular ligaments have been determined, as the capsule is an inhomogeneous structure [17, 18]. In a study by Pieroh et al. capsule ligaments obtained from human cadavers were subjected to uniaxial tensile testing, within a pre-determined range of elastic deformation. Strain data and elastic moduli were extracted from the resulting load-deformation curves and found values of maximum elastic strain and elastic modulus for the iliofemoral (strain 129.8 ± 11.1%, elastic modulus 48.8 ± 21.4 N/mm^2), ischiofemoral (strain 128.7 ± 13.7%, elastic modulus 37.5 ± 20.4 N/mm^2) and pubofemoral (strain 133.2 ± 23.7%, elastic modulus 49.0 ± 32.1 N/mm^2) ligaments were reported as stated [19]. However, uniaxial loading tests as was done in this study may not appropriately reflect the mechanical properties of the capsule ligaments as they behave *in situ*.

Along with the accepted knowledge of origin and insertion points of the capsular ligaments, these differences dictate the strengths of each ligament and offer insight as to in which direction they contribute to joint stability. Stability can be described both as resistance to rotation and minimal translation. A joint's "close-packed position" is the orientation in which the joint capsule and supporting ligaments are maximally tight, resulting in the least possible motion and thereby, the position in which it is most stable [20]. "Accessory motion" is the term used to describe relative movement between articulating joint surfaces. Even in its close-packed position, accessory motion between joint surfaces is not eliminated, as it is necessary during both passive and active movements, for full and pain free range of motion. The hip's close-packed position is in full extension, wherein all three of the capsular ligaments are engaged. The iliofemoral, pubofemoral, and ischiofemoral ligaments therefore all contribute to joint stability during extension [6, 21-24].

It has been reported that each individual capsular ligament's role in stabilizing the joint expands beyond their combined contribution in providing stability during extension. The ischiofemoral ligament contributes to overall stability in internal rotation [21–23], and combined flexion-adduction positions [21]. The pubofemoral ligament prevents undesired inferior translation [22] and adds to stability when externally rotated or hyperabducted [6, 21–23]. The iliofemoral ligament is thought to be the strongest of the capsular ligaments and predominantly provides stability during movements requiring external rotation while protecting against anterior [21, 22, 24] and inferior translation [24].

With surgical intervention such as hip arthroscopy, both rotational laxity and translations risk being impacted, secondary to incision or repair of the hip capsule. The following studies employ the unique opportunity for dynamic biomechanical evaluation of the hip joint, in response to mimicked arthroscopy incisions and repairs to evaluate changes to torque and joint translation (beyond accessory motion).

Chapter 3

3 Establishing a Biomechanical Model for Evaluation of Capsular Constraint at Discrete Flexion Angles

This chapter begins with a brief introduction to the use of robotic systems in biomechanics research and introduces a new servohydraulic system to be applied to the hip joint. The expected range of motion of the hip is contrasted against the system's capabilities. Additionally, this chapter aims to validate the experimental setup and characterize the system's fitness to evaluate hip joint kinematics.

3.1 Introduction

Developing the most complete understanding of native hip joint kinematics is essential for continual improvement of surgical intervention and rehabilitation strategies, and further comprehension of pathologies and mechanisms of injury that plague the hip joint. This has encouraged the development of *in vitro* and *in vivo* studies alike. Orthopedic biomechanics research has adopted the use of robotic systems for a variety of applications. Knee and shoulder biomechanics research have progressed greatly, benefiting from serial and parallel robot manipulators to quantitatively evaluate native joint kinematics and changes in response to surgical intervention [25–28] .

The large range of motion (ROM) of the hip increases experimental complexity and requires more sophisticated systems capable of multiple degree of-freedom (DOF) movements. Recent advances in joint simulator technology have enable more realistic *in vitro* biomechanical testing of human cadaveric joints. The AMTI VIVO (Advanced Mechanical Technologies Inc., Massachusetts, USA) is a general use six DOF servo-hydraulic joint motion simulator. This platform has the unique capability of applying loads and motions about and along all six DOFs, each with the ability to be controlled by force or displacement driven values, for sophisticated control of simulated loading scenarios.

The most commonly referenced values of normal hip mobility are those published by the American Academy of Orthopaedic Surgeons (AAOS) [29]. Supplementary to these values, researchers have assessed healthy ranges while considering differences in sex, age, and joint morphology [12–14, 30], some with the explicit goal of aggregating findings and creating a database for comparison in subsequent studies such as this. The method of collection here differs greatly; aggregated data have been collected via *in vitro* and *in vivo* studies alike, with comparable results. *In vivo* studies tend to mimic positions for clinical relevance such as those used during clinical diagnosis. *In vitro* studies have the advantage of exploring joint limits without risking injury to a patient and evaluating the affects and effectiveness of procedures without a specific diagnosis, no matter how destructive.

The purpose of this study was therefore to establish the suitability of the VIVO as a 6 DOF robotic system for continued cadaveric hip biomechanics studies by assessing the comparative accuracy or range of motion limits during simulated rotational tests to literature reported averages at four discrete flexion angles.

3.2 Methods

Overview of robotic system

The VIVO utilizes Grood & Suntay coordinate conventions [31] and operates within the bounds of the specifications listed in Table 3-1. It manipulates joints via relative motion of two actuators. The upper actuator provides flexion/ extension and abduction/ adduction (AA) rotations. The lower actuator provides internal/ external (IE) rotations and is also responsible for medial/ lateral (ML), anterior/ posterior (AP), and superior/ inferior (SI) translations. Additionally, all forces and moments experienced by the joint during testing are measured using a 6-DOF load cell held within the lower platen. Via closed-loop controls, each of the machine's DOFs can be operated in force or displacement control. The VIVO's native defined DOFs did not accommodate the expected range of motion of a healthy hip and were modified to enable the performed cadaveric testing. To maximize the use of machine workspace and native rotational allowances of the VIVO, orientation of the joint with respect to the machine was modified. The native flexion/ extension of the VIVO became the experimental abduction/ adduction axis of the hip and vice versa (Figure 3-1). However, this change severely diminished the available flexion and required further adaptation. A stepper motor (86HSE154 RATTM-Motor, 12 Nm holding torque, RATTM-Motor, Beijing, China) was placed in series with the arm of the upper actuator and rigidly attached to the custom fixture which held the specimen (Figure 3-2). This configuration ensured that the flexion axis was still passing through the machine origin. The stepper motor was controlled via a customized Arduino script that allowed the joint to be flexed and extended at discrete increments. Available range of motion became ±45° in IE rotation, 75° abduction, 35° adduction, and 0-90° flexion.

Table 3-1: AMTI VIVO's rotational specifications when operating in Grood & Suntay mode

Degree of Freedom	Flexion/ Extension	Internal/ External Rotation	Abduction/ Adduction
Native specification	110°	±45°	±25°
Hip configuration	90°	±45°	75° / 35°

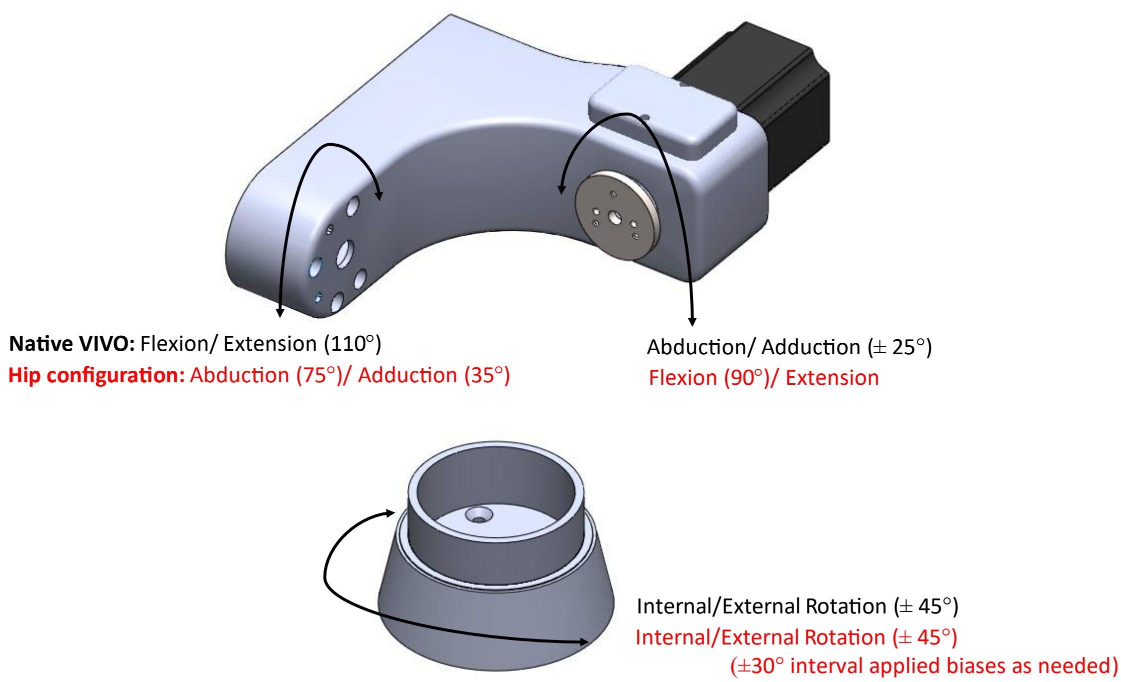


Figure 3-1: AMTI VIVO rotations

VIVO's native rotations (labelled in black) and reassigned experimental directions (labelled in red)

Specimen preparation

Ten (10) fresh-frozen hemi-pelvis with proximal femur specimens (6 male, 4 female, 2 pairs, 48-69 years of age) were used in this study. Included specimen were limited to donors with a body-mass index (BMI) under forty (40), no prior history of cancer with metastases to the bone, none with presumed or officially diagnosed with arthritis. Adequate joint health was confirmed via screening of computed tomography (CT) scan by a surgeon. The CT scans were checked to ensure the absence of arthritis, bony overgrowth, and abnormalities in joint shape which may have prematurely limited range of motion. Then, the specimens were left to thaw at room temperature for up to 36 hours prior to testing. All soft tissues except the capsule ligaments were removed and subsequently inspected for any damage caused during dissection.

Hip Neutral Orientation

Available pelvic anatomy, and previously published averages of maximum hip extension (15°) and abduction (45°), were used to help establish neutral position in the coronal and sagittal planes. A surgeon manipulated the joint to these limits and brought the femur to a position of 0° relative to the end-range positions before drilling 1-2 pins through the neck of the femur and across the joint to temporarily immobilize it. A second pin, placed quasi-parallel, was occasionally needed in more mobile joints to ensure the femur and pelvis were rigid with respect to one another. Alignment in the transverse plane was achieved subsequent to the pelvis being cemented in a 3.5” diameter pot. This required osteotomizing the pubis and ilium, taking care not to injure the origin of the capsular ligaments. Once the bone cement had cured, the specimen was mounted to the VIVO and the specimen could be rotated within the fixture until the stabilizing pin(s) pointed laterally and the femur’s coronal plane was perpendicular to the work surface. Prior to any testing, the position was confirmed by a surgeon (RD).

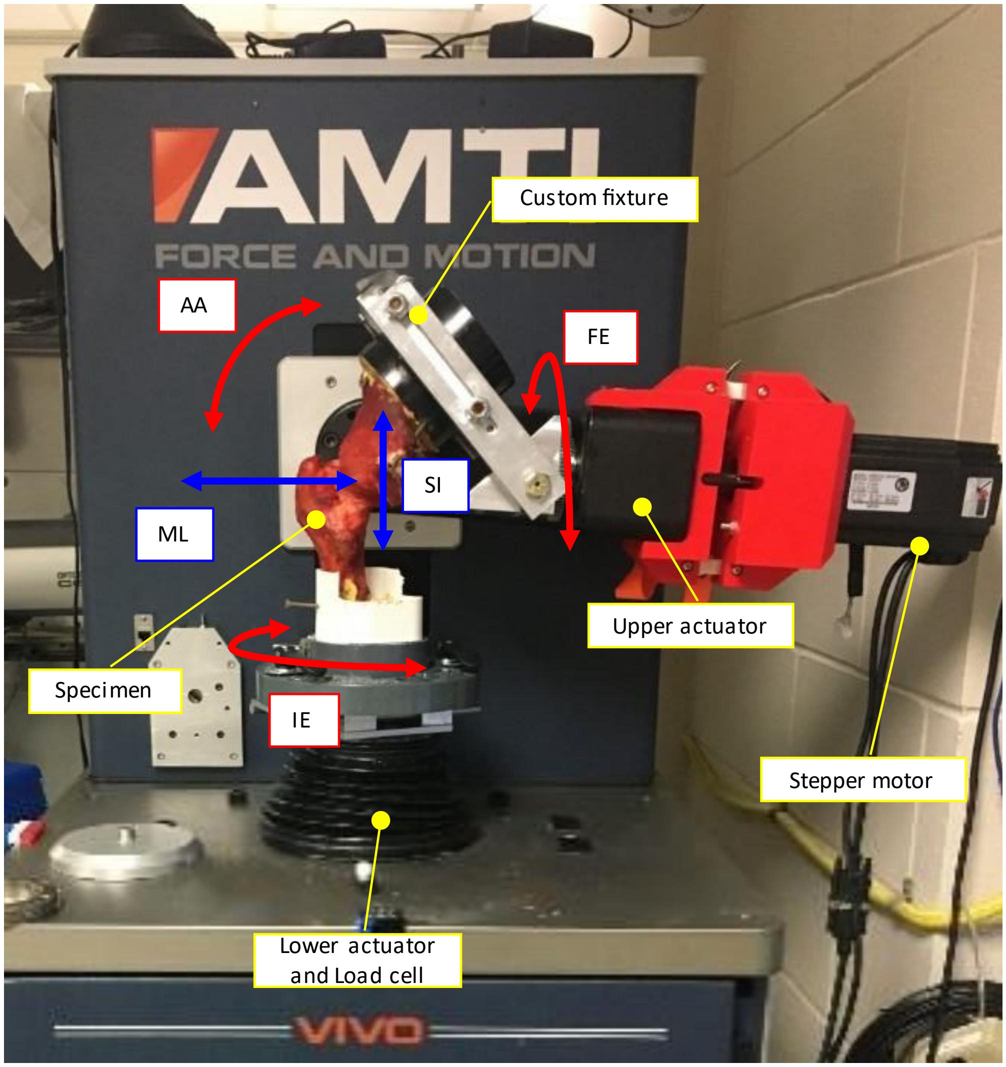


Figure 3-2: Experimental setup

Experimental setup of a right-sided specimen, utilizing a motor external to the VIVO to maximize available range of motion paired with the VIVO's native capabilities. Joint rotations depicted in red (FE: flexion/extension, AA: abduction/ adduction, IE: internal/ external rotation), and anterior view translations in blue (ML: medial/ lateral, SI: superior/ inferior)

Control Parameters

For the translational axes (ML in the medial-lateral directions, AP in the anterior-posterior directions and VL in the superior-anterior directions), inputs were in Newtons (N) and millimeters (mm) during force and displacement control respectively. Rotational axes (IE for internal-external rotation, AA for abduction-adduction, FE for flexion-extension) received inputs in torques (Nm) and angles (°).

Manual determination of limits

Hip ROM was assessed in internal rotation (IR), external rotation (ER), abduction (ABD) and adduction (ADD) under a 5 Nm torque, as selected based off previous literature [8, 32, 33] and pilot testing results which confirmed that the joint could withstand torques greater than 3 Nm [1] without tearing of capsule tissues. During each test, 10 N compressive forces were directed medially and superiorly to maintain joint reduction. The joint was manually cycled between 0 and 5 Nm to condition the joint. On the third repetition, the angular position at 5 Nm was recorded, indicating end ROM. These tests were completed at four discrete flexion angles of 0, 30, 60 and 90 degrees. Rotation was restricted in the direction that was not being tested, to maintain neutral position (ABD/ADD rotation held at 0° during IR/ER trials, and IR/ER rotation held at 0° during ABD/ADD tests). The remaining DOF's were nulled in force control which allowed translations to occur freely. During abduction trials, it was possible that the mechanical limitations of the joint motion simulator interfered with the joint's ability to reach its full ROM. When this occurred, abduction was capped at 35°. Similarly, mechanical ROM limits could have been reached while evaluating IE limits. In this case, a known rotational bias was applied to the femur via the lower fixture to allow for testing to resume. The magnitude of the applied bias was recorded and accounted for during post-processing.

Statistical Analysis

Relative difference (RD) was used as a measure of comparative accuracy of manually determined ROM limits and assessed with respect to previously published ROM means.

3.3 Results

Results for ROM limits were reported as means (±SD) in internal rotation, external, rotation, abduction, and adduction at discrete flexion angles of 0°, 30°, 60° and 90°. (See Figure 3-3 and Figure 3-4). Mean internal rotation ranged from 12.3° ± 9.6 at 90° of flexion to 31.4° ± 6.4 at 30° degrees flexion. Mean external rotational increased as the flexion angle also increased, spanning 40.7° ± 11.7 to 70.8° ± 19.0. Average abduction and adduction were smallest at 90° of flexion, with respective values of 36.9° ± 16.6 and 15.0° ± 6.1. Additionally, average abduction (49.2° ± 9.9) and adduction (32.5° ± 3.1) were largest at 30° of hip flexion.

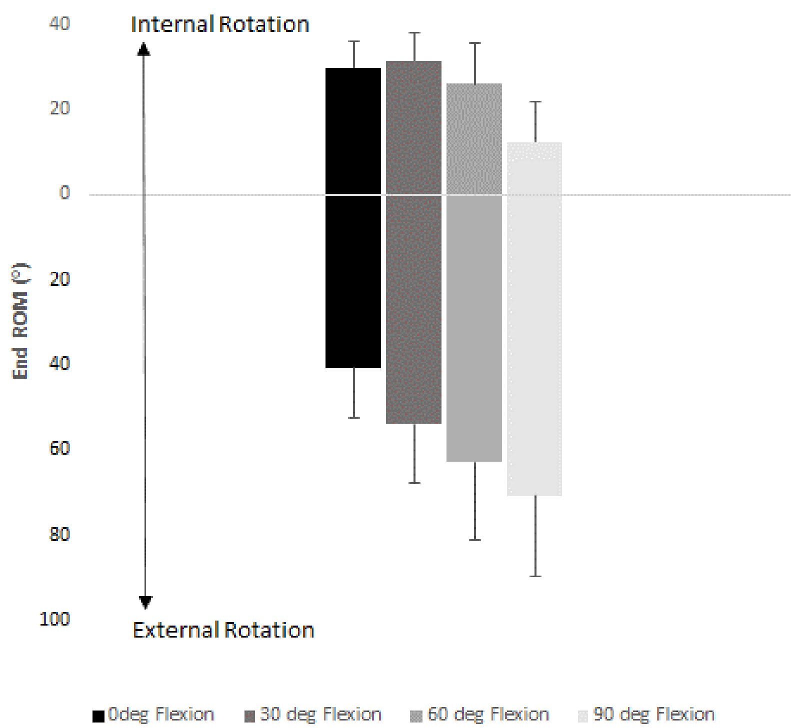


Figure 3-3: Range of motion limits during internal and external rotation

Mean end range of motion (ROM) of the intact joint in internal rotation (+SD) and external rotation (+SD)

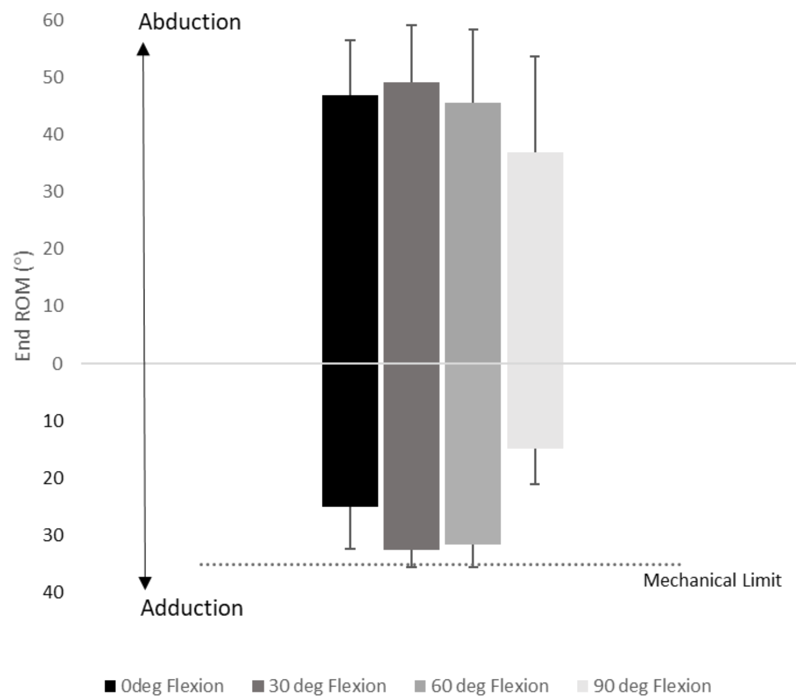


Figure 3-4: Range of motion limits during abduction and adduction

Mean end range of motion (ROM) of the intact joint in abduction (+SD) and adduction (+SD)

<u>Comparative accuracy</u>

Difference was used to compare manually determined hip ROM limits to those reported by Philippon et al. [34] (Table 3-2) across all flexion angles as a measure of accuracy. Difference was also calculated with respect to mean ROM data published by the American Academy of Orthopaedic Surgery (AAOS). This data set amalgamates data from reputable sources and acts as a gold standard for comparison – only for the hip at 0° of flexion – and yielded the following: Internal rotation, RD = 0.10; External rotation, RD = 0.34; Abduction, RD = 0.02; Adduction RD= 0.19. Relative difference was computed as the ratio of absolute difference of the mean manual limits to the literature reported values.

