ABSTRACT

Characterizing Hip Motion during Activities of Daily Living

Carley E. Fuller, M.S.B.M.E.

Mentor: Jonathan Rylander, Ph.D.

Hip dislocation occurs in between 2% and 11% of total hip arthroplasty patients. Hip motion and dislocation are related, but there is a lack of concise information on the 3D motion of the hip during common activities of daily living in literature. Therefore, doctors are not always able to answer confidently when their patients ask about returning to particular activities following surgery. The purpose of this thesis is to establish safe muscle strength testing protocols and establish normative hip kinematic data in younger and older healthy individuals for activities of daily living. The results from these studies indicate that standing is a repeatable position for isokinetic muscle strength testing and that there are hip kinematic differences between younger and older individuals during common activities of daily living. The work contained in this thesis will serve as the foundation for future studies exploring the connection between movement and hip dislocation.

Characterizing Hip Motion during Activities of Daily Living

by

Carley E. Fuller, B.S.E.

A Thesis

Approved by the Department of Mechanical Engineering

____

Kenneth Van Treuren, Ph.D., Interim Chairperson

Submitted to the Graduate Faculty of
Baylor University in Partial Fulfillment of the
Requirements for the Degree
of

Master of Science in Biomedical Engineering

Approved by the Thesis Committee

____

Jonathan Rylander, Ph.D., Chairperson

____

Carolyn Skurla, Ph.D.

____

Jaeho Shim, Ph.D.

____

E. Garrison Benton, M.D.

Accepted by the Graduate School

August 2017

____

J. Larry Lyon, Ph.D., Dean

Page bearing signatures is kept on file in the Graduate School.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADL	Activities of Daily Living
ASA	American Society of Anesthesiologists
BMI	Body Mass Index
BRIC	Baylor Research and Innovation Collaborative
BS&W	Baylor Scott & White
ICC	Intraclass Correlation Coefficient
IPD	Intraprosthetic Dislocation
IRB	Internal Review Board
OA	Osteoarthritis
PCT	Point Cluster Technique
PT	Physical Therapist
ROM	Range of Motion
STS	Sit to Stand
THA	Total Hip Arthroplasty

ACKNOWLEDGMENTS

I would like to first thank my advisor, Dr. Jonathan Rylander, for guiding this project into its final form and assisting with every step (from building to reviewing statistics). Secondly, I would like to thank Dr. Carolyn Skurla, who provided guidance and encouragement as needed throughout my undergraduate and graduate career. Next, I would like to acknowledge Dr. Benton and the other clinicians at Baylor Scott & White for sharing their knowledge and their input on interesting and important activities related to the study. Additionally, it was reassuring to have the support team at Vicon adjust our lab to be the best it could be. I would also like to thank the undergraduate assistants who have helped me over the years. First, Lisa Choe who was with me when I started my first project – the motivation for this thesis. Next, Zach Hostetler who was instrumental in comfortably completing the muscle strength mini study by finding people, setting up times, and being a co-collector of the data. Next up is the summer team: Sara Pelayo, Sarah Kaus, and Danny Spaulding, who helped with building activity structures and some of the collections. Lastly, Kevin Bui, for helping with data processing. Of course, I would also like to thank the various study participants who made my collection experiences enjoyable and were vital to this project.

DEDICATION

To my Mom and Dad,
as well as
those here at Baylor who supported me every step of the way

CHAPTER ONE

Introduction

Motivation

In the United States alone, 332,000 people receive a total hip arthroplasty (THA) each year [1]. Surgeons use various surgical approaches to complete a THA including posterior [2, 3], posterior mini-incision [3, 4], lateral approaches [2, 3, 5, 6], anterolateral approach [3, 7], and the anterior approach [3, 8]. However, hip dislocation occurs in between 2% and 11% of THA patients [9, 10] and is estimated to cost at least $74 million per year, assuming a dislocation rate of 3% [11]. Described as either posterior or anterior, dislocations can occur for all surgical approach types. They are painful both physically and mentally. On patient forums dislocation sufferers commonly share their feelings of depression and even fear of attempting their day to day activities [12]. Additionally, some patients may have an unstable hip after surgery and experience multiple dislocations until it is stabilized through manipulation or an additional surgery [13, 14].

To provide context to the problem of dislocations after THA, knowledge about the anatomy of the hip, THA, and the mechanisms for dislocation are necessary.

Anatomy of the Hip

The hip is a ball and socket joint surrounded by several muscles, tendons, and ligaments (Figure 1.1). Starting with the center of the joint, the femoral head acts as the ball while the acetabulum in the pelvis is the socket. Articular cartilage, which is avascular and aneural, covers the contacting surfaces. Surrounding the articular cartilage and joint space is the liner of the joint capsule, the synovial membrane, which lubricates the cartilage and creates a smooth, near frictionless surface [15]. The connecting ligaments wrapped around the joint make up the joint capsule and provide stability to the joint (Figure 1.2).

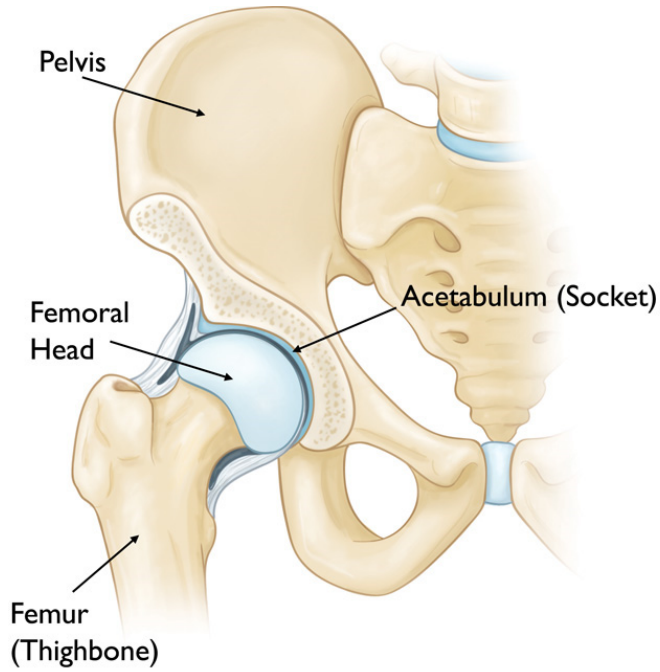

Figure 1.1. Image of "Normal hip anatomy". Reproduced with permission from OrthoInfo. ©American Academy of Orthopaedic Surgeons. http://orthoinfo.aaos.org.

Additionally, the capsule serves as the origin of the rectus femoris muscle, and it attaches and is covered by the gluteals, other quadriceps (vastus lateralis, medialis, and intermedius), iliopsoas, hamstrings, and groin muscles [15]. Together, the capsule, muscles, and bones allow the hip to bend and straighten.