Table 3-2: Comparative accuracy of identified ROM limits. Using relative difference as assessment of accuracy with respect to literature reported means

	0° Flexion			30° Flexion			60° Flexion			90° Flexion		
Direction of Applied Torque	**Philippon et al.* (°)**	**Manual Limits(°)**	**Relative Diff.**	**Philippon et al.* (°)**	**Manual Limits{°)**	**Relative Diff.**	**Philippon et al.* (°)**	**Manual Limits(°)**	**Relative Diff.**	**Philippon et al.* (°)**	**Manual Limits(°)**	**Relative Diff.**
Internal Rotation	23.8	29.8	0.25	26.0	31.4	0.21	24.0	26.0	0.08	17.1	12.3	0.28
External Rotation	26.1	40.7	0.56	41.4	54.0	0.30	47.7	62.8	0.32	44.2	70.8	0.60
Abduction	28.0	46.9	0.67	40.1	49.2	0.23	43.7	45.6	0.04	46.5	37.0	0.21
Adduction	10.1	25.0	1.47	25.7	32.5	0.26	27.9	31.7	0.13	19.6	15.0	0.24

*Mean ROM limits of an intact hip reported by Philippon et al.[34]

3.4 Discussion

Comparative analyses were made to establish a state-of-the-art joint motion simulator as an appropriate platform for biomechanical hip research with cadavers. The use of six-degree of freedom robotic systems in biomechanics research has been done frequently at the knee and the shoulder, fewer studies have applied this technology to the hip joint. El Doau et al. have explored the Staubli Tx90 robot (Staubli Ltd, Switzerland) for cadaveric hip testing. Similarly, Goldsmith et al. validated the use of a KUKA KR 60-3 (KUKA Robotics Corp, Augsburg, Germany) for evaluation of passive hip motion and ROM representative of that needed to perform clinical examinations of the hip joint, having demonstrated that robotic joint manipulation results in much more repeatable results compared to manual exam [33]. In both cases, these 6 DOF robotic arms had to be complimented by external or accessory load cells to create a more complete system.

There are seemingly endless resources listing the ROM of the hip. These reports can be divided into accounts of (1) active and (2) passive range of motion; cadaveric research falls into the latter. The results were comparable to those in literature, with the exception of limits during adduction at 0° of flexion. The results from this study saw adduction with the hip flexed to 0° to be 25.0° ± 7.4; larger than the 10.1° ± 3.9 reported by Philippon et al. [34]. We tested both male and female specimens for this study, whereas Philippon et al. included only males. As such, the greater adduction range of motion available in the female hip [35], [36] may be an influence on our differing results.

Furthermore, differences in experimental protocol may have impacted the definition of joint neutral, and subsequently 0° flexion, contributing the experienced difference. When compared to the AAOS dataset, a much lower relative difference (0.19 vs 1.47) was achieved. Of note, the AAOS dataset averages values primarily collected from clinical studies evaluating passive ROM. In a clinical setting, these are often measured with a patient in supine (on their back) or prone (on their stomach) positions. During *in vivo* measurements, there are additional anatomical variance that contribute to available ROM. Knee alignment [11], lumbar flexibility [37], and musculature [9] have demonstrated to have a close relationship with hip mobility, none of which are included variables during the current study.

These factors are considered and attempted to be accounted for during the potting and mounting process. Nevertheless, it is possible that some unintentional rotational biases could have been applied. Looking at the external rotation limits in particular, greater flexion angle resulted in larger external rotation, potentially the result of imperfect potting. As a result, observing the total rotational arc (from internal rotation limit to external rotation limit) may be a helpful metric for comparison. Total IE rotation was similar across flexion angles from 0 to 90 degrees as follows: 66.1° ± 9.9, 82.0° ± 7.7, 86.4 ± 11.5, 79.5° ± 11.5

It is also important to note that the VIVO's mechanical ROM limit in adduction was exceeded prior to reaching 5 Nm of torque for one specimen at both 30° and 60° flexion, and for an additional 3 specimen at 30°. However, observing relative kinematics aids in minimizing the impact of this limitation on the outcomes of the performed experiment.

As a commercial product, the VIVO is an established system. Calibration accreditation reports expanded uncertainty measurement of 0.3° along the DOFs utilized for hip IE and AA rotations [38] – native VIVO IE rotation and flexion, respectively. Adopting the system for cadaveric research provides the benefit of precise and repeatable motions, which is essential for examining small changes in joint biomechanics such as the those that may result be observed during serial sectioning studies.

Chapter 4

4 The Relative Biomechanical Contribution of the Hip Capsule in Joint Laxity Across Successive Incised and Repaired Capsulotomy States

This chapter begins with a brief introduction to previous approaches towards evaluating the contributions of the hip capsule to joint laxity. A servo hydraulic joint motion simulator is used to investigate the impact of successive capsulotomies and their repairs on joint laxity and capsule stiffness. Additional data to that presented in the text can be found in Appendix 1.

4.1 Introduction

The capsule is comprised of 3 ligaments – the iliofemoral, ischiofemoral and pubofemoral ligaments – and is the final layer of soft tissue resistance against rotational torques. During arthroscopic hip surgery, these tissues are inevitably penetrated via a set of incisions called a capsulotomy. Currently, the choice of incision pattern for performed arthroscopies is largely dependent on the procedural physician's preference and the logistics of the pathology being treated (i.e. location and required visibility or access), without consideration of the biomechanical impact to the joint following the procedure.

Along with the intact state, cadaveric studies tend to assess the hip capsule in six states representative of the three capsulotomy approaches used prevalently in the field and their respective repairs: portal incisions, interportal capsulotomy and T-capsulotomy. Philippon et al. assessed range of motion kinematics in two additional capsular states: large capsular defect, and full capsular reconstruction (of the large defect) [34]. Previous biomechanical studies that have been performed to evaluate the effect of progressive capsular injuries have concluded that rotational laxity is increased with increased injury, and kinematics equivalent to those of the intact joint can be reestablished with repair [1], [34]. Joint laxity is nearly always quantified as changes in rotational position, and never as a difference in experienced torque. Other biomechanical studies have attempted to determine which anatomical movement the independent ligaments work to constrain with conflicting results. The iliofemoral ligament, for example, has been evaluated to be the strongest capsular constraint acting in tension, to offer resistance to external rotation in flexion and extension, and internal rotation in extension [21–23]. Its role in limiting internal rotation, however, is not recognized consistently in literature [6]. These contradictions may result from the inherent destructive nature of serial sectioning studies, wherein experimental setup is difficult to reproduce. Understanding there is control of incision placement during capsulotomies, the ability to measure torque at end range of motion, in addition to the existing knowledge of directional restraint of the capsular ligaments allows for bridging the gap in knowledge.

Therefore, the primary objective of this cadaveric study is to examine changes in torque as influenced by capsulotomies and capsular repair technique on hip joint biomechanics within the established available range of motion.

4.2 Methods

Specimen Preparation

After establishing range of motion limits as described in Chapter 3, the same ten (10) fresh-frozen hemi-pelvis and proximal femur (6 male, 4 female, 2 pairs, 48-69 years of age) were used in this study. Donors over the age of seventy (70), with a body-mass index (BMI) greater than forty (40) or having a history of cancer with metastases to bone were excluded from this study. In addition, the donor summary for each specimen was screened to ensure the absence of osteoarthritis according to next of kin. Upon receipt, a computed tomography (CT) scan was done for each specimen. The scans were viewed by a surgeon and used to confirm the absence of arthritis, and to check for bony abnormalities that would have unnaturally limited range of motion. Specimen were left to thaw for up to 36 hours as dictated by size and BMI. Once thawed, all soft tissue superficial to the capsule was removed. A surgeon manipulated the joint and established its neutral position based on specimen specific range of motion. One or two pins were drilled through the neck of the femur and into the pelvis to temporarily fix the joint in the established position (Figure 4-1). Biomechanical testing of each joint was performed using a VIVO joint motion simulator (Advanced Mechanical Technologies Inc., Massachusetts, USA).

Potting of the pelvis

Mounting the specimen to the VIVO required the pelvis be osteotomized to fit the confines of the designed pot. Large portions of the ilium, pubis and ischium were removed with a bone saw, ensuring to leave ample surface around identified capsule insertion points and enough bony anatomy for securing in dental stone (Modern material Golden Denstone Labstone, Modern Materials, Kulzer GmbH, Hanau, Germany). The specimen was deemed to be in the correct orientation for cementing when:

1. Guided by custom pieces, the femur was positioned to reconstitute the 7° angle [11] between the mechanical and anatomical axes of the femur (Figure 4-1).

2. Visually, the pot's cylindrical axis passed through the centre of the femoral head

The pelvic pot (3.5" inner diameter, polyvinyl chloride pipe coupling) was held in a custom fixture that connected to the VIVO's upper actuator. Correct rotational positioning within the upper pot was achieved by making the stabilizing pins lie parallel to the coronal plane of the VIVO. Having satisfied the two positioning conditions prior to potting and rotational alignment when mounting to the upper actuator, the joint was said to be neutrally rotated in the three degrees of freedom as well as with respect to the machine. Once established, the stabilizing pins were removed allowing for the joint to mobilize freely.

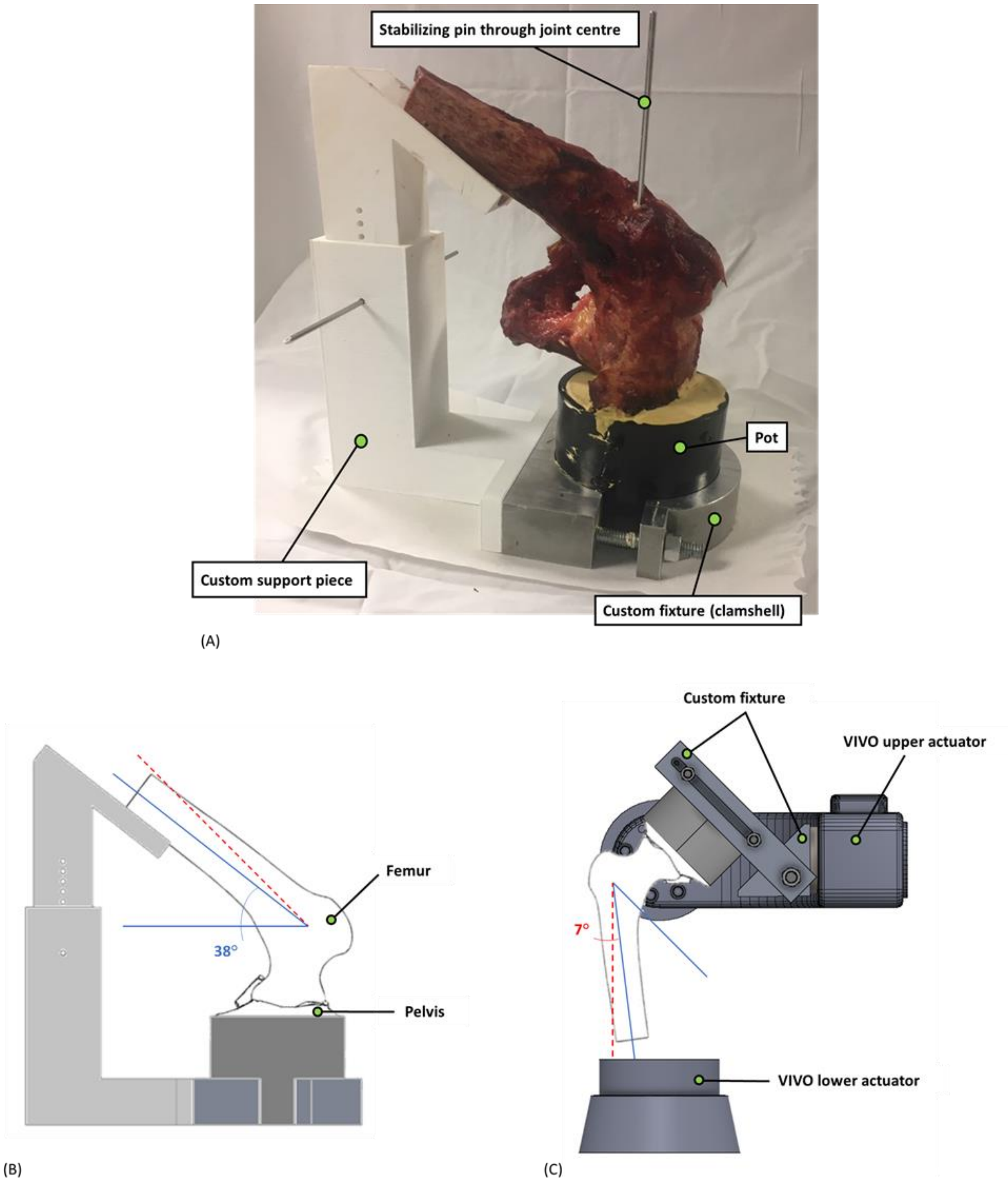


Figure 4-1: Pelvis potting

(A) Experimental setup of pelvis potting. (B) Schematic of setup and accessories for potting the femur and, (C) how it translates to anatomical alignment once mounted on the VIVO.

Establishing joint centre

A custom fixture was used to allow for specimen alignment with the machine centre. The centre of the femoral head is accepted to be the approximate centre of rotation of the joint [37, 38] and was the targeted point for alignment with the machine. With the pelvic pot held stationary in the upper fixture, a tracker was mounted to the lateral-distal aspect of the femur. The tracker was visualized by an Optotrak Certus (Northern Digital Inc., Waterloo, CA) and co-registered to the VIVO's coordinate system using a second tracker placed on the machine's body. While manually reducing the joint, the femur was circumducted during which flexion was limited to less than 30° [41] The femoral shaft was modelled as a needle point whose displacements during circumduction were transformed to model a sphere (at the femoral head). The motion capture provided coordinates for the centre of the sphere with respect to the VIVO's coordinate system. The specimen's position was adjusted via the fixture and to within two (2) mm from the machine's origin in all translational DOFs. The specimen was then deemed to be in an anatomically neutral position with respect to the machine.

Potting of the femur

A surgeon reestablished neutral IE rotation and flexion of the femur with respect to the pelvis (previously established prior to pinning). The angle of the femur was verified with a goniometer to be 7° from vertical [11] for confirmation of neutral abduction. In this position it was cemented in place.

Force controlled intact test

Two (2) compressive forces of 10 N were applied to the femur. The first acted directly superiorly, and the second acted directly medially through the approximate joint centre to maintain joint reduction. Pure rotational torque of five (5) Nm was sequentially applied to the specimen via manual input in internal rotation, external rotation, abduction, and adduction. While applying IE torques, the joint was held in its neutral anatomic abduction position, and in anatomic neutral IE rotation while applying AA torques. The entire sequence was repeated three (3) times to condition the joint and diminish the potential hysteresis effects of ligament creep. On the last repetition in each direction, the maximum angular position was recorded to two (2) decimal places, quantifying end range of motion. This sequence was done at the four (4) fixed flexion angles of 0, 30, 60 and 90 degrees, resulting in a total of sixteen (16) identified limits. It is important to note that adduction range of motion was restricted by mechanical limitations of the joint motion simulator. From the anatomical neutral position, the available range of motion in adduction is capped at thirty-five (35) degrees. Had mechanical range of motion limits been reached in IE rotation, a known rotational bias was applied by repositioning the lower fixture, and testing resumed.

Baseline displacement control

The same compressive forces were applied to the joint as describe for Force controlled intact testing above. To establish a displacement controlled baseline, the healthy joint was rotated through its range of motion; starting at 0° and ending at the maximum angular position recorded during the previously conducted Force controlled trials. A total of sixteen (16) intact runs were completed; one (1) in each of the four directions, at four (4) distinct flexion angles.

Displacement controlled test

During displacement controlled trials, angular position was the independent variable driving joint movement in the observed direction (i.e. internal rotations were applied, while IE torques were recorded). Again, with medially and superiorly directed forces of 10 N, the joint was rotated from 0° to the end internal, external, abduction and adduction ROM, repeated at discrete flexion angles of 0, 30, 60 and 90 degrees.

These trials were repeated with the joint in states of increasingly large capsular incision and their respective repairs. These clinically relevant states were tested sequentially as follows: portals, interportal capsulotomy, interportal capsulotomy repair, full T-capsulotomy repair, partial T-capsulotomy repair, and T-capsulotomy (Figure 4-2). All incision placement determinations and sutures were performed by a surgeon. An anterolateral and mid-anterior portal, each approximately 1 cm long, were made in the iliofemoral ligament for the first capsular state. A straight incision connects the portals to create an interportal capsulotomy (IPC). Four (4) interrupted simple sutures closed this incision for the interportal repair. A perpendicular incision half the length of the interporal (approximately 1.5 cm) at its midpoint formed the T-capsulotomy state. The T-capsulotomy was fully repaired with two and four interrupted sutures on the vertical and horizontal limbs, respectively. Next, the sutures of the vertical cut were removed to create a partial T-capsulotomy. Finally, all sutures were removed to test the unrepaired T-capsulotomy. This order was optimized for experiment day workflow. Torques and positions in the 6 degrees of freedom were recorded through the entirety of each trial. After complete repairs, the joint was manually brought to its determined ROM to ensure that the repairs did not over-constrain the joint.

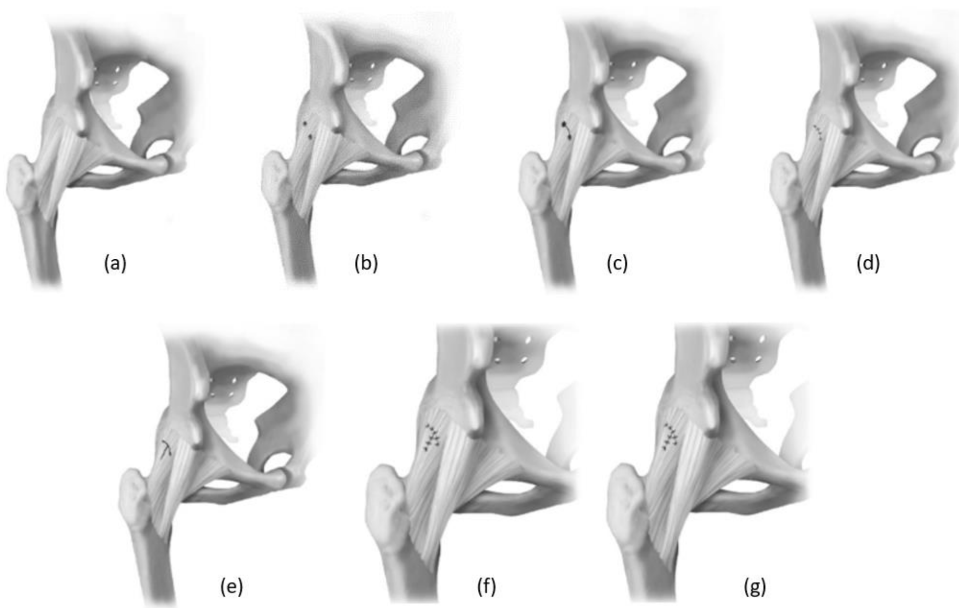


Figure 4-2: Tested capsulotomy states

Kinematic data was collected in seven capsular conditions: (a) intact, (b) portal incisions, (c) interportal capsulotomy, (d) interportal capsulotomy repair, (e) T-capsulotomy, (f) full T-capsulotomy repair, (g) partial T-capsulotomy repair (Adapted image. Use permitted by SAGE publishing)

Data sampling and scaling

Data was collected at a sampling rate of 500 Hz. The following data scaling was done using MATLAB (MathWorks, Massachusetts, USA). The data was smoothed via a Butterworth filter and down-sampled to 1000 points per full motion. Data from internal and external rotation trials and abduction and adduction trials were respectively concatenated to observe the total articular range (TAR) of motion about the respective axis. Specimen specific targets were identified, spanning the TAR at 1-degree intervals (Figure 4-3). Data was further down-sampled to the size of identified targets, at index points where the rotational position was closest the established targets across all elements, and subsequently interpolated to 100 points in length for each specimen.

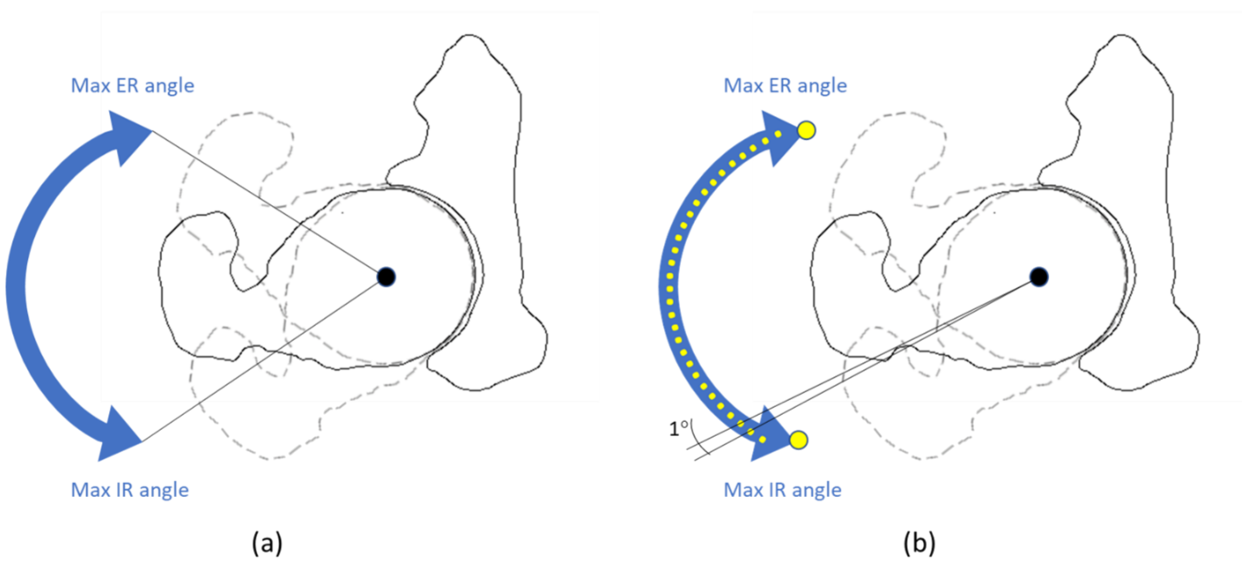


Figure 4-3: Total articular range (TAR)

Depiction of the total articular range (TAR) where internal and external rotation trials are combined (a), and the angular targets identified within it at 1-degree intervals (b)

Torque and angle data were normalized to a percentage scale as a solution to inter-specimen variability of range of motion limits, and experienced torque at these limits during intact. As a result, presented torque is a percent of the torque at end range of motion during the intact state.

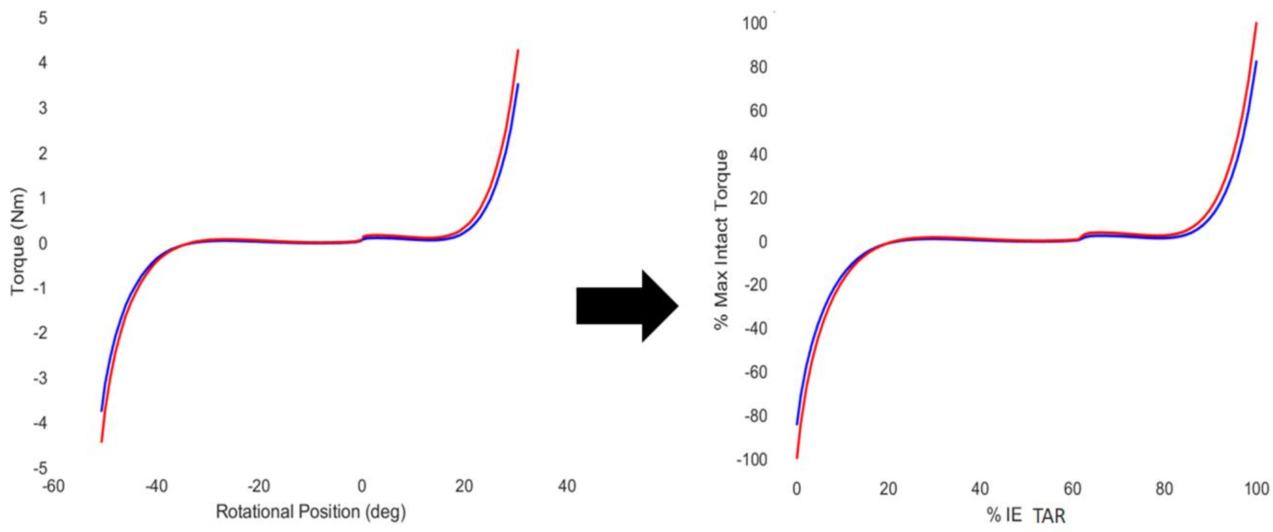


Figure 4-4: Scaling relative torques and rotations

Sample data for a single specimen displaying how IE position is converted from a value in degrees to percentage and torque is scaled to a percentage with respect to intact (red curve) after creation of portals (blue curves).

Range of motion limits are scaled from 0 to 100 percent across the entire rotational envelope; zero percent range of motion is maximum external rotation or adduction, and one hundred percent range of motion is maximum internal rotation or abduction.

Statistical Analysis

The results were reported as the mean ± SD of torque with respect to intact for all specimen. In addition, capsule stiffness (Nm/deg) as the joint approached the end of range of motion was measured. Torsional stiffness was calculated over the final 10% of the TAR in each direction (0-10% for external rotation or adduction, and 90-100% for internal rotation or abduction). Statistical comparisons were confined within a given flexion angle. At each, the following were compared: (1) intact versus all subsequent conditions, (2) portals versus all subsequent conditions, (3) IPC versus IPC repair, (4) T-capsulotomy versus full T-capsulotomy repair, and (5) T-capsulotomy versus partial T-capsulotomy repair. One-way ANOVA with subsequent post-hoc analysis for multiple comparisons were used to assess significant differences at the four discrete flexion angles, where a *p* value of < 0.05 was considered statistically significant for all tests.

4.3 Results

Internal Rotation

Full T-capsulotomy repair significantly increased the torque at end range of motion compared to the open T-capsulotomy by 21.9 ± 20.2 % end range of motion torque at 60° (*p*=0.05) and 22.2 ±14.2 % at 90° (*p*=0.04) flexion. All capsule conditions were significantly different from intact at end range of motion with the hip flexed to 0°, 30° and 60°, except for portals at 30° flexion (*p*=0.2). Relative torque during partial T-capsulotomy repair was significantly different from intact across all flexion angles in addition to being significantly different from portals at 0° (*p*=0.03). T-capsulotomy was also significantly different from portals at 0°, 60° and 90° flexion.

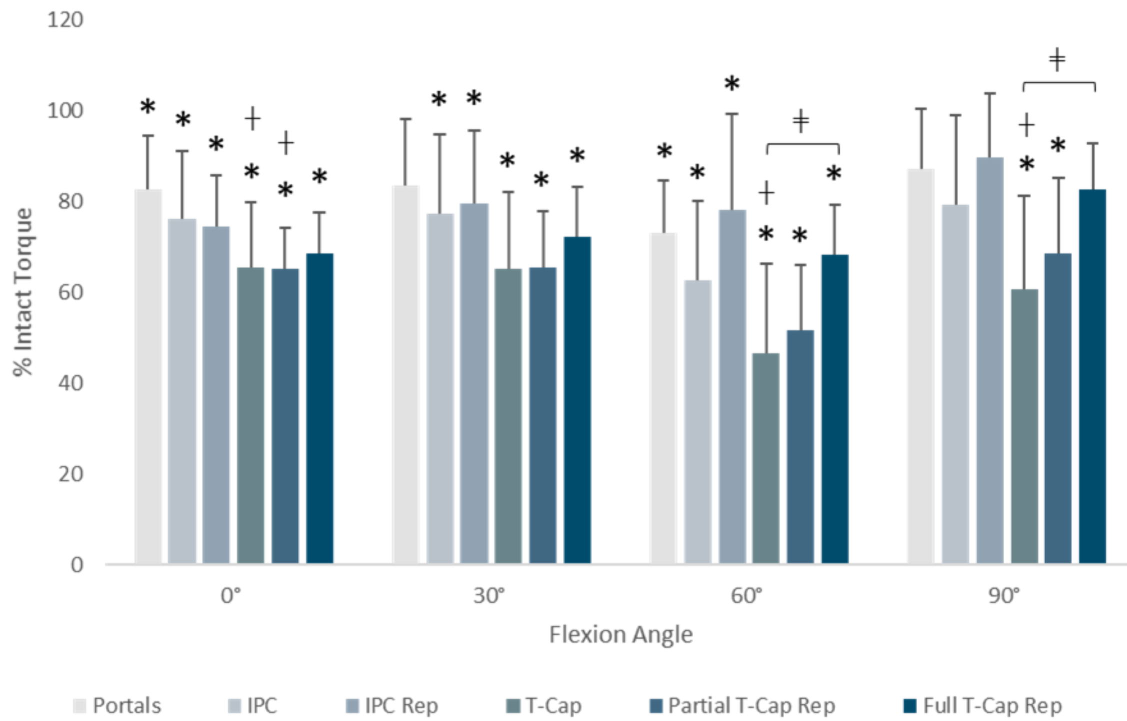


Figure 4-5: Mean Percent torque during internal rotation

Comparison of the mean percent torque (+SD) with respect to intact at maximum internal rotation across all capsule states, at four flexion angles (*significantly different from intact, ┼significantly different from portals, ╪significantly different after repair)

External Rotation

Open capsulotomy procedures (IPC and T-capsulotomy) resulted in significant decreases to the experienced torque at full external rotation compared to the intact state at 0°, 30° and 60° of flexion. Significant difference from portals is also true under these conditions, while no statistical difference exists between portals and the intact state. Interportal, partial and full T-capsulotomy repairs significantly increased the torque at maximum external rotation compared to their respective open capsulotomy state at 0°, 30° and at 60° only for IPC repair. From 30 to 90 degrees of flexion, repair states (IPC repair, full and partial T-capsulotomy repair) were not significantly different from the intact state, apart from partial T-capsulotomy repair at 30° (p <0.01).

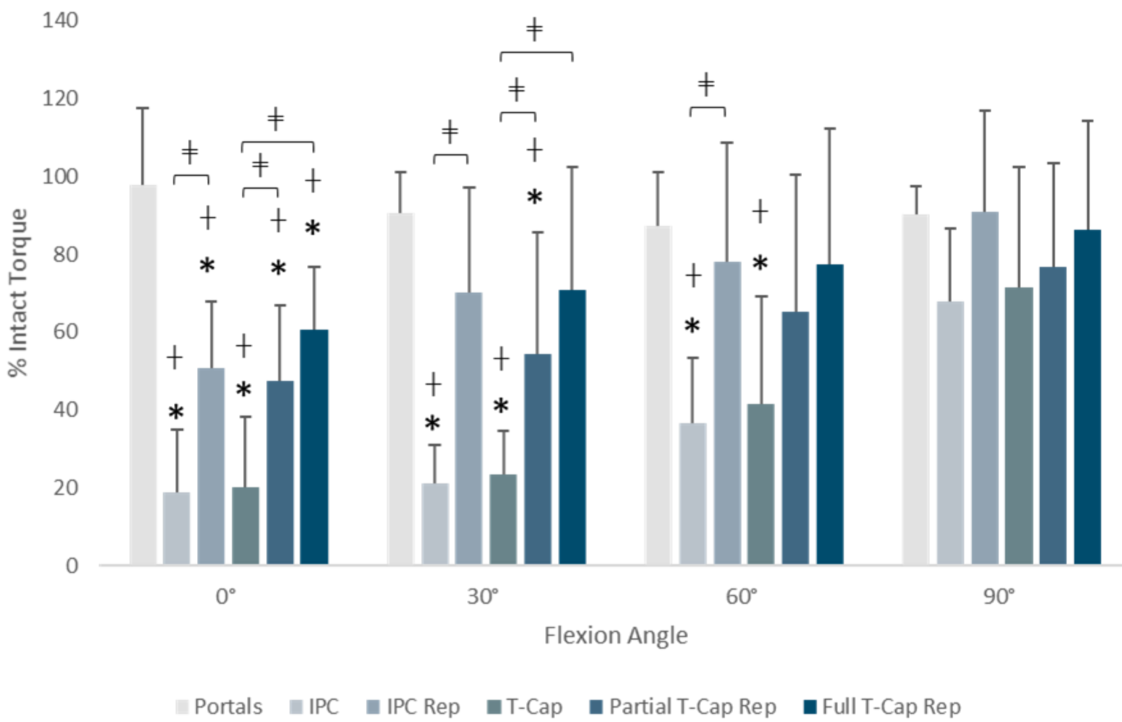


Figure 4-6: Mean Percent torque during external rotation

Comparison of the mean percent torque (+SD) with respect to intact at maximum external rotation across all capsule states, at four flexion angles (*significantly different from intact, ┼significantly different from portals, ╪significantly different after repair)

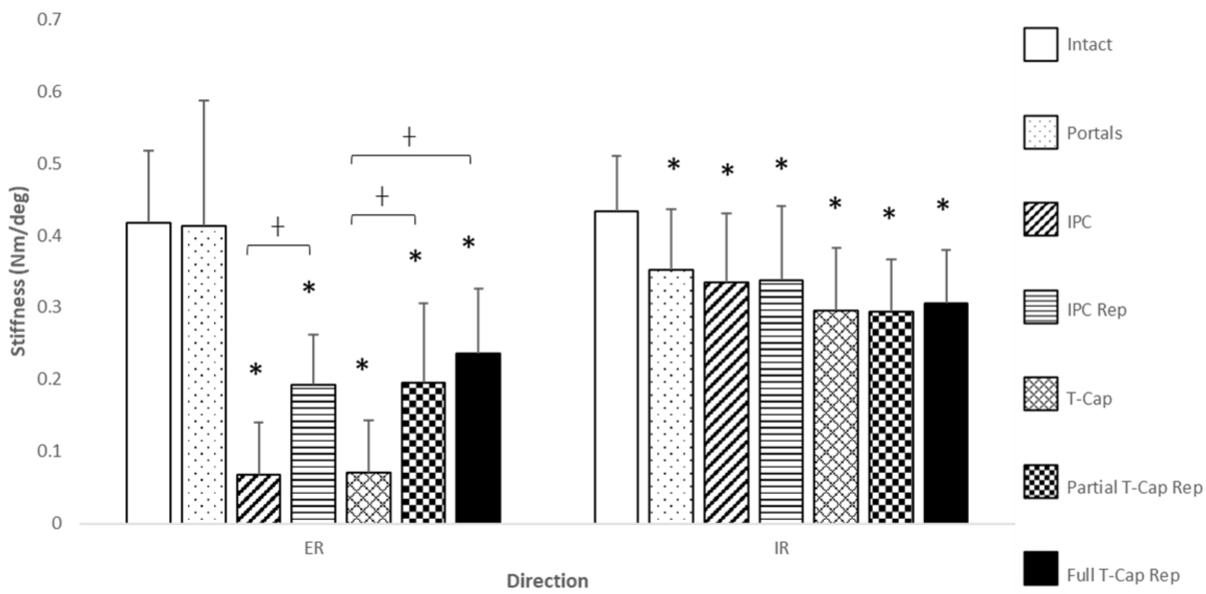


Figure 4-7: Capsule stiffness at IE limits at 0 degrees flexion

Mean capsule stiffness (+SD) as joint approached end range of motion in external and internal rotation with the hip flexed to 0 degrees (*significantly different from intact, ┼significantly different after repairs).

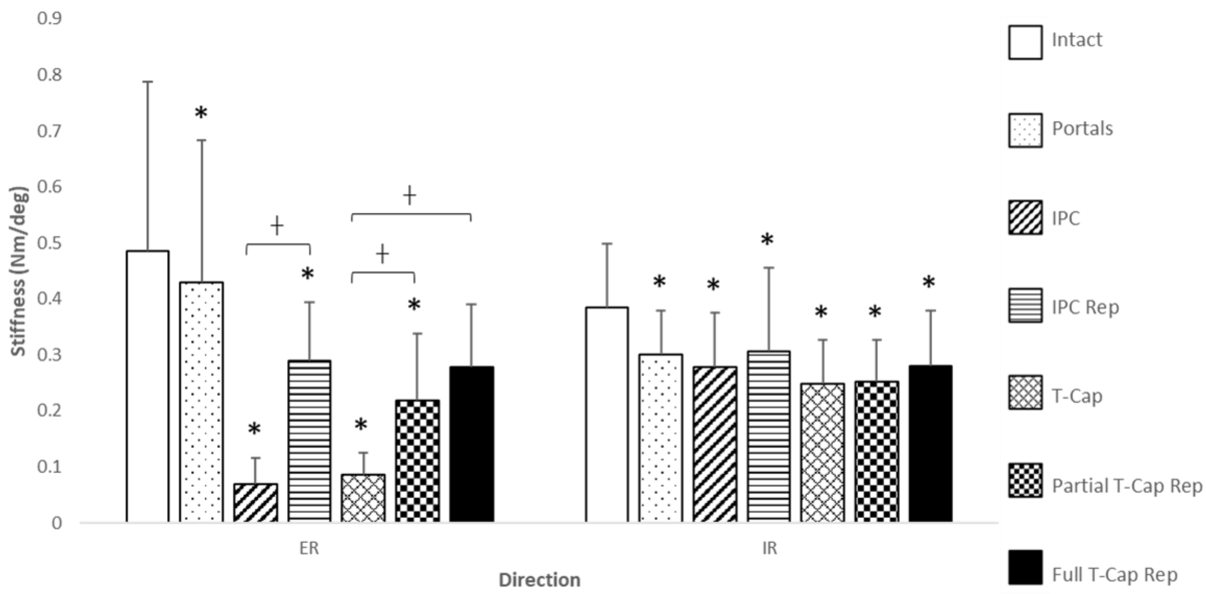


Figure 4-8: Capsule stiffness at IE limits at 30 degrees flexion

Mean capsule stiffness (+SD) as joint approached end range of motion in external and internal rotation with the hip flexed to 30 degrees (*significantly different from intact, ┼significantly different after repairs).