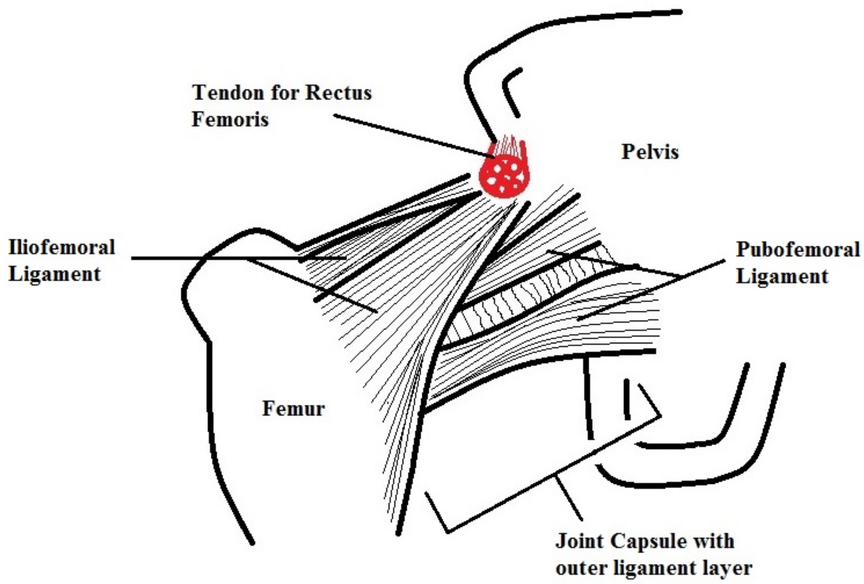

Figure 1.2. Anterior side of the joint capsule with the wrapping ligaments. The areas of thinner lines in black are ligaments that come together to form the joint capsule and then the red is the tendon of the rectus femoris muscle. Not pictured is the Ishiofemoral ligament that is on the posterior side of the joint.

Joint Movement

Since the hip is a ball and socket joint, the femoral head may rotate in the acetabulum in three planes of motion [16], the sagittal, frontal, and transverse planes (Figure 1.3). This rotational movement is caused from muscles contracting, and the subsequent movement between the thigh and torso can be described in three planes (Figure 1.4). In the sagittal plane, bending at the hip that brings the femur closer to the pelvis is flexion, which involves the iliopsoas, rectus femoris, sartorius, pectineus, and tensor fascia latae muscles [17]. Opposite of flexion, extension is straightening at the hip that brings the femur away from the pelvis. Extension activates the gluteus maximus, adductor magnus (from the hamstrings), biceps femoris, semimembranosus, and semitendinosus [17]. In the frontal plane, bending at the hip that brings the leg out from the side of the body towards the midline is adduction, which involves the adductors, pectineus, gracilis, and obturator externus muscles [17]. Opposite of adduction, abduction is bending at the hip that moves the leg away from the midline. Abduction activates the gluteus medius, gluteus minimus, tensor fascia latae, sartorius, and piriformis muscles [17]. In the transverse plane, internal rotation is turning the thigh inwards, which involves the gluteus minimus, tensor fascia latae, semitendinosus, semimembranosus, and the anterior portions of the gluteus medius and adductors [17]. Opposite of internal rotation, external rotation is turning the thigh outwards. External rotation activates the piriformis, gemellus superior, obturator internus, gemellus inferior, obturator externus, and quadratus femoris muscles [17].

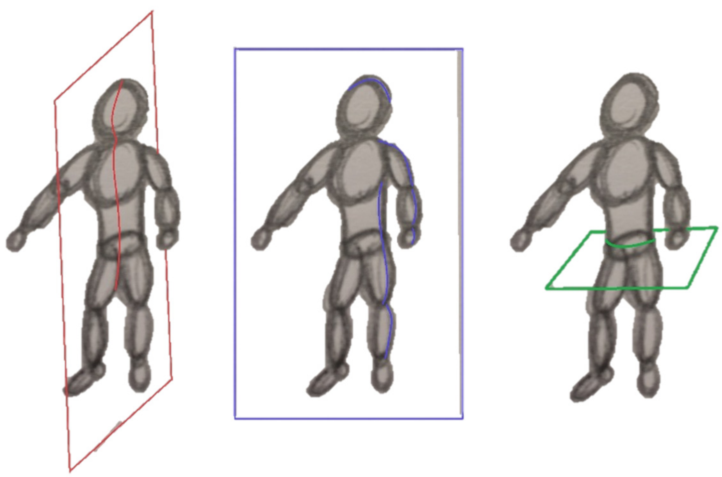

Figure 1.3. The three planes of motion: the sagittal, frontal, and transverse planes (displayed in order left to right). The sagittal plane divides a person into left and right halves. The frontal plane, also known as the coronal plane, divides a person into anterior and posterior halves. The transverse plane divides a person in horizontal slices.

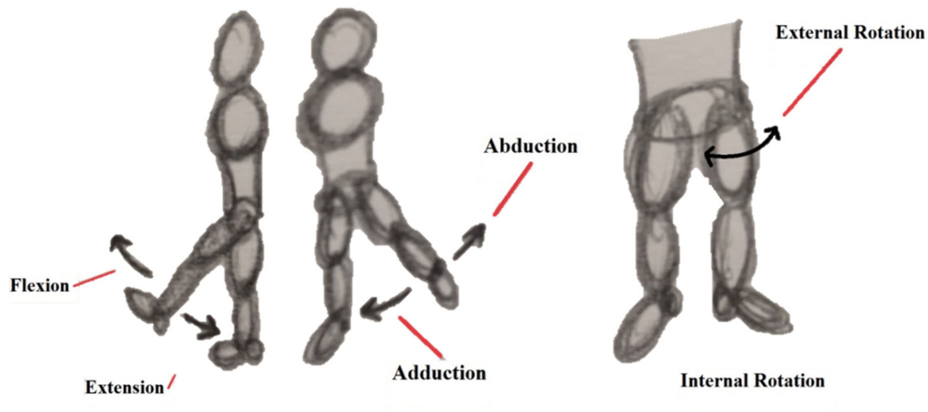

Figure 1.4. Muscles contracting produce flexion, extension, adduction, abduction, internal rotation, and external rotation in the three planes of motion. In the image on the left, flexion and extension occur in the sagittal plane. In the central image, adduction and abduction occur in the frontal plane. In the image on the right, internal and external rotation occur in the transverse plane.

Altogether, the hip is a complex joint comprised of muscle, ligaments, and tendons that allows rotational motion in three planes. However, with trauma and age, the hip may degrade and require surgical repair.

THA

THA is a surgical treatment for hip diseases (Figure 1.5). One such disease is hip osteoarthritis (OA) in which the tissues of the hip joint degrade due to trauma or age. In OA, the articular cartilage degrades and subsequently underlying bone, which contains nerves and blood vessels, is exposed. OA causes pain or stiffness in the joint. The purpose of THA is to relieve symptoms, such as pain and stiffness, and restore function to the patient.

During a THA, an orthopedic surgeon makes an incision into the skin, cuts through some of the muscular and ligamentous tissues, and dislocates the hip to reach the joint. Next, the surgeon removes the femoral head and reams out the acetabulum in preparation for inserting the replacement pieces. On the acetabular side, the replacement components are a metal acetabular cup and polyethylene liner, which the surgeon implants in that order into the pelvis. On the femoral side, the replacement component is a metal stem implanted into the shaft of the femur. This metal stem is part of a commonly used modular implant, and it has a Morse taper at the end. The other part of the modular implant is a metal ball. The size of the ball is determined through templating prior to surgery using x-rays. The two parts of the modular component are press fit together. Before press fitting the stem with a replacement ball, the surgeon tests the placement of the stem and acetabular pieces using a temporary ball.

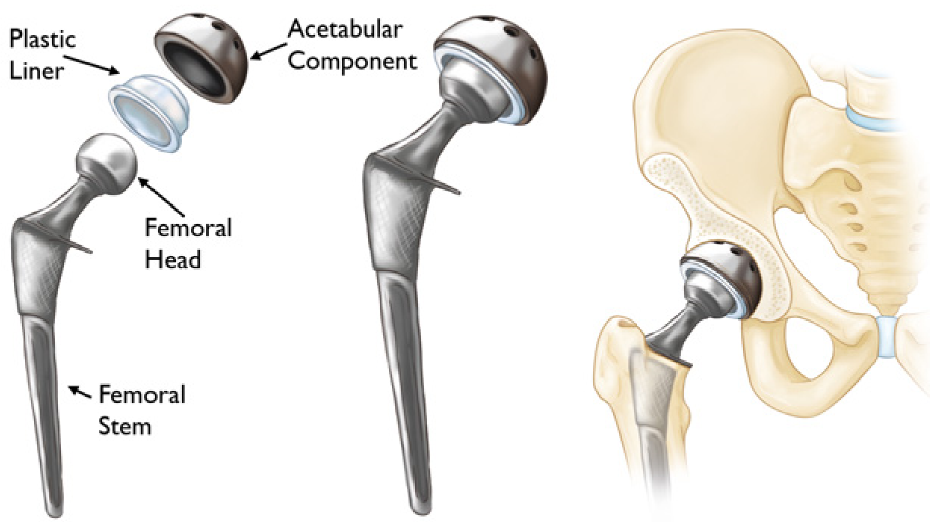

Figure 1.5. Components of a THA and a visual of the implant in the hip [15]. Reproduced with permission from OrthoInfo. ©American Academy of Orthopaedic Surgeons. http://orthoinfo.aaos.org.

With the temporary ball on the stem, the femur is inserted into the polyethylene liner and the placement of the replacement components is tested by manipulating the leg through different ranges of motion. At this point, doctors may take an x-ray to verify proper placement. Finally, they repair ligaments and muscles before stitching or stapling the incision closed.

Surgical Approaches

Surgical approach varies by surgeon's preference and training and is the path they follow to reach the joint. Surgeons have created and refined these paths to reduce damage to the muscles of the hip. The muscles described as damaged or not damaged are the muscles closest to the joint capsule. Other muscles are split to reach these deeper muscles, but they are only minimally damaged. These approaches are the posterior [2, 3], posterior mini-incision [3, 4], lateral approaches [2, 3, 5, 6], anterolateral approach [3, 7], and the anterior approach [3, 8]. The basic concepts behind the posterior, lateral, and anterior approaches are discussed below and limited to the location of the starting incision and types of muscles that are damaged during surgery.

Posterior approach. During the posterior approach, also known as the modified Sourthern, the surgeon's incision centers about the posterior end of the greater trochanter. The incision points toward the posterior superior iliac crest for about six cm, and from the center runs in the opposite direction along the femur about six cm [2, 3]. The muscles damaged are the hip's short external rotator muscles [2, 3].

Lateral approach. During the lateral approach, also known as the Hardinge, the surgeon's incision centers about the lateral side of the greater trochanter [2, 3, 5]. It runs a few centimeters proximal and distal from the trochanter. It is between 10 and 15 cm in length. The muscles damaged are the gluteus medius, gluteus minimus, and the vastus lateralis, which are some of the hip's abductor muscles [2, 3, 5].

Anterior approach. Unlike the posterior and lateral approaches, the anterior approach is relatively new. Despite this approach's newness, it is becoming popular because it does not damage muscle. During the anterior approach, also known as the Smith-Peterson, the surgeon's incision starts at the middle of the iliac crest and continues to the anterior superior iliac spine before curving down towards the trochanter for eight to 10 cm. After the incision, this approach takes advantage of the internervous planes [3, 8]. The internervous planes are divisions of muscles based on the nerve that controls their function. By knowing these planes, the surgeon pulls the rectus femoris and tensor fascia latae in opposite directions with retractors to access the joint [3, 8]. Thus, the surgeon does not damage these muscles.

To summarize, all three approaches have starting points about the trochanter at differing angles. The posterior and lateral approaches damage muscles while the anterior approach does not. The damage to the muscles also relates to in hospital recovery time. While the recovery time is similar for posterior and lateral, the anterior approach is generally shorter [3, 8]. Despite the faster recovery and the intact muscles, the anterior approach comes at a higher risk for nerve damage, which is why some surgeons are not immediately adopting the approach [3]. The surgical approach also affects post-operative complications, one of which is dislocation. The patient's movements that cause dislocation vary by surgical approach.

Research has been and still is conducted into how dislocation occurs and why it occurs for the main purpose of improving implant selection and post-operative instructions and rehabilitation. The results of this research show that dislocation has a relationship with different factors, such as implant type and demographics, and that there is a need for new studies about the relationship between motion and dislocation.

Factors and Mechanisms of Dislocation

Dislocation is the separation of the femoral head and acetabular cup of a joint and causes both physical and mental pain. The 2-11% dislocation rate [9, 10] equates to a significant number of patients, which is why surgeons desire to decrease the rate. This desire has fueled the study of factors and mechanisms of dislocation. Both older and recent studies have been used to identify surgical and demographic factors related to dislocation [18]–[32]. Other researchers are beginning to study dislocation using computer models [33]–[35]. One researcher in particular, Patel et al., focuses on the relationship between motion and dislocation [35]. Currently, all studies can fall under different methodologies including retrospective review, component retrieval, cadaver, and computer modeling studies. Since component retrieval and cadaver models are used to study specific implants, the topics below are limited to studies with retrospective review and computer modeling methodologies.

Retrospective Review Studies

Surgical and demographic information is collected from every patient who underwent THA. Surgical information comes from x-rays and other documentation about the surgery. Post-op x-rays contain information on the implant's placement including the angle and offset of the components. The other documentation contains the femoral head size, other specifics about the implant used, what surgical approach was used, and why the patient elected to have surgery. The demographic information contains the patient's health history, age, gender, and other details. If a patient dislocates, then that is documented in their patient file along with the available details about how the dislocation occurred and was treated. During a retrospective review, the patient file information is statistically tested for significance related to dislocation. Implant positioning, femoral head size, and demographic information is extensively studied through retrospective reviews.

Implant positioning. The positioning of the components is related to dislocation through impingement. Impingement occurs when the bone or prosthesis contacts another part of the bone or prosthesis. For example, the metal femoral stem may contact the acetabular cup. Bony or prosthetic impingement can cause the prosthesis to separate from the socket due to the force generated from the impingement.