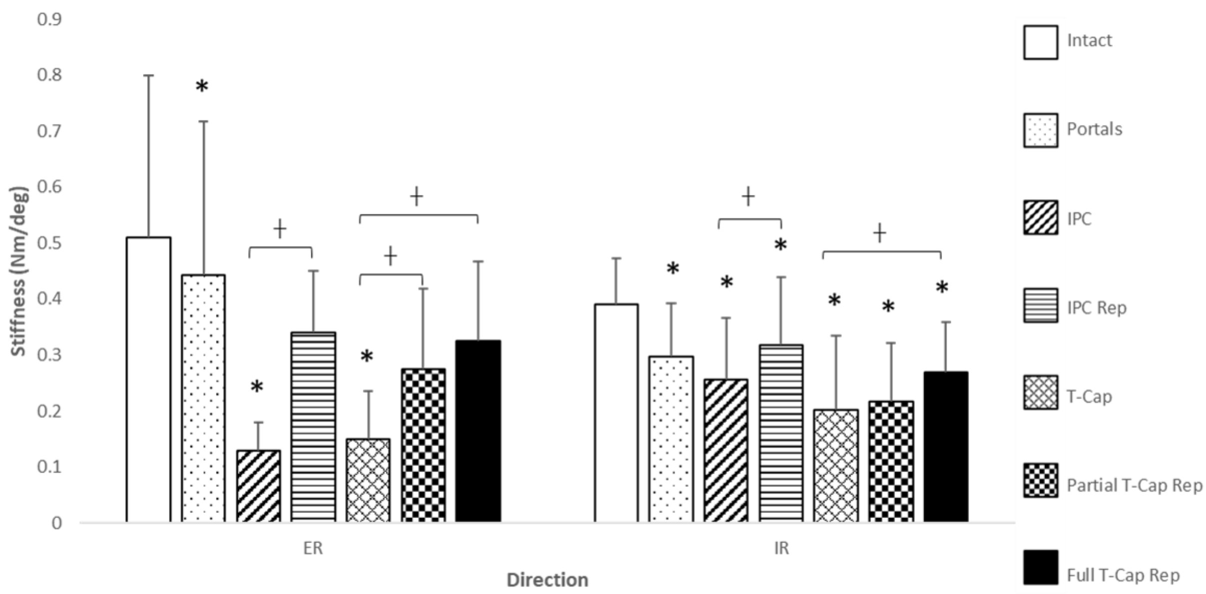


Figure 4-9: Capsule stiffness at IE limits at 60 degrees flexion

Mean capsule stiffness (+SD) as joint approached end range of motion in external and internal rotation with the hip flexed to 60 degrees (*significantly different from intact, ┼significantly different after repairs).

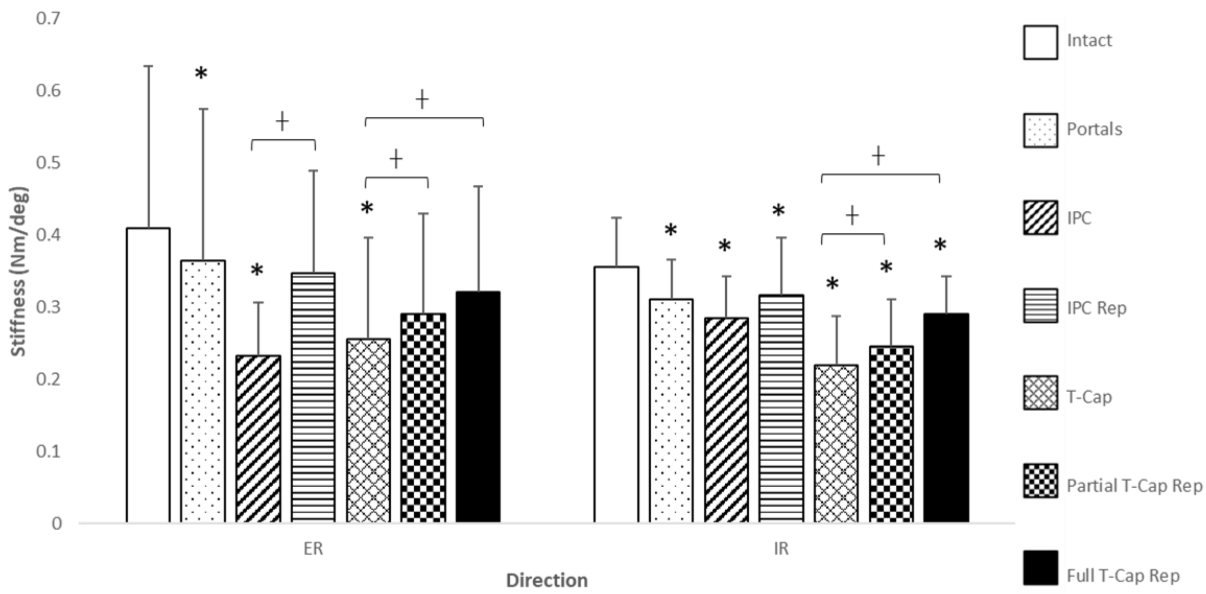


Figure 4-10: Capsule stiffness at IE limits at 90 degrees flexion

Mean capsule stiffness (+SD) as joint approached end range of motion in external and internal rotation with the hip flexed to 90 degrees (*significantly different from intact, ┼significantly different after repairs).

Abduction

Throughout flexion, T-capsulotomy resulted in significant differences from intact as did IPC at the two highest flexion angles. Significance was maintained with partial T-capsulotomy repair at 0° and 60°.

Adduction

Open capsulotomies resulted in significant reductions in torque at maximum abduction; at 0° for IPC (71.9 ± 20.7 % intact torque, p= 0.2), 0° and 90° for T-capsulotomy. Similarly, torque remained significantly reduced with respect to intact with partial T-capsulotomy repair when the hip was flexed to 90°.

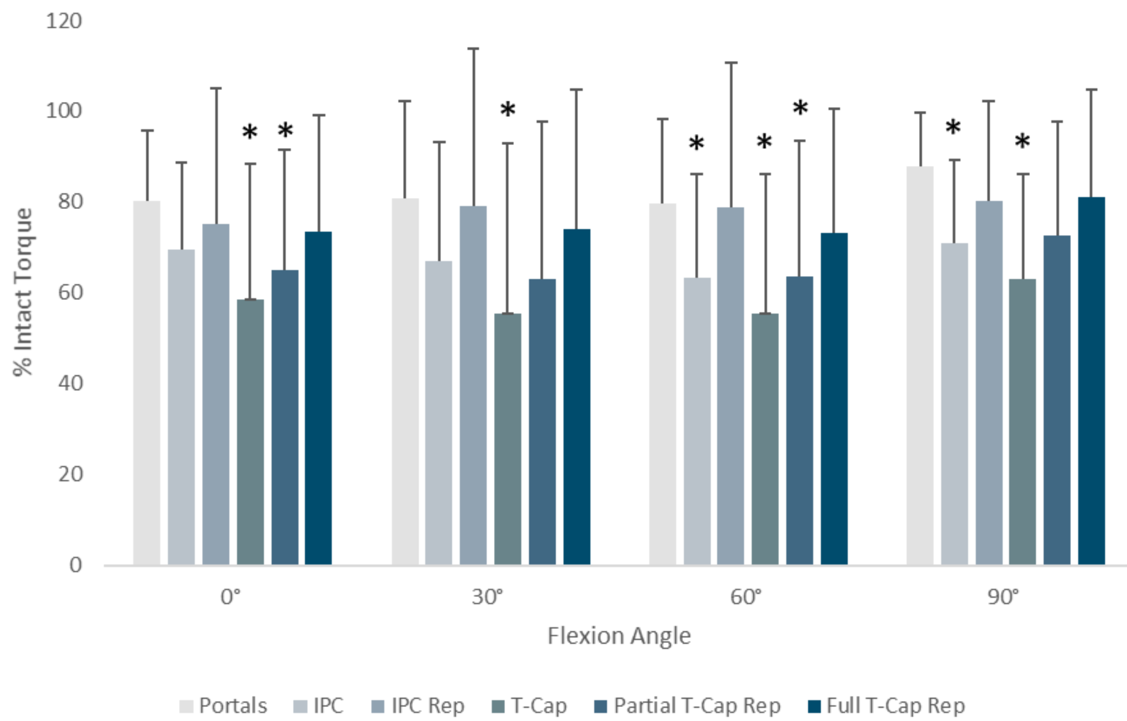


Figure 4-11: Mean Percent torque during abduction

Comparison of the mean percent torque (+SD) with respect to intact at maximum abduction across all capsule states, at four flexion angles (*significantly different from intact, ┼significantly different from portals, ╪significantly different after repair)

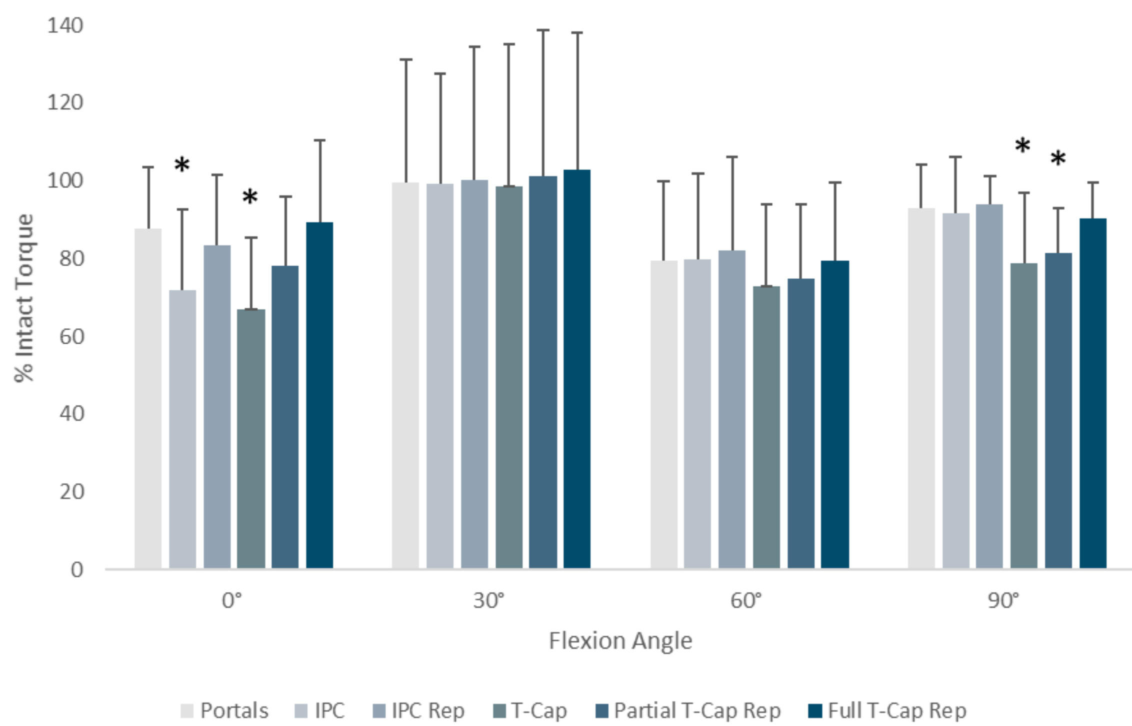


Figure 4-12: Mean Percent torque during adduction

Comparison of the mean percent torque (+SD) with respect to intact at maximum adduction across all capsule states, at four flexion angles (*significantly different from intact, ┼significantly different from portals, ╪significantly different after repair)

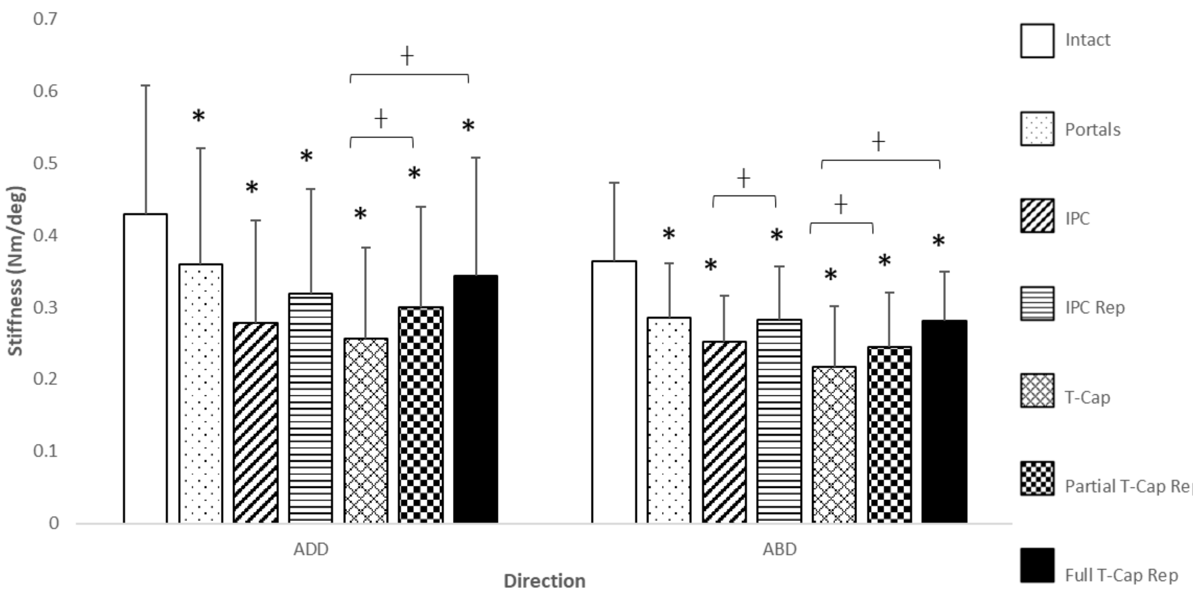


Figure 4-13: Capsule stiffness at AA limits at 0 degrees flexion

Mean capsule stiffness (+SD) as joint approached end range of motion in adduction and abduction with the hip flexed to 0 degrees (*significantly different from intact, ┼significantly different after repairs).

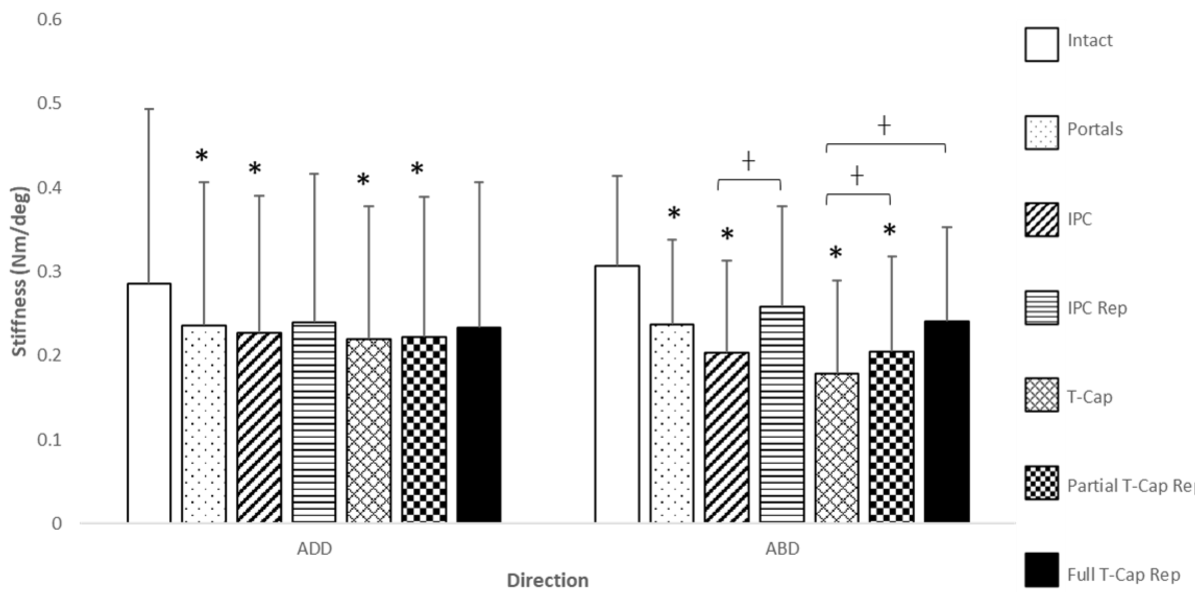


Figure 4-14: Capsule stiffness at AA limits at 30 degrees flexion

Mean capsule stiffness (+SD) as joint approached end range of motion in adduction and abduction with the hip flexed to 30 degrees (*significantly different from intact, ┼significantly different after repairs).

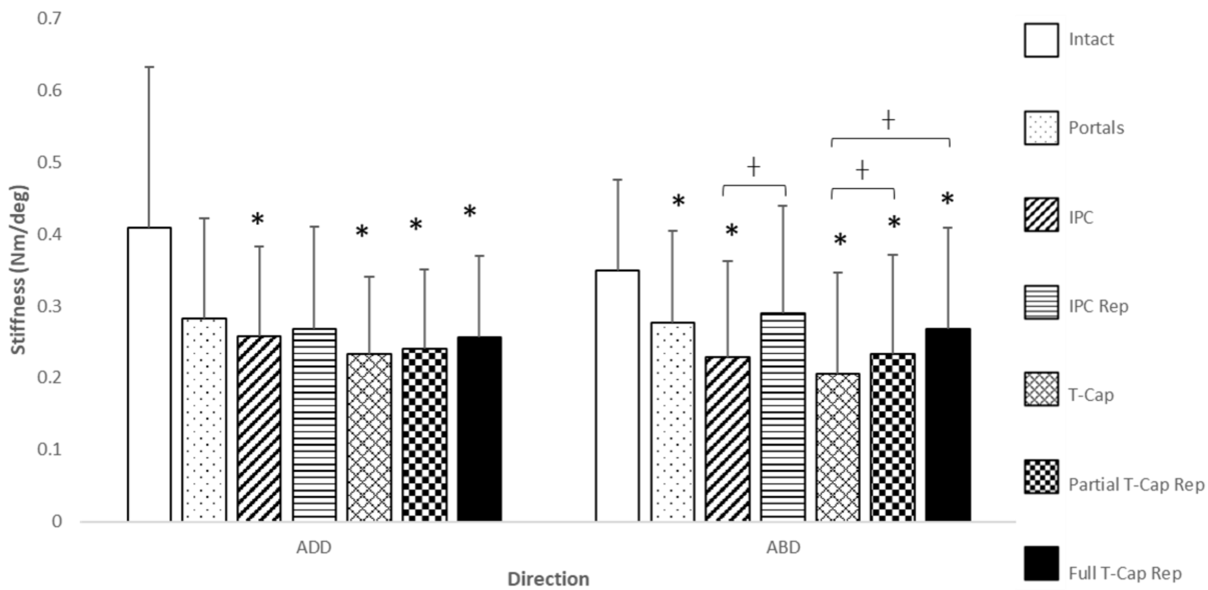


Figure 4-15: Capsule stiffness at AA limits at 60 degrees flexion

Mean capsule stiffness (+SD) as joint approached end range of motion in adduction and abduction with the hip flexed to 60 degrees (*significantly different from intact, ┼significantly different after repairs).