Implant positioning refers to the cup angle, cup offset, femoral angle, and femoral offset (Figure 1.6). More specifically, the cup angle is divided into anteversion and abduction angles while the femoral angle is an anteversion angle. Both offsets are based off the center of rotation for the hip. The anteversion angle of the acetabular cup is a measure of how much the cup is turned towards the anterior side of the body. The abduction angle of the cup is a measure of how much the cup is tilted towards the vertical from a frontal view. The offset of the cup is a measure of how close the cup is to the true acetabular floor [36]. The true acetabular floor is defined from the teardrop, which is a point on the medial wall of the acetabulum found above the obturator foramen of the pelvis. Similar to the anteversion angle of the cup, the anteversion angle of the stem is a measure of how much the femoral stem's neck axis is turned towards the anterior side of the body [36]. The offset of the stem is the distance from the center of rotation of the femoral head to a line bisecting the long axis of the femoral stem. Researchers have published suggested values for optimal positioning as well as formulas to determine optimal placement for all patients.

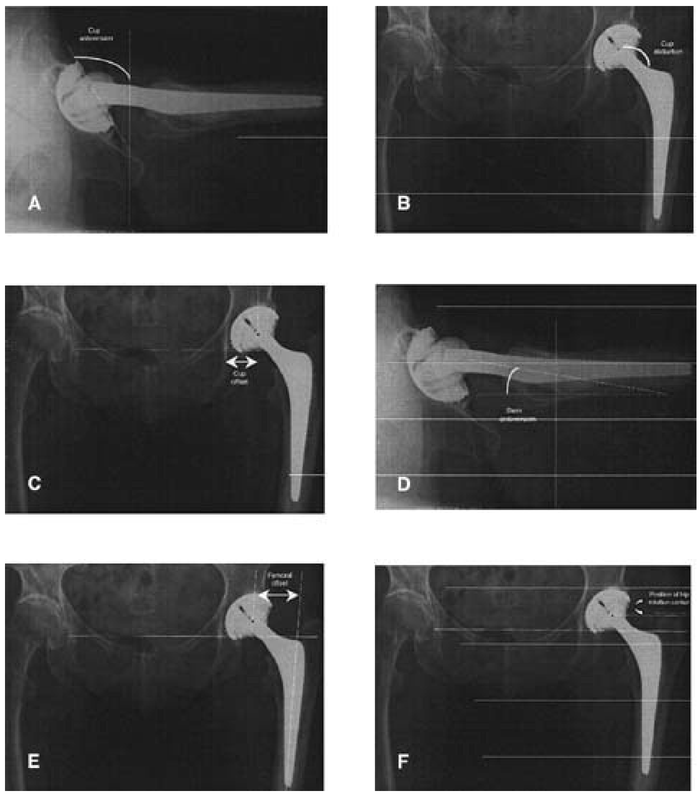

Figure 1.6. An x-ray with different implant positioning measurement examples. From original caption: (A) Anteversion angle of the acetabular cup. (B) Abduction angle of the acetabular cup. (C) Offset of the cup. (D) Anteversion angle of the stem. (E) Offset of the stem. (F) Height of the hip rotation center [36]. Reproduced with permission from Elsevier. Copyright © 2002 Published by Elsevier Inc.

Yoshimine et al. [18] and Widmer et al. [19] have produced formulas to perfect implant positioning. Yoshimine et al.'s formula to avoid impingement is:

$$c_{ab} + c_{an} + 0.77 * (s_{an}) = 84.4 \quad (1)$$

$$s_{an} = \frac{37° - c_{an}}{0.7} \quad (2)$$

In Yoshimine et al.'s formula, c_{ab} is cup abduction, c_{an} is cup anteversion, and s_{an} is stem anteversion [18]. Using the same variables, Widmer et al. used Equation 2 to determine an optimal placement was defined with 40° to 45° of cup abduction, 20° to 28° of cup anteversion and a stem anteversion between 12° and 24° [19]. In general, the reality of obtaining the optimal position while operating on a person can be challenging.

Scheerlinck reviewed methods of optimal cup positioning from literature. Based on his review, he concluded that an abduction angle of 40° and an anteversion of 25° will result in a good clinical outcome when paired with a stem anteversion angle of 20° [20]. Combining the anteversion angles will produce the 45° degree target that several researchers suggest [19], [21], [22]. Clinically, the "safe zone" is defined as 40° ± 10° of cup abduction [21], [22] and either 15° ± 10° [21] or 30° ± 10° of anteversion [22]. Generally, it is easier for a surgeon to control the cup anteversion than the stem's anteversion, which is why optimal positioning is focused on the cup positioning. Furthermore, orthopedic textbooks are produced with different surgical positioning suggestions due to all of the formulas and recommendations generated.

Jolles et al. noticed that suggested placements varied by orthopedic textbooks and that a study was needed to determine what placement should be suggested [23]. Jolles et al. studied the angles and offsets of the acetabular cup and femoral stem from two groups of 21 patients. One group of 21 patients had experienced a dislocation, and the other group had not. All 42 patients were from a larger group of 2,023 patients that received their surgery from the same location over a seven-year period. The anteversion angle of the cup and stem were added together to produce the total anteversion angle. Similarly, the offset for both the cup and stem were added to produce the total offset. Only the total anteversion angle was a predictor of dislocation [23]. Moreover, if the total anteversion was not between 40° and 60° the dislocation risk was 6.9 times higher [23]. Jolles et al. suggests that to decrease the dislocation rate, surgeons have to focus on the anteversion angle of both the cup and the stem. Additionally, any of the recommended placements (i.e., from 35° to 55°) for the abduction angle are acceptable [23].

Khan et al. in 1981 determined that both the anteversion and the abduction angles of the cup were factors related to dislocation [24]. The most common surgical error was having the acetabular cup too anteverted or too abducted [24]. Khan et al.'s study was based on 142 dislocations out of 6,774 patients from the Royal Orthopedic Hospital in Birmingham, Winford Orthopedic Hospital in Bristol, and Coventry Hospital. Similar to Jolles et al.'s study, Khan et al. found that often the acetabular and femoral components were both malpositioned [24]. At the time of the THAs, accurate measurements of the cup were impossible to obtain because the radiographs could not be taken in standard positions [24]. Since the completion of this study, surgeons now have access to standard radiographs for accurate implant measurements. From this improvement in radiographic technique, it appears that the abduction angle was removed as a factor for dislocation.

Kim et al. and Dudda et al. have also recently reviewed implant placement [25], [26]. Kim et al.'s study consisted of 60 dislocated hips from 1,648 total hips using the posterior approach. Kim et al. reviewed the literature to select and determine angles above which the risk for dislocation would be greater. Additionally, a total postoperative offset that was 10% inferior to the preoperative one and a lowering of the postoperative hip rotation center greater than 2 mm compared with the preoperative position were other risk factors tested. Kim et al. found cup and stem anteversion that were too low or too high increased risk of dislocation [25]. These results mirrored Jolles et al. and Scheerlinck's findings.

Using a slightly different analysis method, Dudda et al.'s study consisted of 175 cases of dislocations compared against 651 patients (i.e., controls) who did not experience dislocation [26]. Patients were matched for age, gender, body mass index, primary diagnosis, cup design, hospital, and year of intervention. Dudda et al. found that two implant positioning ranges were acceptable and another was ideal [26]. One range for an acceptable position of the cup was 35° - 40° or greater than 50° for the abduction angle when paired with 10° to 15° for the anteversion angle. Other acceptable positions were 35° - 50° for the abduction angle when paired with greater than 15° for the anteversion angle. The ideal position was 45° - 50° for the abduction angle when paired with 10° - 15° for the anteversion angle [26]. Dudda et al. found that the cup and stem positioning combined were significant risk factors for dislocation [26]. Cases that were graded as acceptable in position of the cup and stem were at a significantly higher risk of dislocation than those with the ideal position [26].

Altogether, the combined anteversion angle from the acetabular cup and femoral stem is the most critical step of implant positioning. With the improvements of radiographic technique, the measuring of angles has become easier and already improved THA through the removal of the abduction angle as a significant factor of dislocation.

Femoral head size. In the past when there were other factors heavily influencing the dislocation rate, the size of the femoral head was not considered to be significant [37]. Recent retrospective review studies were used to re-evaluate the relationship between femoral head size and the risk of dislocation. From recent results, surgeons have started to use a larger femoral head for those at risk for dislocation. The three most common femoral head sizes (i.e., diameter of the head) are 22 mm, 28 mm, and 32 mm.

Both Berry et al. and Hailer et al.'s studies have shown that the femoral head size does affect dislocation rate [27], [28]. Berry et al. examined the femoral head size's effect on dislocation with respect to different surgical approaches. The study's population was 868 dislocations out of 21,047 hips from one institution. The study followed up with several of the individuals to produce a ten-year dislocation rate based on the femoral head size and the approach (Table 1.1). The 22 mm femoral head had the largest cumulative dislocation rates of 3.8% for the anterior approach and 12.1% for the posterior surgical approach [27]. As for the transtrochanteric approach, the dislocation rate for the 22 mm and for the 28 mm femoral heads were 3.5%. Overall, the femoral head size had more of an impact on the posterior surgical approach than any other. Surgeons using the posterior approach should use a larger femoral head to reduce the risk of dislocation.

Table 1.1. Berry et al.'s ten-year cumulative dislocation rate for the three femoral heads and surgical approaches with 95% confidence intervals [27].

Femoral Head Size	Anterolateral Approach	Posterolateral Approach	Transtrochanteric Approach
22 mm	3.8 (2.9-4.8)%	12.1 (7.5-16.8)%	3.5 (3.0-3.9)%
28 mm	3.0 (2.4-3.6)%	6.9 (5.8-8.0)%	3.5 (2.0-5.3)%
32 mm	2.4 (1.6-3.1)%	3.8 (1.9-5.7)%	2.8 (1.8-3.8)%

Femoral heads larger than 28 mm became available in 2005. Hailer et al. examined the 22 mm, 28 mm, 32 mm, and the 36 mm femoral heads with respect to dislocation [28]. Their study used data from 399 cases of dislocations that originated in a group of 78,098 hips. The surgical approaches were lateral, posterior, and minimally invasive. Hailer et al. found that the 22 mm head had a larger risk for revision due to dislocation than the 28 mm head [28]. Hailer et al. compared their results to other groups across Europe and found general agreement that larger femoral heads decreased the risk of dislocation, which was true for Berry et al.'s findings as well [27].

Larger femoral heads reduce the risk for dislocation. Thus, surgeons should use larger femoral heads in at-risk patients. Demographics used to identify at-risk patients are discussed in the next section.

Demographic information. For review studies, it is common to study population characteristics to identify subpopulations that are at risk for dislocation. The characteristics studied from the demographic information available can include age, gender, obesity, cognitive dysfunction, and excessive alcohol intake. Each of the named characteristics relate to a possible mechanism for dislocation. For example, age is possibly associated with limited range of motion (ROM) and obese patients with soft tissue impingement both of which could increase the risk for dislocation.

In 1997, Paterno et al. studied age, gender, weight, and excessive drinking on 391 primary THAs completed at a single hospital [29]. Obesity was defined as a body mass index (BMI) of more than 30 kg/m^2. Excessive drinking was determined by information collected from both the patient and family members. A patient who consumed either 2.1 liters (72 ounces) of beer or 0.2 liters (6 ounces) of other alcoholic beverages a day was categorized as excessively drinking. Paterno et al. found no difference for age, gender, weight, or excessive drinking [29]. However, Paterno et al. also determined that the sample population studied was too small to determine significant results for excessive drinking and weight, and that a group of 334 hips per factor was needed for the study.

Other researchers encountered a similar issue and would either limit the study population to patients of one surgeon or expand to multiple surgeons.

Publishing one year later, Woolson et al. compared age, gender, height, weight, pre-op diagnosis, and cerebral dysfunction from two groups of THA patients who had the same surgical approach, surgeon, and post-op therapy protocols to remove confounding variables [30]. One group of 14 patients had experienced a dislocation and the other group of 301 patients had not. Cerebral dysfunction included patients who experienced confusion or disorientation during their hospital stay, patients suffering from mental disorders, and patients with a history of excessive drinking. In this study, excessive drinking was defined as having six or more alcoholic beverages daily. Woolson et al. found that cerebral dysfunction was associated with a higher risk of dislocation [30]. Additionally, there was a trend between increased age (i.e., 70 years old and up) and dislocation that was approaching significance [30]. Despite the smaller sample population, the results of this study highlighted patients with cerebral dysfunction as THA patients for surgeons to consider as at-risk for dislocation and patients who were older age as possibly at higher risk for dislocation. Woolson et al. stated that these patients might be less able to follow protective measures and suggested the use of a modified hip spica cast or a hip brace during the first few weeks following surgery to help prevent dislocation.

During Jolles et al.'s study of implant positioning in two groups of 21 THA patients that was mentioned earlier, the demographics were also examined [23]. The characteristics of interest were age, gender, and the American Society of Anesthesiologists (ASA) score [22]. The ASA score is a measure of physical status and relates to a patient's comorbidities. The scale of the ASA score is one through four with the larger values relating to patients with more severe comorbidities. Jolles et al. found that an ASA score of three or greater was highly predictive of dislocation [22]. Although the ASA score of three or greater was the only significant patient characteristic, age is still important for surgeons to be aware of because there is an increase in incidence of dislocation for older patients. Jolles et al. observed that patients between 80 and 89 years old were twice as much at risk for dislocation than patients under 80 [22]. Additionally, Jolles et al. noted that an equal number of men and women experienced a dislocation, which suggests that there is not a significant difference between the genders for dislocation risk [22]. Paterno et al. and Woolson et al. also noted the lack of relationship between gender and dislocation.