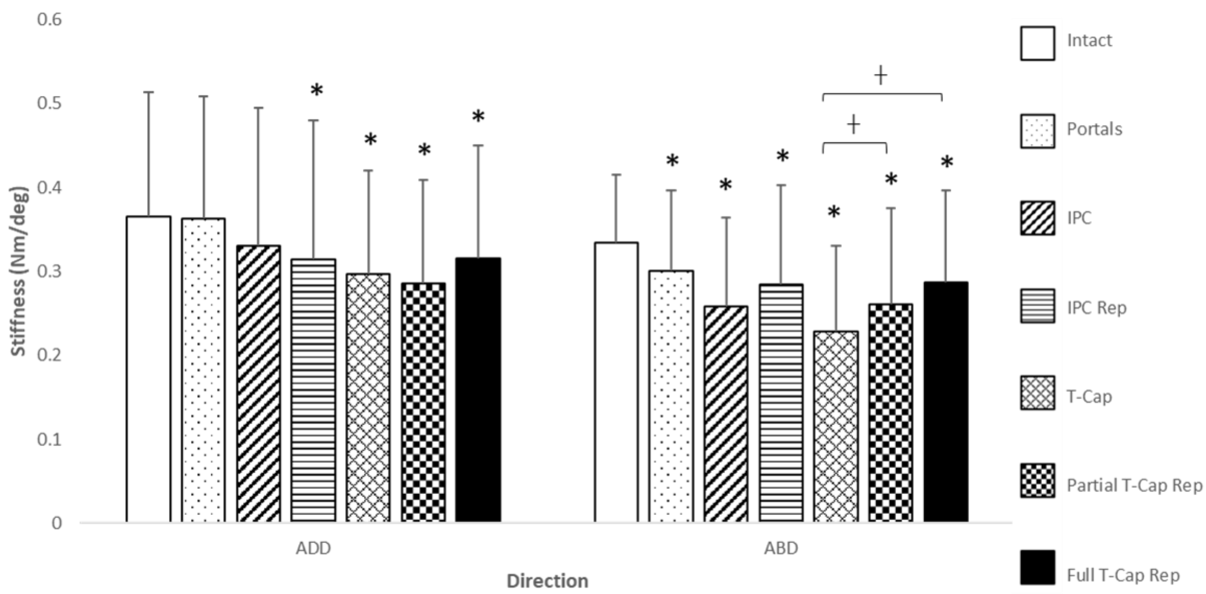


Figure 4-16: Capsule stiffness at AA limits at 90 degrees flexion

Mean capsule stiffness (+SD) as joint approached end range of motion in adduction and abduction with the hip flexed to 90 degrees (*significantly different from intact, ┼significantly different after repairs).

4.4 Discussion

The primary objective of this study was to examine changes in torque as influenced by capsulotomies and capsular repair technique on hip joint biomechanics within range of motion limits.

The results of this study suggest that the capsular ligaments that provide resistance to external rotation are those predominantly affected by capsulotomies. Consequently, resistance to external rotation movements benefit most significantly from repair.

In external rotation, measured torsional stiffness was increased with repair at all flexion angles compared to open capsulotomies, but did not achieve torsional stiffness of the intact hip. Trends were observed in regard to measured stiffness, wherein comparable stiffness to intact was reestablished following all repairs – IPC repair, partial T-capsulotomy repair, and full T-capsulotomy repairs – at each flexion angle. This was done without over-constraint of the joint with repairs as demonstrated by the fact that the torque at end range of motion was decreased with respect to the intact joint. Stiffness values also demonstrate the joint was not over-constrained at end range of motion with repairs, exhibiting similar trends of decrease with respect to intact across capsulotomy states.

Similarly, complete capsular closure – IPC repair, and full T-capsulotomy repair – restored native joint kinematics during abduction movements across all flexion angles, in accordance with other reported findings [1, 34]. This was also true during external rotation at flexion angles 30-90°, and during internal rotation at 90°. At all configurations, all repairs resulted in increased torque at end ROM compared to their respective unrepaired capsulotomy state, although this often failed to reach statistical significance, particularly for partial T-capsulotomy repairs.

As the flexion angle increased, the degree to which capsulotomy repair had to be performed became less important. This pattern correlates higher flexion angles with increased joint congruency; high congruency entails increased bony contact between the femoral head and the acetabulum. This contact provided the necessary restraint to the joint, diminishing the importance of soft tissue resistance at higher flexion angles.

These findings do not necessarily convey the same trends that have been observed when looking at increases in ROM in response to successive capsulotomy repairs. These differences are further highlighted by comparing these patterns in relation to capsule stiffness. Stiffness for the individual capsule ligaments [18, 19, 40], their directional contribution to limiting joint rotation, and their influence on hip ROM [1, 34] have each been previously explored in literature. To the author's knowledge, only one published study has reported torsional stiffness, however, their findings were limited to stiffness of the intact capsule. This study quantifies stiffness as the joint approaches the end of its range of motion in four directions. The values compute well with van Arkel et al.'s determination that hip joint motion transitions from slack to stiff "when the torque-rotation gradient exceed[s] 0.03 Nm/°" [43]. As would be expected at end ROM, all computed stiffness values were greater than this threshold. Only stiffness of the unrepaired capsulotomy states came close to the capsule remaining slack even at the end of its range of motion during external rotation at 0° flexion (IPC 0.07 ±0.07 Nm/° and T-capsulotomy 0.07 ±0.07 Nm/°) and 30° flexion (IPC 0.07 ±0.05 Nm/° and T-capsulotomy 0.09 ±0.04 Nm/°). This correlates well with the understanding that other anatomy plays a role in limiting joint range of motion, in addition to our determination that external rotation is most impacted by capsulotomies.

It has been suggested that increases in ROM post-capsulotomy could be beneficial to a patient. In cases of significant impingement or early arthritis, additional mobility may be afforded to a patient undergoing arthroscopic hip surgery by leaving the capsulotomy unrepaired [44]. Contradictory to that is the concern that the benefits of increased range of motion are shadowed by the potential to destabilize the joint [42, 43]. Apart from adduction rotation at 90 degrees flexion ($p = 0.33$), the results of the current study found that stiffness of unrepaired capsulotomies are significantly less than intact. This suggests adequate torsional resistance may not be provided to maintain stability to a joint whose ROM has been increased iatrogenically. In fact, further investigation may satisfy that increases in available ROM correlate to decreases in torque at the healthy joint's limits.

The ischiofemoral ligament has been identified as limiting excessive adduction in flexion [21]. Interestingly, these results suggest that this might be most true around the range of 30 degrees of flexion. Compared to the other flexion angles, at 30 degrees the mean torque relative to intact during repair stages is closest to replicating intact results, without ever significantly over-constraining the joint, even with repair (IPC, Partial T-capsulotomy, Full T-capsulotomy; $p = 0.9$). With its posterior-facing anatomy, the ischiofemoral ligament is largely unperturbed by the capsulotomy techniques that were employed for this study.

Observing capsular laxity in terms of relative torque allows for interpretation of results unbiased by the reporting of magnitudes of biomechanical changes that may not necessarily represent significant differences in a clinical scenario. Nevertheless, complete capsular closure was demonstrated to restore native hip joint kinematics in abduction, and certain flexion angles during external and internal rotation. Complete capsular closure should be seriously considered for patients who regularly perform activities requiring large abduction and external rotation movements, or who may be otherwise lacking anatomic restraint in these directions.

Chapter 5

5 Changes in the Translation Path of the Femoral Head Through Rotational Range of Motion

This chapter focuses on the translational tendencies of the femoral head in response to varying capsulotomy incision patterns and repairs comparative to the behavior of the intact joint. Results of this study are compared with published literature on the kinematics of the hip joint.

5.1 Introduction

In a healthy joint, an intact labrum, proper femoral head coverage by the acetabulum, and strong capsular ligaments are the primary static stabilizing factors. [3], [5], [32], [46] Instability may result from conditions such as labral and ligament tears, hip dysplasia, impingements, or tears of the ligamentum teres to name a few.

Much of the existing literature regarding translation of the femoral head refers to migration of the femoral component following total hip arthroplasty (THA); however, the phenomenon is not exclusive to artificial replacement joints. The native hip has historically been considered a true ball-and-socket joint. It is suggested this is true up to 30° of flexion [41], however further studies have shown combined rotation and translation during native movement [39, 44, 45], making it appropriate to say that the native hip only *approximates* a ball-and-socket joint. Often, these joint translations are increased by a pathology, such as labral tears, or traumatic or iatrogenic capsular injuries.

“Microinstabilty” is a term used to described increased or unnecessary motion of the femoral head within the acetabulum [39, 46]. Though acknowledged as an established pathology, it remains widely debated amongst physicians partially due to the challenging nature of diagnosis. Despite the ongoing debate, it is suggested that any abnormalities in or changes to the anatomical relationship of the joint’s components, such as those resulting from injury, increase risk of developed instability [3, 5, 46]. Similarly, arthroscopic surgery is a traumatic event, secondary to an underlying cause or initial injury, that has the potential to negatively impact the hip joint’s stability. Therefore, we sought to evaluate the implications of varying degrees of iatrogenic capsular injury on joint translation by subjecting the capsule to progressive capsular incisions.

5.2 Methods

Specimen Preparation

Simultaneous to the torque data presented and analyzed in Chapter 4, position data was collected from the same ten (10) fresh-frozen hemi-pelvis and proximal femur (6 male, 4 female, 2 pairs, 48-69 years of age) for this study. The chosen specimen excluded donors over the age of seventy (70), with a body-mass index (BMI) greater than forty (40) or having a history of cancer with metastases to bone. In addition, the donor summary for each specimen was screened to ensure the absence of osteoarthritis according to next of kin. Additional screening was done upon receipt after computed tomography (CT) scans were done for each specimen. From the images, a surgeon confirmed the absence of arthritis and any other bone morphologies that may have resulted in joint impingement. Specimen were left to thaw for up to 36 hours as dictated by size and BMI. Once thawed, all soft tissue superficial to the capsule was removed. A surgeon manipulated the joint and established its neutral position based on specimen specific range of motion. One or two pins were drilled through the neck of the femur and into the pelvis to temporarily fix the joint in the established position (Figure 4-1). Biomechanical testing of each joint was performed using a VIVO joint motion simulator (Advanced Mechanical Technologies Inc., Massachusetts, USA).

Potting of the pelvis

Mounting the specimen to the VIVO required the pelvis be osteotomized to fit the confines of the designed pot. Large portions of the ilium, pubis and ischium were removed with a bone saw, ensuring to leave ample surface around identified capsule insertion points and enough bony anatomy for securing in dental stone (Modern material Golden Denstone Labstone, Modern Materials, Kulzer GmbH, Hanau, Germany). The specimen was deemed to be in the correct orientation for cementing when:

1. The femur formed a 38° angle with the tabletop. This angle translates to a 7° mechanical axis [11] when the specimen is vertical.

2. Visually, the pot's cylindrical axis passed through the centre of the femoral head

The pelvic pot (3.5" inner diameter, polyvinyl chloride pipe coupling) is held in a custom fixture that connects to the VIVO's upper actuator. Correct rotational positioning within the upper pot was achieved by making the stabilizing pins lie parallel to the coronal plane of the VIVO. With this, the joint was neutrally rotated in the three degrees of freedom as well as with respect to the machine. Once established, the stabilizing pins were removed allowing for the joint to mobilize freely.

Establishing joint centre

A custom fixture was used to allow for specimen alignment with the machine centre. The centre of the femoral head is accepted to be the centre of rotation of the joint and was the targeted point for alignment with the machine. With the pelvic pot held stationary in the upper fixture, a tracker was mounted to the lateral-distal face of the femur. The tracker was visualized by an Optotrak Certus (Northern Digital Inc., Waterloo, CA) and calibrated with respect to a second tracker place on the VIVO. A sphere fit was performed by manipulating the femur to move the hip through its range of motion. Flexion was limited to less than 30° [41]. The motion capture provided coordinates for the centre of the sphere with respect to the VIVO's coordinate system. The specimen's position was adjusted via the fixture and the sphere fit remeasured. These steps were repeated as necessary until the joint centre was reported to be less than two (2) mm from the machine's origin in all translational DOFs. The specimen was then deemed to be in an anatomically neutral position with respect to the machine.

Potting of the femur

A surgeon reestablished neutral IE rotation and flexion of the femur with respect to the pelvis (previously established prior to pinning). The angle of the femur was verified with a goniometer to be 7° [11] from vertical for confirmation of neutral abduction. The

VIVO's lower actuator was moved until the femur fell inside the pot and the distal femur pointed to its centre. In this position it was cemented in place.

Force controlled intact test

Two (2) compressive forces of 10 N were applied to the femur. The first acted directly superiorly, and the second directly medially through the approximate joint centre to maintain joint reduction. Pure rotational torque of 5 Nm was sequentially applied to the specimen via manual input in internal rotation, external rotation, abduction, and adduction. While applying IE torques, the joint was held in its neutral anatomic abduction position, and in anatomic neutral IE rotation while applying abduction torques. The entire sequence was repeated 3 times to condition the joint and diminish the potential effects of ligament creep. On the last repetition in each direction, the maximum angular position was recorded to 2 decimal places, quantifying end range of motion. This sequence was done at the four fixed flexion angles of 0, 30, 60 and 90 degrees, resulting in a total of sixteen identified limits. It is important to note that adduction range of motion was restricted by mechanical limitations. From the anatomical neutral position, the available range of motion in adduction is capped at 35 degrees. Had mechanical range of motion limits been reached in IE rotation, a bias was applied by repositioning the lower fixture.

Baseline displacement

The same compressive forces are applied to the joint as describe for Force controlled intact testing above. The healthy joints rotated through their range of motion; from 0° to the position at maximum torque recorded during the Force controlled trials. For a total of sixteen (16) runs – 1 in each direction at 4 distinct flexion angles.

Displacement controlled test

In addition to the intact sates, these 16 trials were repeated with the joint in states of increasingly large capsular incision and their respective repairs. These clinically relevant states were tested sequentially as follows: portals, interportal capsulotomy, interportal capsulotomy repair, T-capsulotomy, full T-capsulotomy repair, and partial T-capsulotomy repair. All incision placement determinations and sutures were performed by a surgeon. An anterolateral and mid-anterior portal, each approximately 1 cm long, were made in the iliofemoral ligament for the first capsular state. A straight incision connects the portals to create an interportal capsulotomy. Four (4) interrupted simple sutures closed this incision for the interportal repair. A perpendicular incision half the length of the interporal (approximately 1.5 cm) at its midpoint formed the T-capsulotomy state. The T-capsulotomy was fully repaired with two and four interrupted sutures on the vertical and horizontal limbs, respectively. The first set of sutures were removed to create a partial T-capsulotomy. And finally, all sutures were removed to test the unrepaired T-capsulotomy. Torques and positions in the 6 degrees of freedom were recorded through the entirety of each trial.

Data sampling and scaling

Data was collected at a sampling rate of 500 Hz. The following described data scaling was done using MATLAB (MathWorks, Massachusetts, USA). The data was smoothed via a Butteroworth filter and down-sampled to 1000 points. Results collected from left-sided specimen were mirrored to match sign conventions associated with right-sided specimen. The raw displacement data quantifies the travel of centre of the femoral head from the mechanical origin. These displacements are influenced by the accuracy of potting, as the femur is inclined to “chase” an improperly positioned pelvis. Observing relative displacement of the joint with respect to the intact state, minimizes the impact of small misalignments, and creates a baseline for inter-specimen comparisons. The relative displacement in each direction was averaged across a given rotational cycle, in addition to total relative displacement.

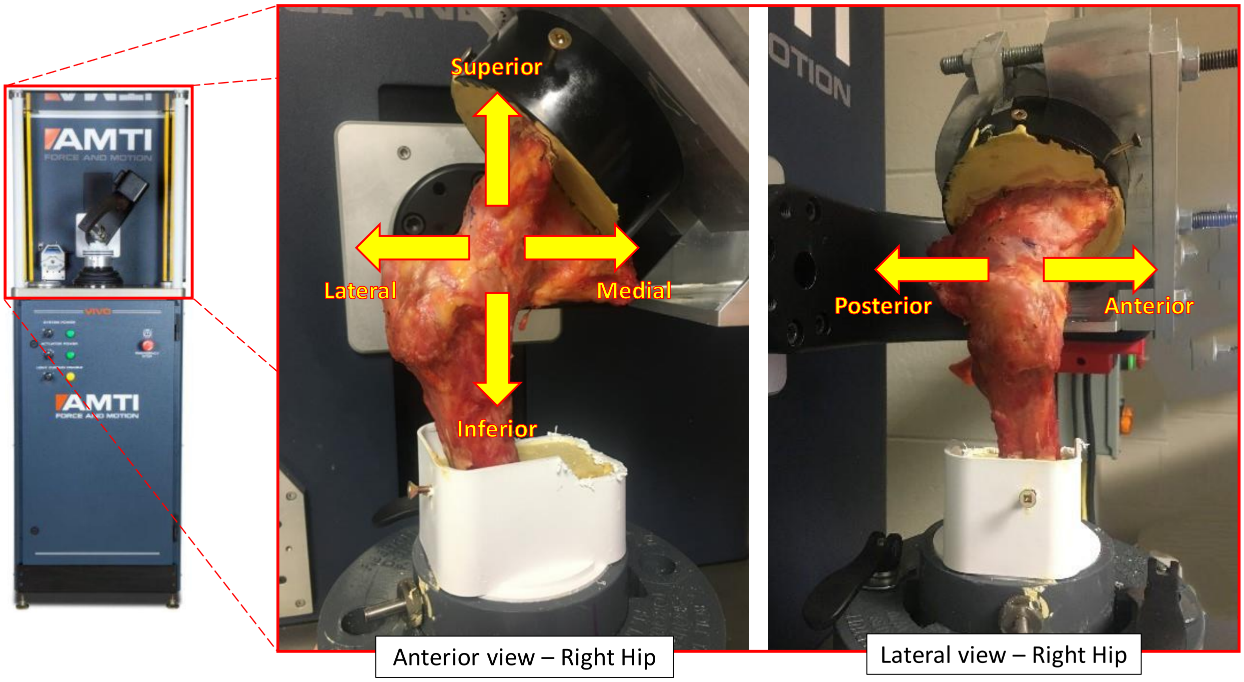


Figure 5-1: Experimental femur translations

Femur translations with reference to experimental setup on the AMTI VIVO joint motion simulator

<u>Statistical Analysis</u>

One-way repeated measures ANOVAs with subsequent post-hoc analysis with Bonferroni correction were used to assess significant differences for the three translational kinematic variables, and total translation across six capsulotomy states. A *p* value < 0.05 was considered statistically significant. Post-hoc analysis included the calculation of effect size (ES/ *Cohen's d* value), specifically to compare the following capsulotomy states: (1) intact versus all subsequent conditions, (2) IPC versus IPC repair, (3) T-capsulotomy versus full T-capsulotomy repair, and (4) T-capsulotomy versus partial T-capsulotomy repair. Small, medium, and large d values are defined as d=0.2, 0.5 and 0.8, respectively. Statistical comparisons were restricted within the prescribed flexion angle and performed using a commercial statistics software package (SPSS, v.27, IBM SPSS).

5.3 Results

None of the performed comparisons resulted in statistically significant difference. However, trends in relative displacement across capsule states and between flexion angles were observed.

Medial-Lateral (ML) Translation

During external and internal rotation movements, the femoral head favored a medial position with respect intact across all flexion angles and capsule states except for IPC states. Instead, mean lateral translation occurred during internal rotation and abduction at all flexion angles except for 60° during internal rotation. During adduction, lateral displacements increased with the flexion angle for T-capsulotomy states, beginning at 0.6 ±1.1mm with the hip flexed to 0° and reaching 0.8 ±1.0mm at 90°. Maximum medial translation was achieved at 0° flexion, for both external rotation (1.1 ±1.3 mm - IPC) and internal rotation and (1.0 ± 1.3mm – IPC repair).

Anterior-Posterior (AP) Translation

During internal rotation, external rotation, and abduction, the joint trended towards a posterior position, with respect to intact across all capsule states and flexion angles except for during abduction and internal rotation at 0° flexion. During each of these rotations, IPC repair (0.2 ±0.5 mm (abduction), 0.2 ±0.6 (internal rotation)), and full T-capsulotomy repair (0.06 ±0.6 mm (abduction), 0.06 ±0.6 (internal rotation)), instead encourages anterior translation of the joint

At 90 degrees flexion, repairs (IPC, partial T-capsulotomy repair, and full T-capsulotomy repair) were more posteriorly positioned that their unrepaired counterpart.

Total Displacements

All capsulotomy interventions beyond creation of the portals resulted in significant increases in displacement of the femoral head with respect to intact through external, internal, abduction and adduction rotations. Under all conditions, translations consistently trended posteriorly and inferiorly. The exception to this was internal rotation at 0 degrees of flexion, which averaged anterior translation of the femoral head relative to its path while intact during IPC repair (0.1 ± 0.6mm) and full T-cap repair (0.5 ± 0.5mm). Mean total displacement between IPC and IPC repair were insignificant in all configurations and loading conditions (p>.05), except external rotation at 90 degrees of flexion (p =.022). Mean total translation between T-cap, partial T-cap repair and full T-cap repair did not significantly differ.

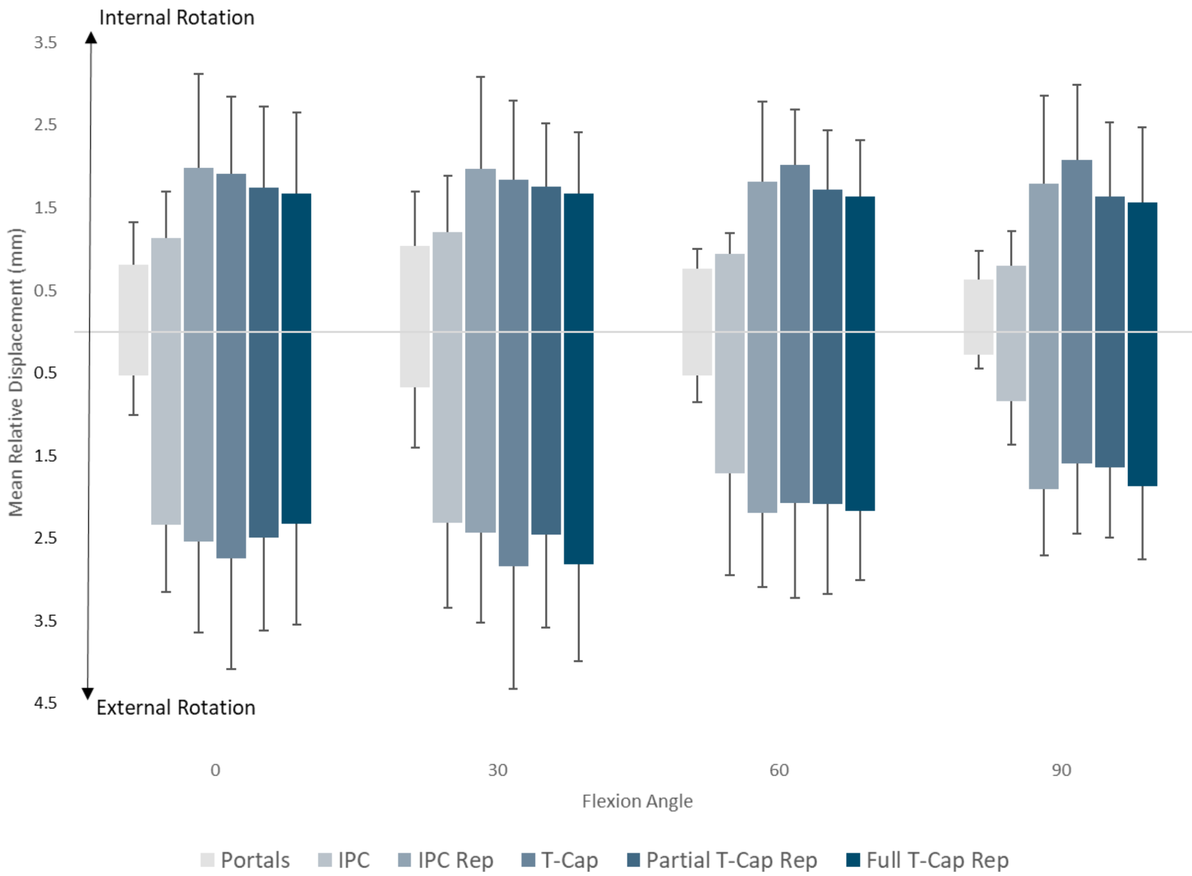


Figure 5-2: Total Relative femoral head translation with respect to intact state at four flexion angles during internal and external rotation

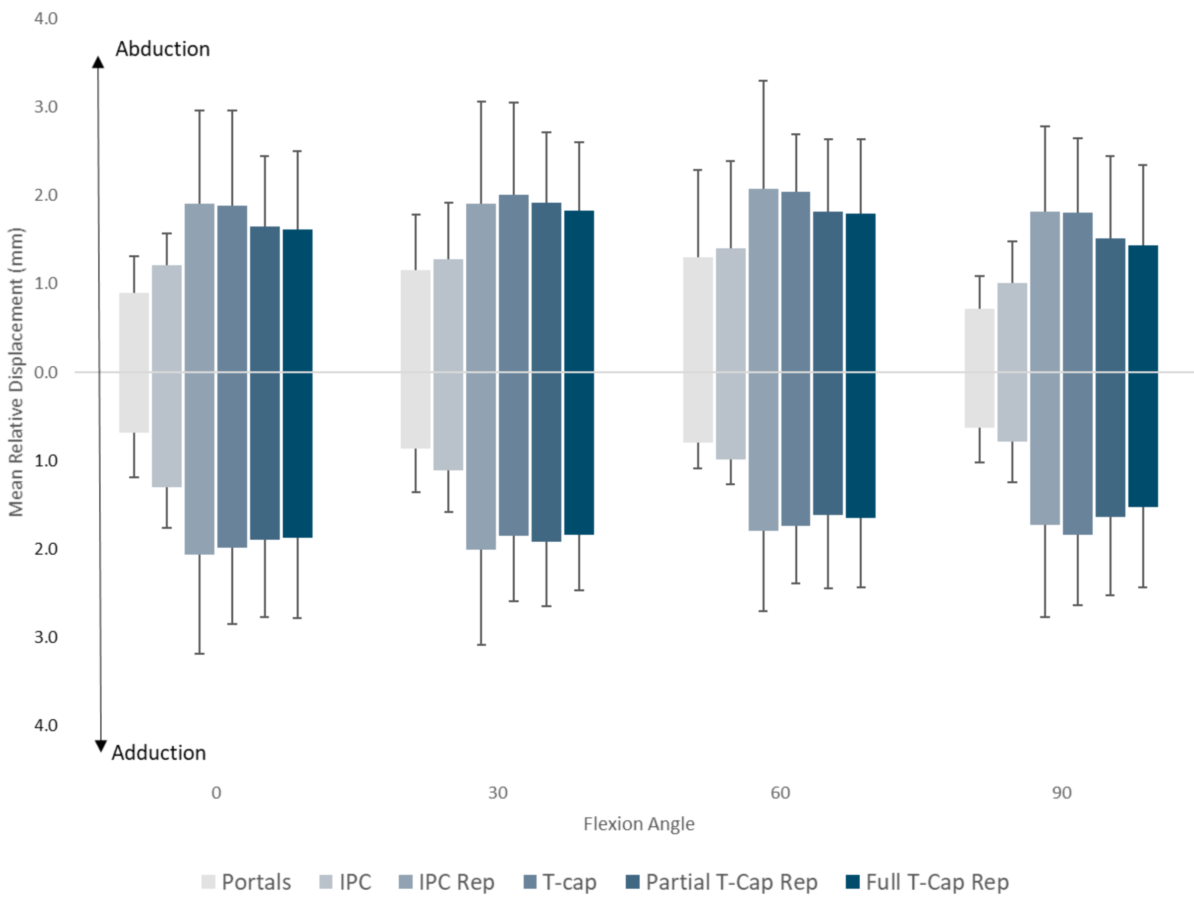


Figure 5-3: Total Relative femoral head translation with respect to intact state at four flexion angles during abduction and adduction

0 Degrees Hip Flexion

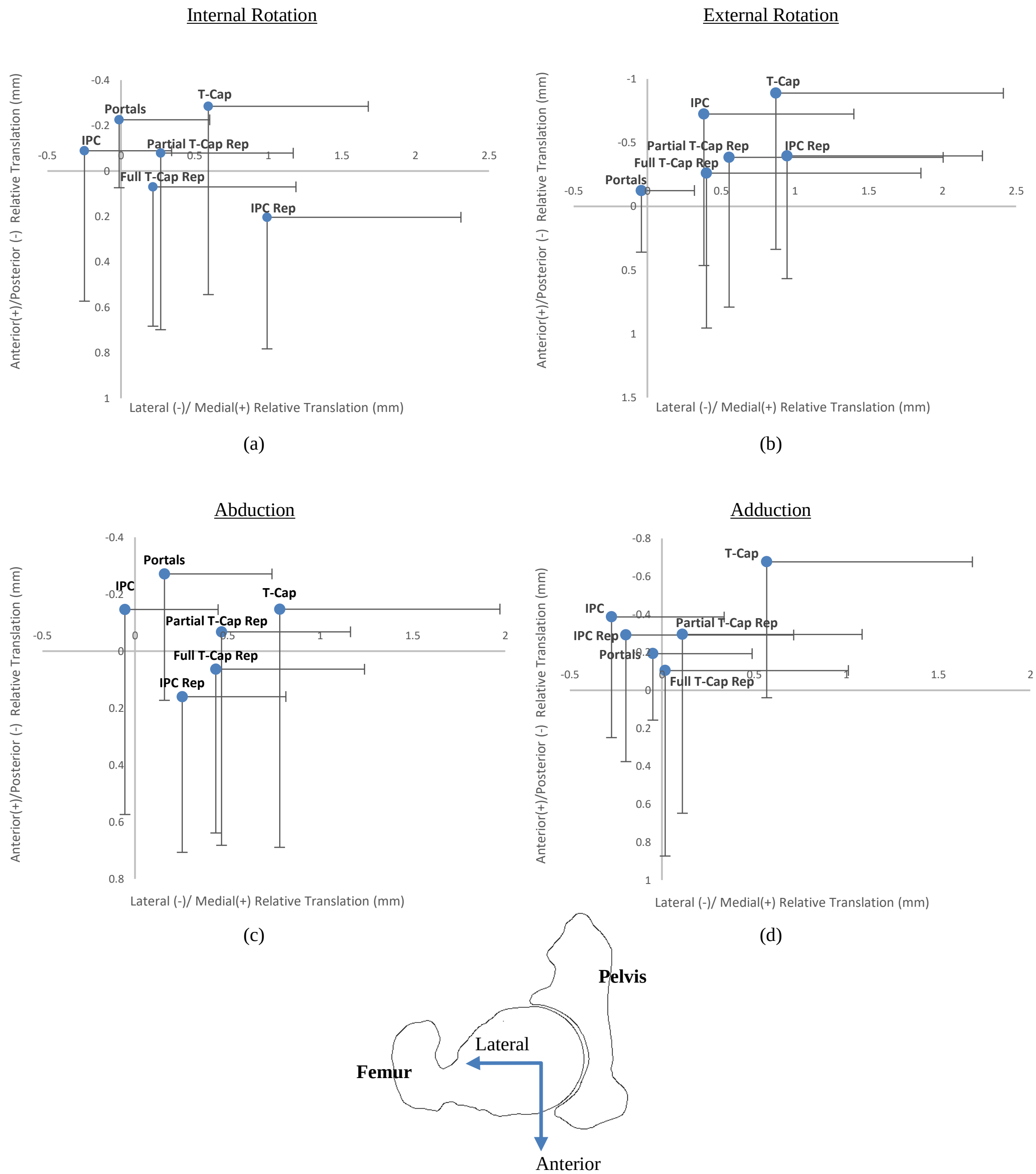
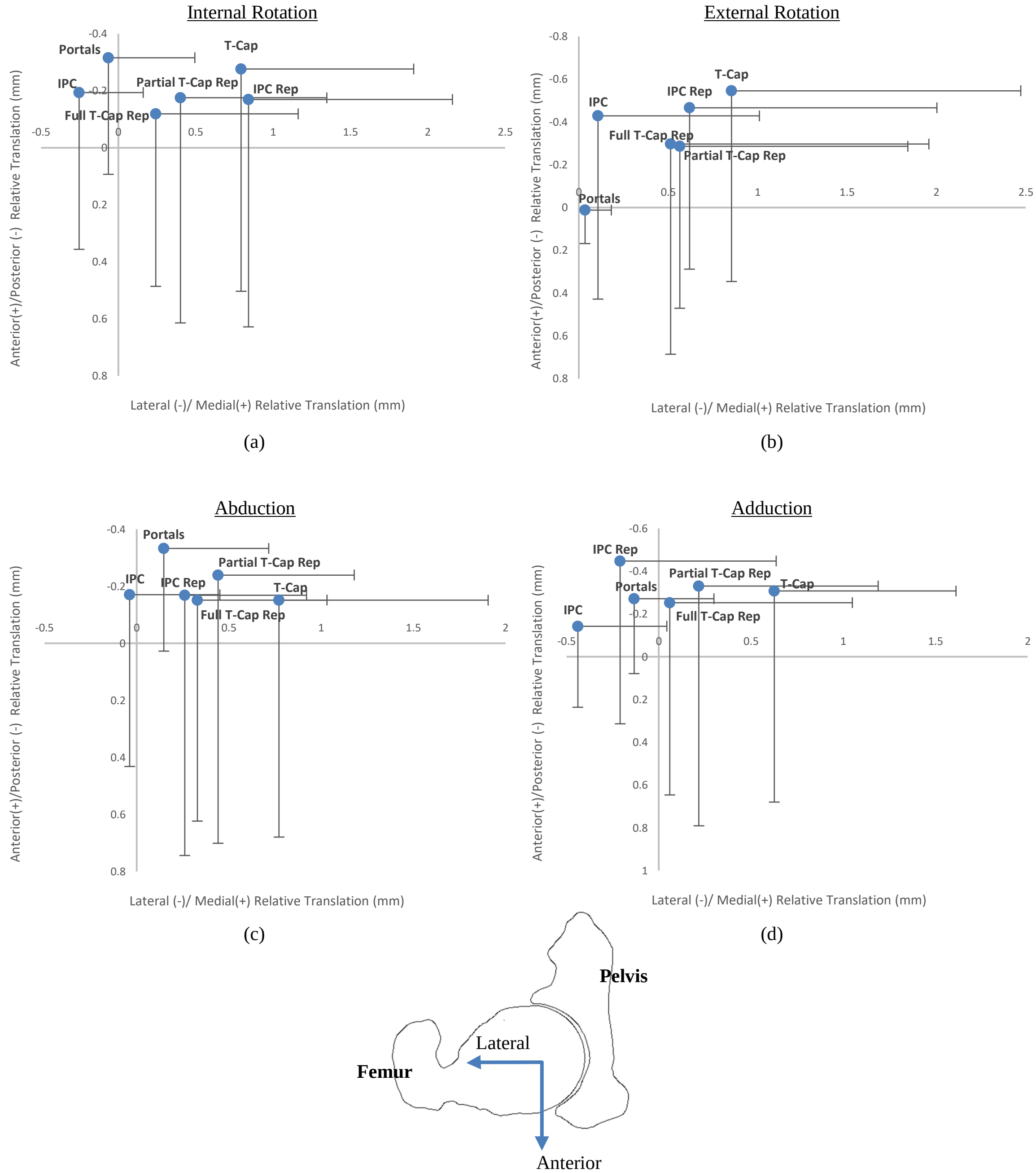


Figure 5-4: Translations at 0° flexion

Translations during 6 varied capsule states are each presented with respect to translation during intact. Mean total anterior/posterior (+SD) vs medial/lateral (+SD) translation as the femur was rotated from neutral to maximum internal rotation (a), external rotation (b), abduction (c) and adduction (d), with the hip flexed to 0 degrees. Transverse cross section of the femoral head and pelvis (e) indicates direction of translations.

30 Degrees Hip Flexion



(e)

Figure 5-5: Translations at 30° flexion

Translations during 6 varied capsule states are each presented with respect to translation during intact. Mean total anterior/posterior (+SD) vs medial/lateral (+SD) translation as the femur was rotated from neutral to maximum internal rotation (a), external rotation (b), abduction (c) and adduction (d), with the hip flexed to 30 degrees. Transverse cross section of the femoral head and pelvis (e) indicates direction of translations.

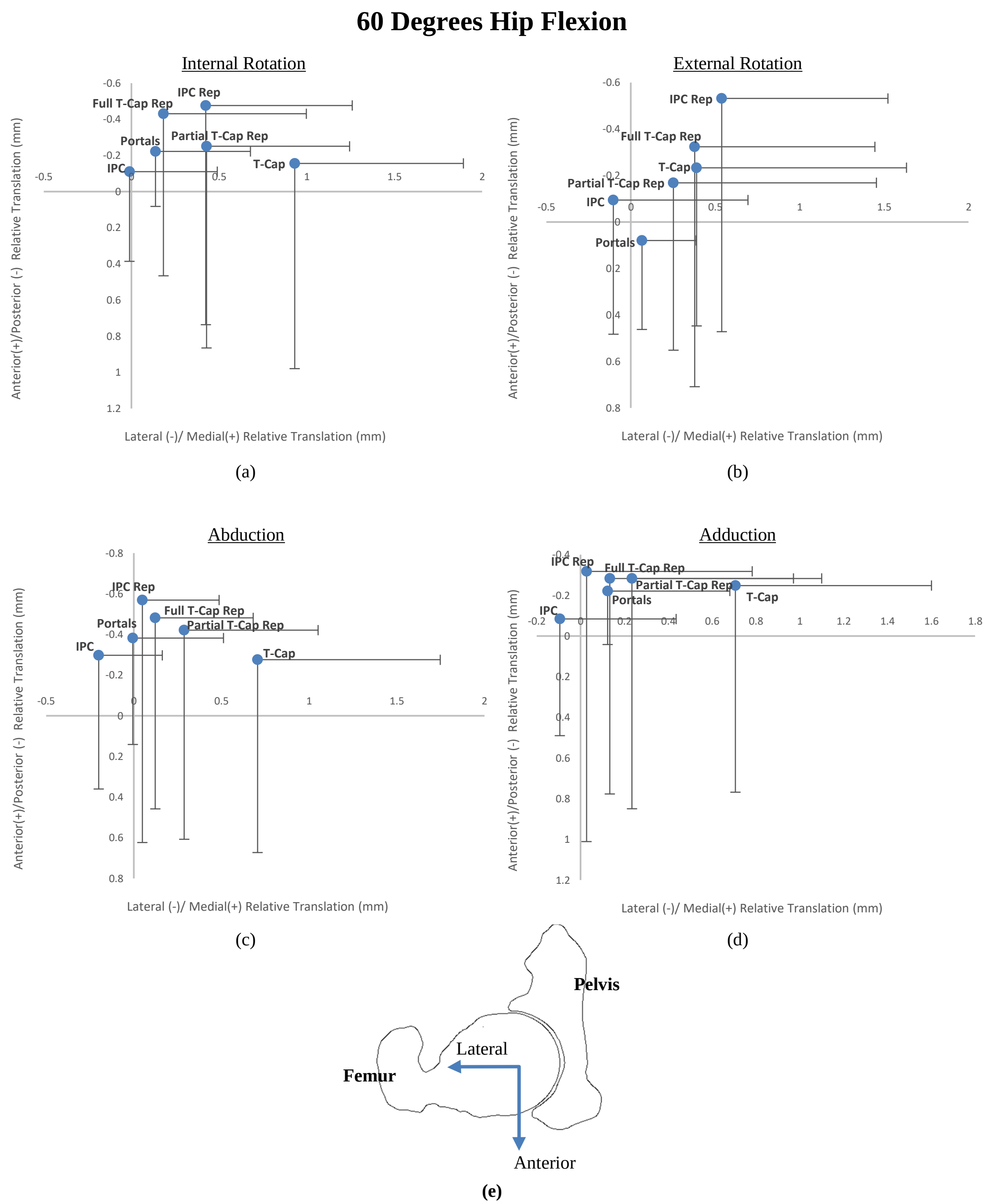


Figure 5-6: Translations at 60° flexion

Translations during 6 varied capsule states are each presented with respect to translation during intact. Mean total anterior/posterior (+SD) vs medial/lateral (+SD) translation as the femur was rotated from neutral to maximum internal rotation (a), external rotation (b), abduction (c) and adduction (d), with the hip flexed to 60 degrees. Transverse cross section of the femoral head and pelvis (e) indicates direction of translations.