Following THA patients from multiple centers, Meek et al. studied the effects of age, gender, other diagnoses and economics on dislocation in 62,175 hips between the years of 1989 and 2004 [31]. All of the centers involved provided their data to the Scottish National Arthroplasty Project, and the project continued to update records as follow up reports were filed. Out of all the THAs performed, 545 first-time dislocations occurred. Parkinson's disease, stroke, femoral neck fracture, and rheumatoid arthritis were the other diagnoses focused on. Meek et al. found that patients older than 85 and patients with femoral neck fracture or rheumatoid arthritis had a greater dislocation incidence [31]. The finding on age is similar to Jolles et al.'s results, which focused on the difference of dislocation rates for age groups instead of a comparison of age between patients who experienced and did not experience a dislocation. Parkinson's disease and stroke were not related to an increased dislocation rate, showing that patients suffering from these conditions are not at a greater risk for dislocation. Similar to the previously mentioned studies, Meek et al. found that there was not a difference in dislocation rates between genders [31]. As for patients from different economic groups, which are defined by the deprivation index, there was no difference in rate of dislocation [31]. Additionally, by studying data collected over time, Meek et al. found that although there was a gradual rise in the number of THAs per year, there was also a gradual decrease in the annual dislocation rate [31]. Meek et al. believed that the decrease in the number of annual dislocations was related to surgical factors, such as prosthesis type, surgical approach, or the surgeon's level of experience. However, they were unable to confirm this belief because at the time the registry did not collect this information. In addition to the information related to the surgery, the registry is now collecting the data used in the ASA score that Jolles et al. reported on.

Although gender has been shown so far to not be a risk factor for dislocation, this characteristic is continually studied. In some cases, there is a gender difference found. In addition to studying implant positioning, Kim et al. studied gender, age, and ASA score in 1,648 hips from one center [25]. One surgeon in between the years 2000 and 2006 completed the THAs. Sixty of the hips experienced a dislocation. Kim et al. found that female patients, patients older than 80, and those with a score of three or greater were more at risk for dislocation [25]. However, Kim et al. commented that the significant finding for older patients might be confounded by comorbidities, specifically cognitive and neuromuscular [25]. There were 20 patients who were older than 80, and out of the 20 patients eight experienced a dislocation. All of the older patients who suffered a dislocation had a comorbidity. As for gender, Kim et al. noted that the more current studies from Paterno et al. and Jolles et al. had opposing results on dislocation risk for the female gender. The cause behind these different results is not fully understood, which is why gender is continually studied.

In addition to studying femoral head size in 399 cases of dislocation, Hailer et al. examined age, gender, and other diagnoses as possible risk factors for dislocation [28]. The patients were divided into different age groups. There were 78,098 hips in total operated on from 61,743 patients with 60% of the patients consisting of females. Other diagnoses included primary OA, femoral neck fracture, femoral head necrosis, inflammatory joint disease, previous pediatric diseases, and an “other” category that consisted of secondary OA caused by previous trauma. Hailer et al. found that femoral neck fracture, femoral head necrosis, and patients who were classified in the “other” category were more at risk for dislocation [28]. This finding is in agreement with Meek et al.’s results. Additionally, Hailer et al. found that age had no influence and that females had a lower risk than males [28]. The lack of a significant result for age is in line with the other studies, but the result for gender is opposite than Kim et al.’s results.

Maisongrosse et al. focused on obesity as a risk factor for dislocation [32]. All of the THAs were completed using a double-mobility acetabular cup, which is a cup with a free moving liner. The study followed patients from a single center that consisted of 77 THAs in patients categorized as obese and 425 THAs in patients categorized as non-obese. Patients categorized as obese have a BMI greater than 30 kg/m^2. Maisongrosse et al. found that with the double-mobility acetabular cup, obesity was no longer a risk factor for dislocation based on the comparison of dislocation rates for the two groups [32]. This result is in agreement with Paterno et al.’s findings.

To summarize the demographic-based studies, the following characteristics were found to not be significant risk factors related to dislocation: age [28]–[30], weight [29], [30], [32], height [29], and economic level based on the deprivation index [31]. However, when looking at dislocation rates of particular age groups, Jolles et al. and Meek et al. noted that the rates were higher for older individuals, which suggests that surgeons should continue to be aware of a patient's age and possibly alter post-op rehab strategies. Additionally, Kim et al. who did have a significant finding stated that it was likely due to the other comorbidities the patients suffered from. The risk for dislocation in obese patients was shown to be lower with the double-mobility acetabular cup. As at-risk populations are identified, it is common that an implant is developed or changed to lower risk of dislocation. Characteristics that increased a patient's risk for dislocation were: excessive drinking [29], cerebral dysfunction [30], an ASA score of three or greater [23], [25], and other diagnoses determined pre-op that included trauma or rheumatoid arthritis [28], [31]. These factors can make following post-op protective measures difficult, which is why surgeons may suggest or alter post-op strategies to help prevent dislocation for patients in any of these categories. A change in a post-op strategy could include the use of a cast or brace or the use of a different implant.

The only remaining characteristic is gender, which Paterno et al., Woolson et al., Jolles et al., and Meek et al. concluded is not a risk factor [23], [29]–[31]. When rates were available based on gender, the dislocation rates were almost equal between genders. However, Kim et al. found that female patients were more at risk [25] while Hailer et al. found that male patients were more at risk for dislocation [28]. Although other researchers have found that gender and dislocation are related, there is not enough information to conclude whether or not gender is a risk factor for dislocation. Regardless of stature, both female and male patients should be able to receive a properly sized implant, and if there are concerns for dislocation there are ways to decrease the risk pre-op and post-op.

Overall, retrospective reviews provide surgeons with useful information about placement of implants, how to use the size of an implant to decrease dislocation risk, and patient groups that are at-risk for dislocation. However, retrospective review studies are dependent on time and the patients that are willing to answer follow-up questions up to a year or more after their surgery. Since the cost of generating computer models has decreased, computer modeling studies are starting to be utilized as they offer a way to study dislocation risk without patients.

Computer Modeling Studies

Computer modeling studies allow researchers to study similar topics to retrospective review studies, such as implant positioning, and topics outside of retrospective reviews, such as the mechanical testing of ligaments or tendons. Early computer models of an artificial hip either excluded or simplified the representation of soft tissues, such as ligaments and tendons. As software packages used in modeling have been improved, soft tissue has been included to produce results that are more realistic. Currently, the computer models are based on THA implants used by surgeons, and generally include the bone in contact with the implant and ligaments. Recent studies about the hip's joint capsule, jump distance (i.e., the distance the femoral head will travel before dislocating), and motion as they are related to dislocation or factors of dislocation are discussed below.

Joint capsule. The joint capsule is composed of the ligaments surrounding the hip joint, and during a THA the joint capsule is removed. Depending on how the surgeon was taught to complete the THA, the joint capsule is either re-attached or removed. Surgeons desire to know whether or not the joint capsule detachment is related to dislocation. Elkins et al. had developed a hip joint model with the capsular tissue at different stages of THA surgery for use in Abaqus in 2004 [38]. More recently, the model has been updated to include fiber-direction-dependence of capsule material properties (Figure 1.7), and it has been used to test the capsule thickness and defects for their influence on dislocation resistance for posterior dislocation. In this study, dislocation resistance refers to the peak moment developed to resist dislocation.