90 Degrees Hip Flexion

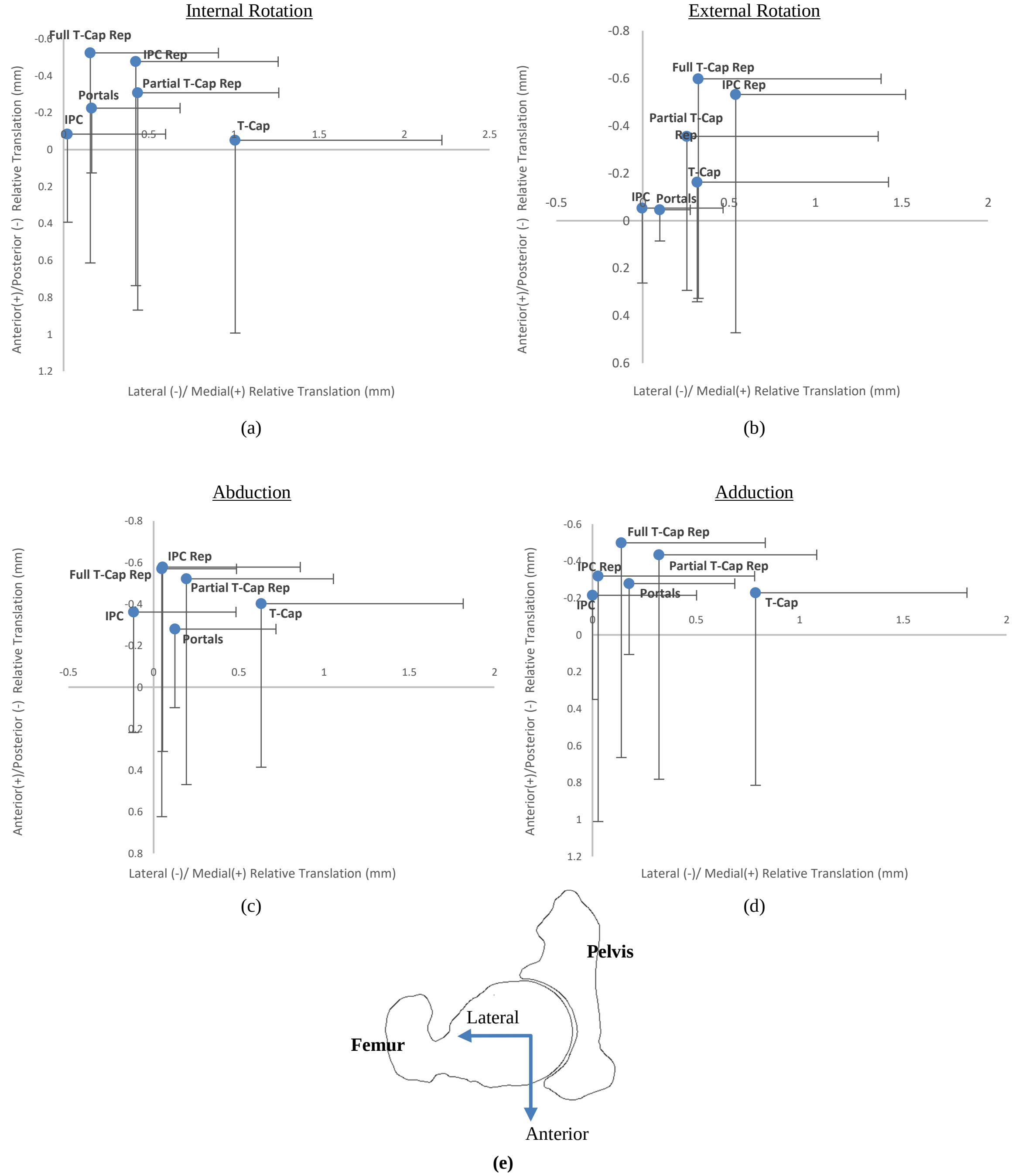


Figure 5-7: Translations at 90° flexion

Translations during 6 varied capsule states are each presented with respect to translation during intact. Mean total anterior/posterior (+SD) vs medial/lateral (+SD) translation as the femur was rotated from neutral to maximum internal rotation (a), external rotation (b), abduction (c) and adduction (d), with the hip flexed to 90 degrees. Transverse cross section of the femoral head and pelvis (e) indicates direction of translations.

5.4 Discussion

This biomechanical study was designed to evaluate the effect of successive capsulotomies and their complementary repairs of the translations of the femoral head. The presented results suggest that no significant changes in translation are introduced with the performance of a capsulotomy, nor do they occur as a result of performing a repair. This is suggested to be true for all translational DOFs, at each of the four discrete tested flexion angles, and independent of the direction of rotation. However, this is not to say that the joint was not influenced at all.

At 90° of flexion, it appears that all capsulotomy repairs encouraged posterior translation relative both the intact joint, and unrepaired counterparts. The relative posterior translation decreased as the flexion angle decreased. Complimentary to this, the iliofemoral ligament has been said to provide resistance to anterior translations [47, 48].

This study observed translation of the hip (i.e., femur relative to pelvis) over the entire envelope of passive ROM, through a serial sectioning protocol. This differs from literature and may help convey a different message. One study that observed changes in translation of the femoral head in response to “pie crusting” (array of patterned incisions) between five prescribed test positions with varying combined FE, IE and AA rotations applied [49]. Connecting the coordinates of the femoral head between these points created their observed femoral head path. They found overall anterior (and inferior) translation as a result of internal rotation torques, where posterior translation was favored during internal rotation movements. However, our results showed relative anterior displacement in abduction instead.

Observing total translation adds to these findings. Suggesting that capsular compromise leads to altered patterns to the path of the femoral head that are not reversed with repair of damaged tissues.

The data from this study supports the understanding that there are other structures within the joint cavity that contribute to resisting joint translations and maintaining stability. Myers et al. [8] conducted a sectioning study focusing on the stability afforded to the hip by just one of the capsular ligaments – the iliofemoral ligament – and the labrum. They found that stability afforded to the joint by the labrum was secondary to the iliofemoral ligament.

Contrarily, Nepples et al. suggest that the labrum is the primary stabilizer in response to distraction forces [51]. Our results support this assumption. Additionally, the lack of significant translations found in the current study is a useful determination clinically. Our results suggest that joint congruency, and an intact labrum are sufficient for maintaining joint stability that is equivalent to intact regardless of damage or changes to the hip capsule. During the current experiment, the labrum was intentionally left unperturbed, effectively maintaining the joint's natural suction seal. Considering the complementary conditions under which the labrum and iliofemoral ligament have been demonstrated to be primary stabilizers of the joint, we suggest capsulotomy repair may be less important for joint stability

The results of the current study suggest that displacement patterns of the femoral head are significantly increased once an interportal incision has been made. Though the direction of these translations is not consistent and bore no significant changes between capsule states across flexion angles and directions of rotation. Though translations can be reduced with repair, total joint kinematics are not comparable to that of the intact joint. External rotation is the movement most susceptible to displacements across all flexion angles and capsule states. Drawn conclusions are limited by the unavoidably sequential nature of the performed capsule states.

Chapter 6

6 General Summary and Future Works

This chapter reviews the objectives and hypotheses that motivated the experiments conducted as means to test them. This chapter also addresses the limitations and strengths of the presented work. Finally, the future directions that research from this study can continue to explore, in addition to its significance towards motivating the approach to capsule management during arthroscopic hip surgery.

6.1 Summary

Hip arthroscopy is a minimally invasive surgery that is being used with increased frequency for the management and treatment of numerous hip pathologies. To access the joint, the surrounding ligaments, called the capsule, must be penetrated, and consequently compromised. There are multiple approaches to incising the capsule. As is widely debated in the field, both the capsulotomy incision pattern and the degree to which it is repaired may impact native joint biomechanics. Advancements in robotic joint-motion systems for have been severely underutilized regarding orthopaedic biomechanics research of the hip.

Chapter 3 introduced and assessed the VIVO joint motion simulator as a suitable platform for evaluating hip joint biomechanics by comparing ROM results from publications that have explored range of motion limits. Though fewer references exist for comparison at discrete flexion angles, joint limits were comparable to those available in addition to clinically referenced limits. Once established, the next objective was to investigate how successive capsulotomies and their respective repairs impacted joint laxity, more specifically, the capsule’s ability to continue providing torsional resistance. We quantified changes in laxity as relative torque at end range of motion and measured rotational stiffness as it reached this point. Interestingly, cross-capsulotomy patterns of comparison for relative torque did not necessarily translate to similar behaviors of stiffness. Therefore, both variables are required to paint a complete picture of the impact an altered capsule has on joint behavior.

Complimentary to rotational laxity in its role in contributing to joint stability, are joint translations. At this hip, translations are measured as the relative displacement of the femoral head with respect to the acetabulum. Chapter 5 investigated changes in the three translational DOFs in response to the same successive capsulotomy incisions and repairs. Unlike rotational laxity, no significant changes in the kinematic data were observed following capsular incisions, nor were any translations behaving significantly differently from the intact state.

6.2 Limitations and Strengths

One limitation of our study is the uncertainty of force application for the VIVO. Technical documentation [38] assigned to the machine assigned the following uncertainties: ± 0.6 Nm for the internal-external torques, ± 1.2 Nm for abduction-adduction torques, and ± 21 N and ± 41 N for the medial and superior reduction loads, respectively. However, applied forces to reduce the joint were small and held constant through a given test.

The sequential nature of the successive capsulotomies did not allow for the randomization of capsule state testing order. As with all cadaveric research, our study is also limited to time-zero kinematics, with no ability to infer the how healing after arthroscopy may impact hip joint kinematics. Additionally, the involved preparation and duration of experiment required a two-day protocol; separating specimen preparation and centering from the beginning of testing and days one and two respectively. However, the stripped and potted specimen were refrigerated overnight and periodically spritzed with saline solution to maintain tissues moisture throughout testing. Storing the specimen between days one and two of the protocol was done via a single bolt to remove the entire fixture from the VIVO without affecting any adjustments made to centre the specimen with respect to the machine’s origin. Once mounted to begin testing on day two of the protocol, the specimen need not be removed until testing was completed.

Despite the identified limitations, the presented work had several strengths. The choice to investigate varied kinematics with respect to the intact joint within an established working range of motion minimized the possibility of damaging the joint or tissues of interest during the experimental process. The impact of aforementioned uncertainty of force application is eliminated by presenting torque experienced during all capsulotomy stages with respect to intact.

Other studies have analyzed the effect of varied capsulotomies on the increases in range of motion at a predetermined torque. Another strength of this study was its inclusion of superior/inferior translation data. Previous studies have focused on anterior/posterior and medial/lateral translations.

6.3 Future Work

As a continuation to the gained knowledge from the presented studies, it will be important to evaluate the impact of these same capsulotomy and repair states, on joint biomechanics during activities of daily living (ADL). Since the joint is rarely brought to its limits during activities such as walking or stair-climbing, each capsulotomy may have a lesser or different influence on joint biomechanics. Similarly, investigating changes in biomechanics through successive capsulotomies during more specific movements such as a squat or a lunge would target athletes and expand on commonly reported ADLs to reflect the more youthful population who largely contribute to the frequency with which hip arthroscopies are being performed in North America. In addition, similar studies should be performed while subjecting the femur to differently directed forces. The changes in translation through capsulotomy stages as a result of an anteriorly, posteriorly, or laterally directed force could inform on the joint's resistance to or propensity for dislocation. Since our results are already suggesting posterior translations under compressive forces. Similarly, evaluating changes in displacements in response to a larger medially directed force could simulate behavior of the joint during the performance of low- or high-impact activities

6.4 Significance

This study is the first to use the VIVO joint motion simulator for investigating the biomechanical behavior and role of the capsule ligaments of the hip in response to serial sectioning and complementary repairs. Establishing use of this sophisticated system for biomechanical evaluation of cadaveric hips not only allows for analysis of the joint under increasingly complex or combined motions but could also lead to hybrid computational-experimental studies by employing the VIVO's virtual ligament capabilities. The findings from this study could inform surgeons on their choice of capsulotomy incision pattern and degree of repair. It was demonstrated that both translations and torsional stiffness play a role in contributing to joint stability and can be manipulated via minimally invasive surgical approach to influence joint laxity relative to pre-arthroscopy to the benefit of the patient.

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Appendices

Appendix A: Relative Torque Through Capsulotomy Stages

The figures below depict torque through rotational displacements with respect to torque experienced by the intact joint at the ends range of motion. Values are expressed as percentages. The sign of the expressed percentages differentiates the direction of the performed rotation. (Internal rotation (+) vs External rotation (-), and Abduction (+) vs Adduction).

Appendix A.1: Relative torque through capsulotomy states during IE rotations

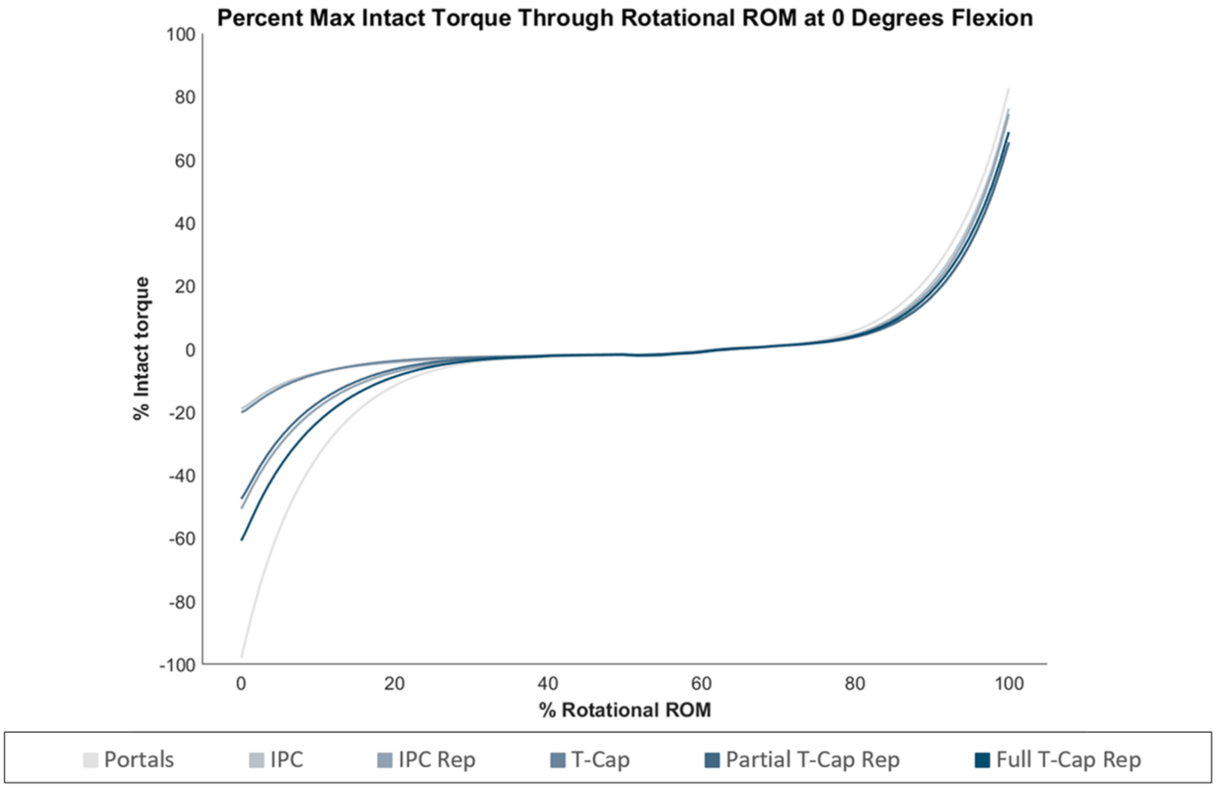

Figure A1-1: Relative torque during IE rotation at 0° flexion

Percent of intact torque at end range of motion experienced across entire rotational range of motion with the hip flexed to 0 degrees across all capsule states.

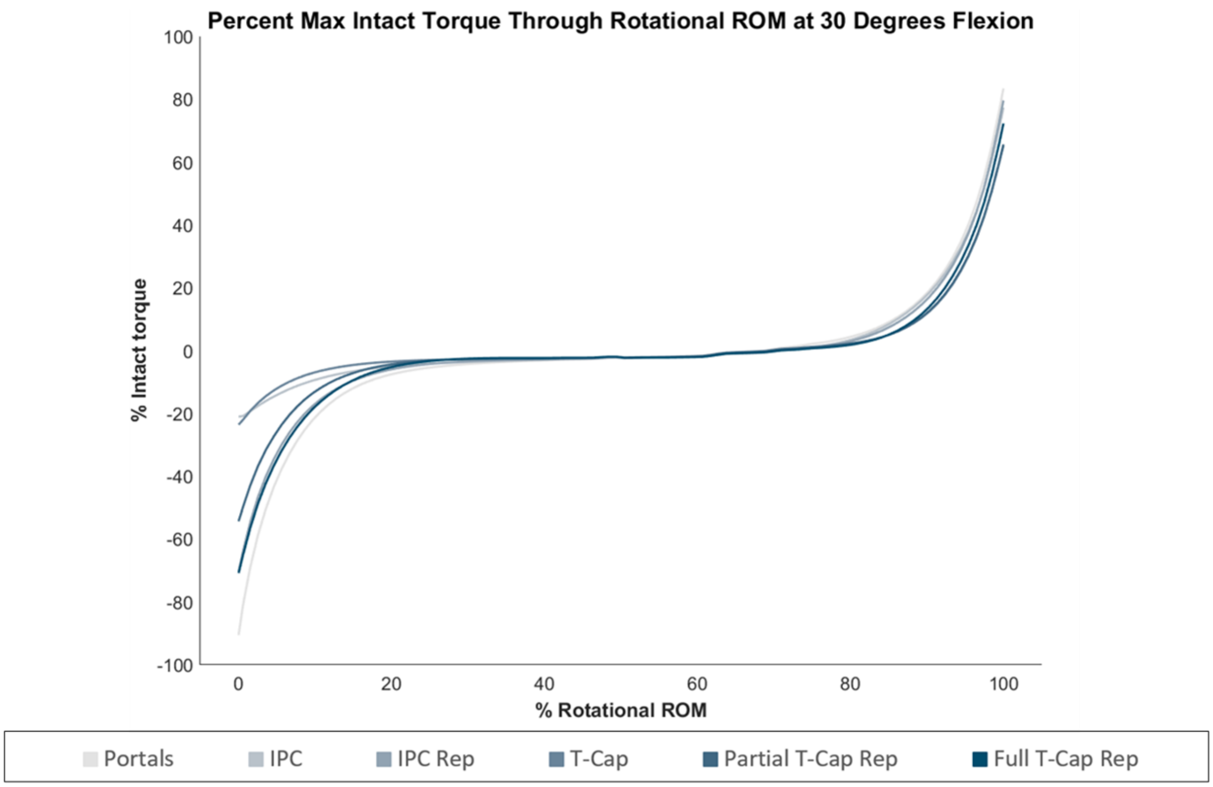

Figure A1-2: Relative torque during IE rotation at 30° flexion

Percent of intact torque at end range of motion experienced across entire rotational range of motion with the hip flexed to 30 degrees across all capsule states.

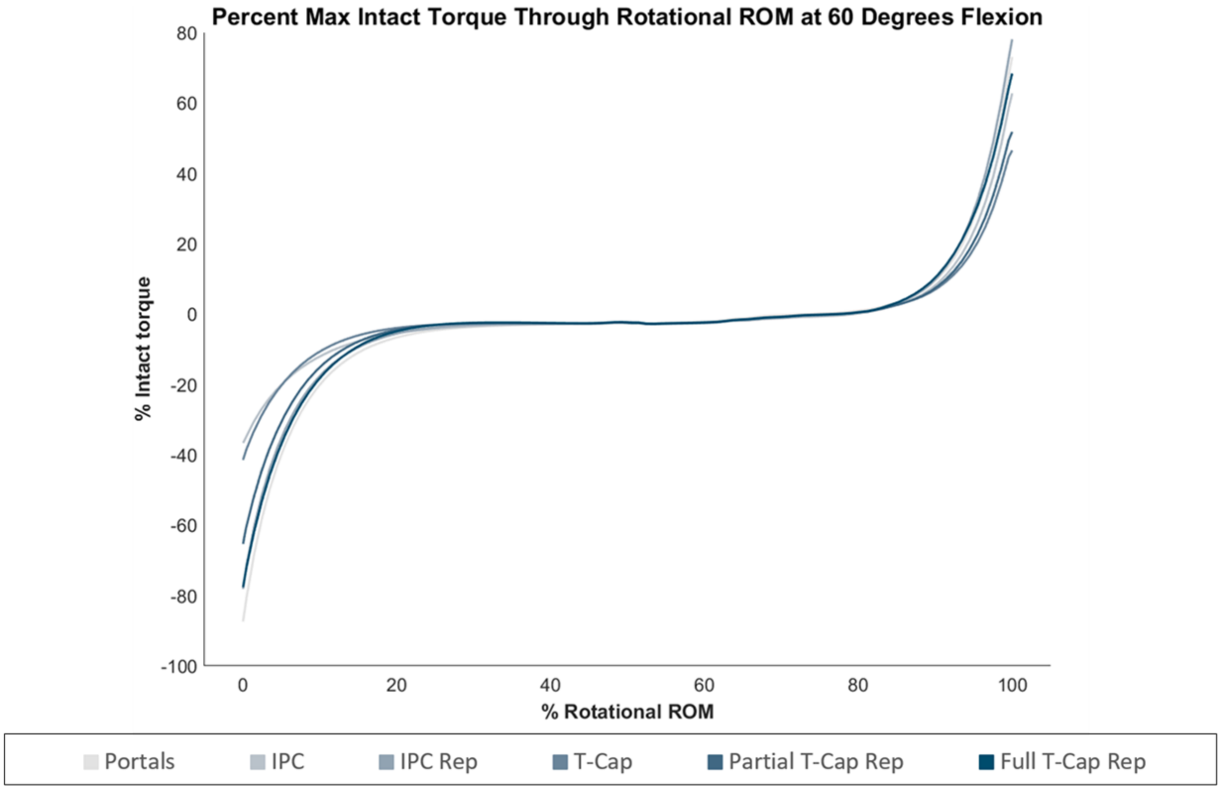

Figure A1-3: Relative torque during IE rotation at 60° flexion

Percent of intact torque at end range of motion experienced across entire rotational range of motion with the hip flexed to 60 degrees across all capsule states.

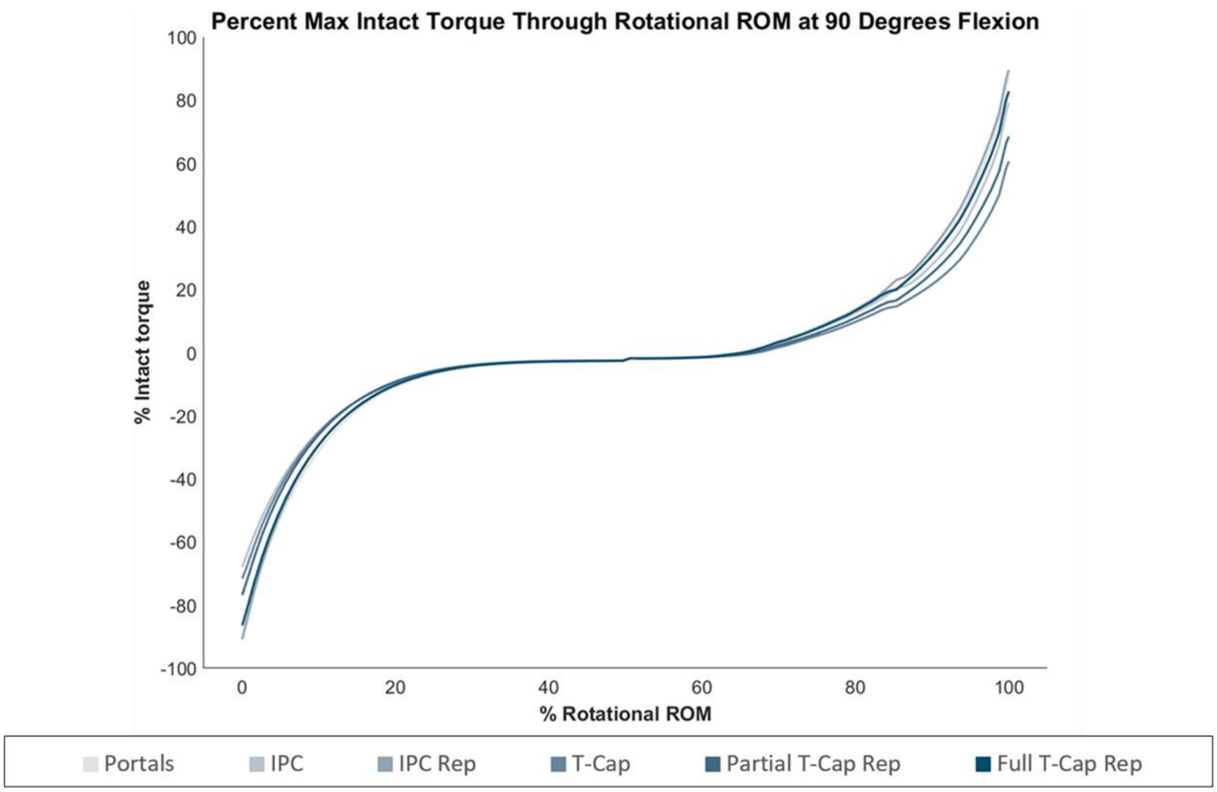

Figure A1-4: Relative torque during IE rotation at 90° flexion

Percent of intact torque at end range of motion experienced across entire rotational range of motion with the hip flexed to 90 degrees across all capsule states.

Appendix A.2: Relative torque through capsulotomy states during AA rotations

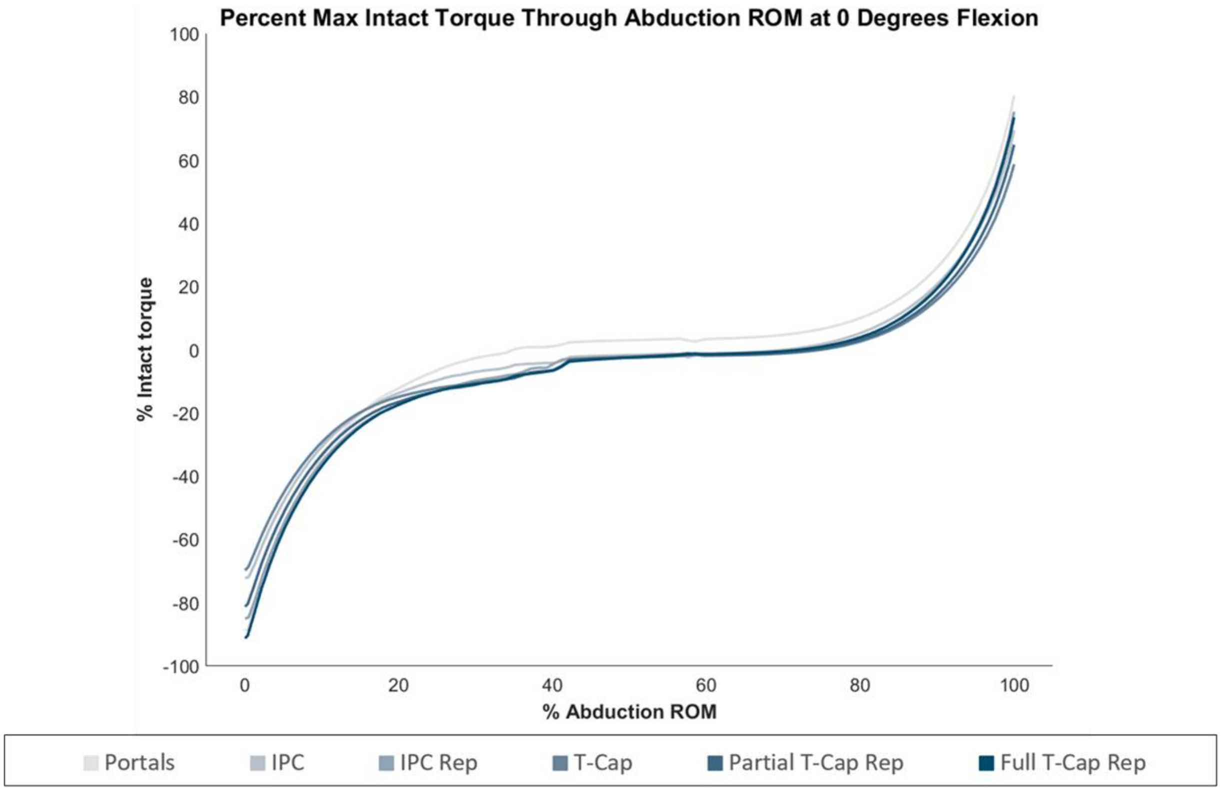

Figure A2-1: Relative torque during AA rotation at 0° flexion

Percent of intact torque at end range of motion experienced across entire abduction range of motion with the hip flexed to 0 degrees across all capsule states.

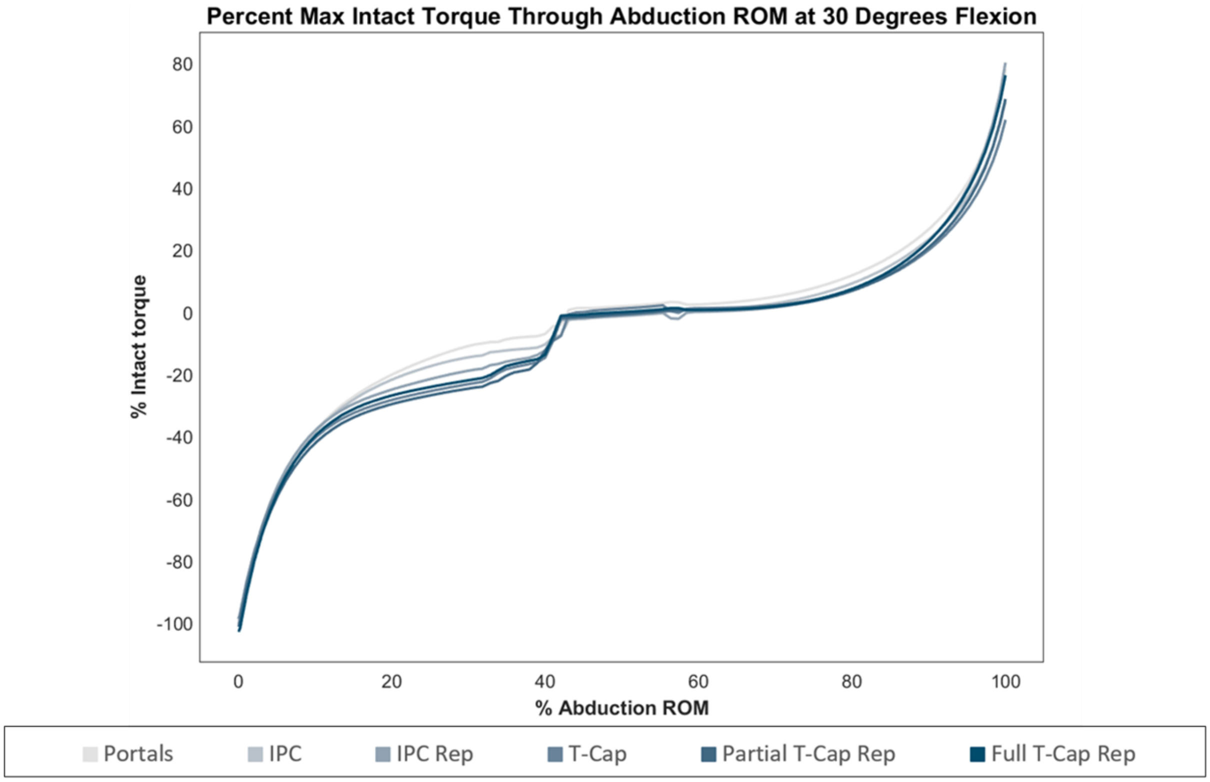

Figure A2-2: Relative torque during AA rotation at 30° flexion

Percent of intact torque at end range of motion experienced across entire abduction range of motion with the hip flexed to 30 degrees across all capsule states.

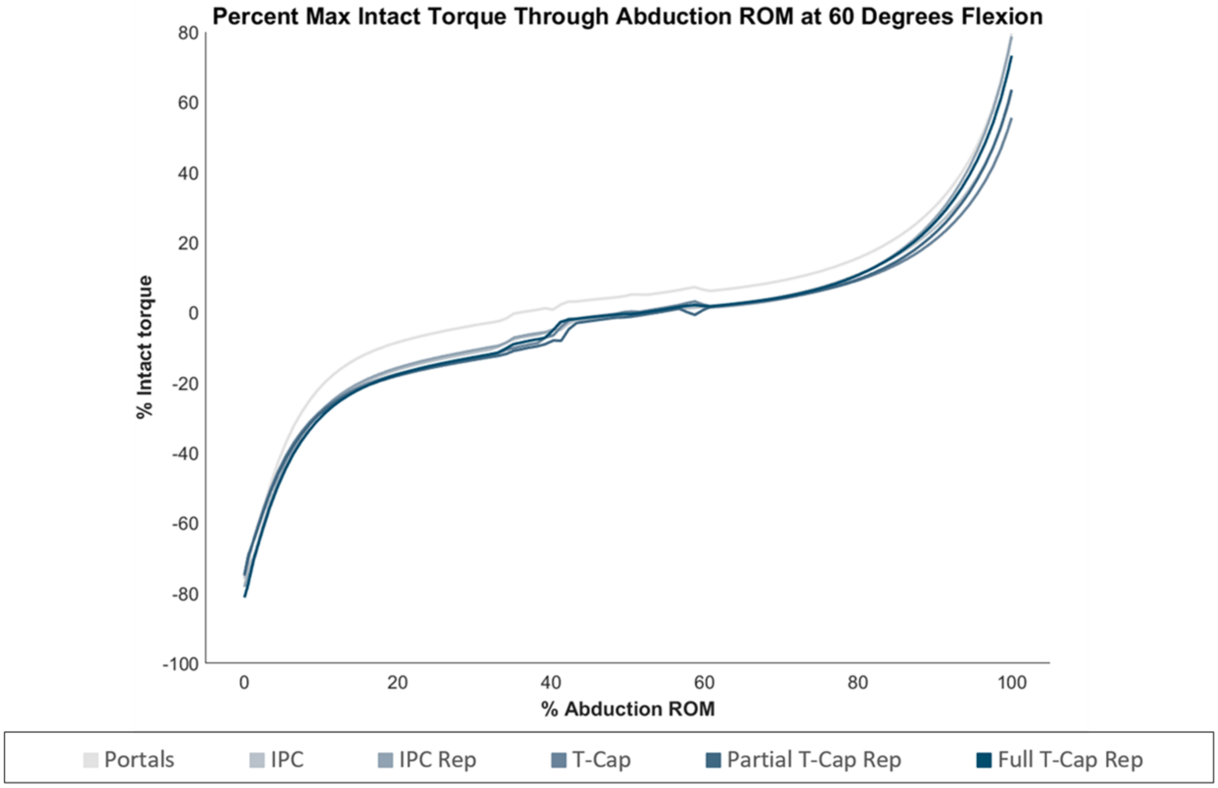

Figure A2-3: Relative torque during AA rotation at 60° flexion

Percent of intact torque at end range of motion experienced across entire abduction range of motion with the hip flexed to 60 degrees across all capsule states.

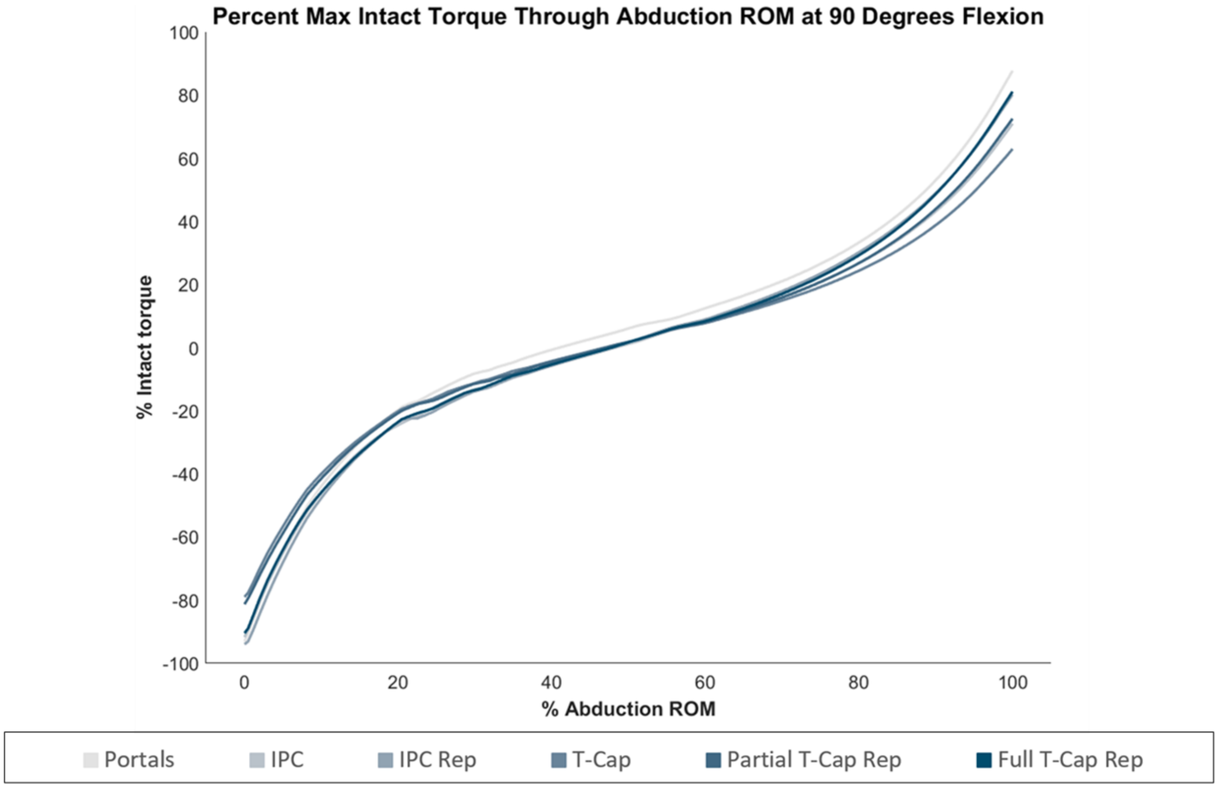

Figure A2-4: Relative torque during AA rotation at 90° flexion

Percent of intact torque at end range of motion experienced across entire abduction range of motion with the hip flexed to 90 degrees across all capsule states.

Appendix B: Specimen Demographics

Results presented in this document were collected during biomechanical evaluation of ten (10) cadaveric hip specimen with the following demographics.

Sex	6 Male 4 Female
Chirality	7 Right 3 Left
BMI	19.8 - 40.7 28.7 (avg)
Age	48-69 years 58.9 (avg)
Total	**n = 10**

Curriculum Vitae

Name:	Emma Donnelly
Post-secondary Education and Degrees:	University of Hartford West Hartford, Connecticut, United States 2012 – 2016 B.Sc.
	The University of Western Ontario London, Ontario, Canada 2018 – 2020 M.E.Sc
Honours and Awards:	Ontario Graduate Scholarship (OGS) 2018 - 2019
Related Work Experience	Teaching Assistant The University of Western Ontario 2019 – 2020