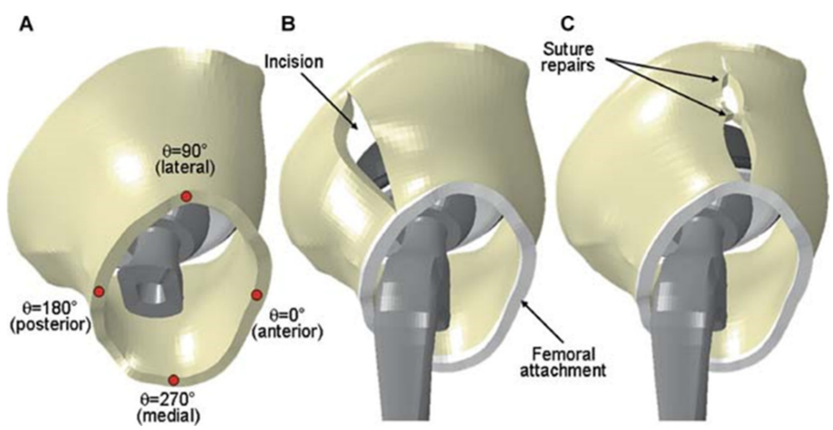

Figure 1.7. Elkins et al.'s hip joint model with the capsule [33]. The intact capsule is displayed in A. In B, the model is shown with an incision in the capsule that would be made during surgery, and then in C is the model repaired. Reproduced with permission from Wiley. Copyright © 2011 Published by John Wiley & Sons Inc.

The joint capsule is on average between one and five mm thick [39]. Elkins et al. completed 109 simulations with the model: one with the model pre-surgery, 22 varying the thickness between one and six mm, and 86 varying defects in the capsule and repairs of those defects. Elkins et al. found that variations in thickness affected stability (Figure 1.8) and defects in the capsule's insertion reduced dislocation resistance by more than 50% [33]. When repaired, the dislocation resistance was brought to within 10 to 20% of the baseline value [33]. The thicker capsules increased the resisting moment.

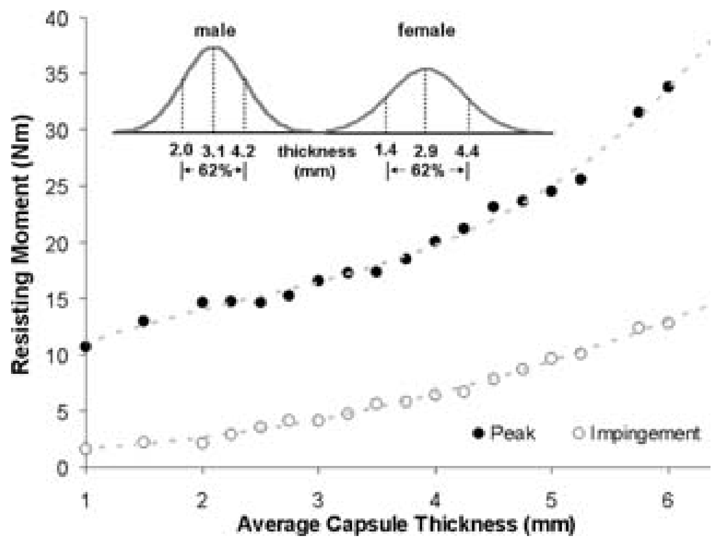

Figure 1.8. Elkins et al.'s results for the capsule's resisting moment versus capsule thickness [33]. As the thickness increases, the moment resisting dislocation increases. The inserted curve was replotted by Elkins et al. from the data of Dihlmann et al. [39].

Based on the results, Elkins et al. recommended that the capsule be retained during a posterior THA. Similar to the earlier mentioned factors, such as age or implant positioning, learning about the relationship between the forces acting through the joint and how the joint resists dislocation can be used to improve implants and knowledge about implants used in pre-op planning.

Jump distance. Nevelos et al. focused on factors related to the three-dimensional distance the femoral head will travel before dislocating, also known as the jump distance

[34]. The factors investigated were the stability of four acetabular cup designs, implant placement, and pelvic inclination angles. The four designs were two hemispheric cups with a 28 and 36 mm inner diameter, one resurfacing cup with a 48 mm diameter, and a dual-mobility cup with a 48 mm diameter. A resurfacing cup is an acetabular cup that tries to mimic the natural shape of the acetabulum. Implant placement included both acetabular anteversion and inclination angles. Two pelvic inclination angles were used as a representation of a person standing and a person sitting in a low chair. Nevelos et al. found that the dual-mobility design had a larger jump distance for all angles and thus a greater resistance to dislocation [34]. They suggested that these implants be used for higher risk patients. Additionally, for the acetabular cups that accommodated larger femoral heads the jump distance increased [34], which is fitting with the earlier discussed implant positioning results. For the resurfacing cup, the small acetabular inclination angle of 30° negatively affected the jump distance [34], increasing the risk for dislocation. While retrospective review studies made the same conclusion that larger femoral heads decreased dislocation based on dislocation rates from THA patient groups, the computer modeling studies produced the same result from quantitative testing of the acetabular cups and femoral heads. Additionally, Nevelos et al.'s study pointed out that there are exceptions to the larger femoral head finding, such as the resurfaced cup having a negative impact on jump distance.

Motion. Patel et al.'s study focuses on the relationship between implant placement (i.e., acetabular cup anteversion and abduction) and ROM during nine simulated motions for eight models reconstructed from computerized tomography scans [35]. This model did not include soft tissue because it was used to detect when bony or prosthetic impingement occurred. To simulate a motion, the model's pose was changed in increments over time. Motions simulated included rising from a sitting position, stooping, tying shoes, crossing legs, pivoting in a standing position, and rolling over in a bed. Additionally, the model was tested in pure flexion and pure extension. Patel et al. found normal motion was restored with an anteversion angle at either 10° or 20° and an abduction angle of 45° [35]. Additionally, Patel et al. found that an increase in anteversion by 10° would increase the motion possible in flexion activities by 8° to 12°, but it would also cause a decrease in extension activities by 8° to 12° [35]. Studying ROM and implant positioning in a computer model allowed Patel et al. to learn more in depth about how to improve implant positioning and decrease dislocation risk. Additionally, there appears to be a relationship between ROM and dislocation that would be valuable to further explore.

In summary, retrospective review and computer modeling studies have shown:

- The anteversion angle of the cup is an important surgical factor with the correct angle reducing the risk of dislocation
- A larger femoral head size should be utilized for patients at-risk for dislocation
- Patients that fall into categories of older age and cerebral dysfunction are more at-risk for dislocation
- Activities, such as sitting on a low chair or standing, have their ROMs influenced by implant positioning, which in turn might impact dislocation risk

Retrospective review studies can be used to determine risk factors from just patient files, but there is a limit to the depth of information these studies can provide. On the other hand, computer modeling studies can be used to provide more detail about particular mechanisms of dislocation (i.e., capsule strength and jump distance) and implant positioning as it relates to motion and ROM. However, computer modeling studies are dependent on the quality of their model, which is affected by the depth of the anatomical structures included, complexity of the motion applied to the model, and other factors. It is common for models to exclude the ligamentous soft tissue [35], [40]. Additionally, motion is usually made in pre-defined increments over time to represent a real motion [35], [40], which is different from using kinematics from a motion capture study. When a model is simplified, the results may not entirely reflect reality, but simplifying is part of a tradeoff. By simplifying the model, researchers can reduce computation time. Despite the limitations of both methodologies, the results produced from both types of studies appear well founded and lead to improvements in implants and knowledge about patients that are at-risk for dislocation. Additionally, computer modeling is starting to include motion in their simulations used in testing factors for their relationship to dislocation. From the previously mentioned studies and other documents, particular motions are known to be related to either anterior or posterior dislocation.

Motions that Lead to Dislocation

Motions that lead to dislocation can be named from the documents and work of physical therapists (PTs) and researchers. PTs provide THA patients a list of general guidelines, called the Hip Precautions (Appendix A), which are intended to help prevent dislocation after the patient's THA. There are two versions of the Hip Precautions, one for patients receiving a posterior THA and one for those receiving an anterior THA. Additionally, researchers have compiled lists of motions that place patients at risk for dislocation based on motion capture studies and simulation tests of hip ROM. Altogether, the Hip Precautions and these other lists provide the current list of motions that are related to posterior and anterior dislocation.

Motions related to posterior dislocation. According to the Hip Precautions, THA patients should not cross their legs, not turn their toes in, and not bend their hips greater than 90° [41], [42]. Additionally, THA patients who have the posterior approach should sleep with a foam wedge between their legs when in bed. These guidelines influence what chairs patients can sit in as well as going to the bathroom, sleeping, and other activities of daily living (ADL). PTs recommend that beds and toilet seats be raised in addition to other changes around a patient's house to remove tripping hazards. The posterior Hip Precautions are not a list of specific motions, such as sitting in a low chair or gardening. Instead, PTs describe the joint's movements, such as flexion or internal rotation, that are the primary concern in easy to understand terms for the patients. These guidelines are reflected in the motions studied in computer modeling studies.

According to Fillingham et al., "posterior dislocations occur with flexion and internal rotation of the [femur relative to the pelvis] (as when sitting on a low chair or reaching for the foot)" [43]. Fillingham et al. are a group of surgeons that discussed anterior and posterior dislocation in a case report. From the previously mentioned computer modeling study by Patel et al. the list of activities related to posterior dislocation were pure flexion, rising from a sitting position, stooping, tying shoes, and crossing legs [35]. These motions were tested in Patel et al.'s impingement simulation for testing different implant positions. In the case of pure flexion, Patel et al. determined that bony or prosthetic impingement starts at 118.8° of flexion for one of the standard implants and positioning of that implant (i.e., a 28 mm head with the cup at 45° of inclination and 20° of anteversion) [35]. This is without soft tissue impingement, which according to Woerner et al. will decrease that peak flexion value by at least 20° [44]. Additionally, a 20° decrease would occur for extension, abduction, and adduction while a 10° decrease would occur in external rotation [44]. Since impingement can occur roughly at 98° of flexion, low chairs and beds would be worrisome for patients, which is in agreement with the motions found in the lists from the PTs' Hip Precautions and the motion described by Fillingham et al. Furthermore, Patel et al. included stooping, tying shoes, and crossing legs, which are activities that could be determined as risky from the Hip Precautions. Some of the motions that are risky to patients who have a posterior THA are depicted in Figure 1.9.

Figure 1.9. Images of some of the motions related to posterior dislocation. From left to right: sitting cross legged, turning toes in, and tying shoes. (Images on the left and right are licensed under the Creative Commons Zero license).

In a similar study to Patel et al., Shoji et al. virtually tested the ROM of 71 patients in a THA planning software that could detect bony and prosthetic impingement

[40]. In the simulated tests, a single implant was used, and the implant was placed as it would during a THA to return normal function to the patient. Another similarity between Shoji et al. and Patel et al.'s studies is that the computer models did not include soft tissue. Shoji et al. found a ROM of 114.2° until impingement occurred, which agrees with Patel et al.'s ROM for pure flexion [40]. Additionally, for internal rotation Shoji et al. found a ROM of 28.6° [40]. According to Woerner et al., unlike the other joint movements, internal rotation did not experience a significant decrease in ROM when soft tissue was included [44]. Although the ROM for internal rotation is not significantly impacted, the motions mentioned by Patel et al. that would include internal rotation are primarily dominated by flexion. Alternatively, when patients are in bed rotation of the hip can cause dislocation, which is why the Hip Precautions state that patients should have a foam wedge between their legs in bed.

Altogether, in general terms posterior dislocation can occur during flexion and internal rotation. More specifically, posterior dislocation can occur during sitting in a low chair or toilet, standing from a sitting position, stooping, tying shoes, and crossing legs. The above documents and studies also provide information on anterior dislocation.

Motions related to anterior dislocation. According to the Hip Precautions, THA patients should not cross their legs, not turn their toes out, and not step backwards [41], [42]. Additionally, THA patients should use a pillow between their legs when rolling in bed. The anterior dislocation guidelines influence fewer ADLs than the posterior Hip Precautions, but rolling over and laying down in bed is still a point of concern for patients with the anterior approach. Similar to the posterior Hip Precautions, the anterior Hip

Precautions are written in a general format that can be used to infer unsafe motions. Specific activities can be identified from the computer studies.

According to Fillingham et al., “anterior dislocations are the result of external rotation and extension (as was seen in this case, when the patient rolled over in bed)” [43]. In addition to the motions related to posterior dislocation, Patel et al. listed pure extension, pivoting in a standing position, and rolling over in a bed for motions related to anterior dislocation in their methods. Using the earlier mentioned standard implant (i.e., a 28 mm head with the cup at 45° of inclination and 20° of anteversion) Patel et al. showed that impingement starts at 44.0° without soft tissue for extension [35]. For a pivot, impingement starts at 34.1° of external rotation [35]. When accounting for soft tissue impingement, only 24° of extension and external rotation would be possible. This reduction in ROM highlights taking a step backwards and pivoting as at-risk activities for patients of the anterior approach. Both of these activities are already covered by the PTs’ Hip Precautions and the general motions described by Fillingham et al. Furthermore, Patel et al. included rolling over in a bed, which is also covered by the Hip Precautions. Motions that are risky to patients who have a anterior THA are depicted in Figure 1.10.

Figure 1.10. Images of some of the motions related to anterior dislocation. From left to right: turning toes out and taking a step backwards.

In Shoji et al.'s virtual tests of ROM in a THA planning software that could detect bony and prosthetic impingement pure external rotation was tested. Shoji et al. found that the ROM for external rotation until impingement occurred was 37.7°, which is similar to Patel et al.'s ROM for a pivot [40]. With the soft tissue accounted for, the external rotation's ROM would be 27.7°, which still highlights pure external rotation as a motion that could cause impingement and subsequent dislocation. Besides the pivot, stepping backwards, and rolling in bed there are not any other named motions that can be attributed to anterior dislocation.

Overall, activities related to posterior dislocation are sitting on low chairs or toilets, stooping, tying shoes, crossing legs, and laying or rolling in a bed. These activities involve primarily flexion and/or internal rotation of the hip. Activities related to anterior dislocation are taking a step backwards, pivoting, rolling in bed, and crossing legs. Opposite from the activities related to posterior dislocation, these activities involve extension and/or external rotation.

The Hip Precautions that are provided to THA patients are a good set of general guidelines. However, patients have specific questions about personal activities, and they ask their doctors and PTs about these activities. During those moments, clinicians would like to refer to literature in addition to the particular patient's file. In this case, literature would come from motion capture studies for specifics about ROM for ADLs. According to Nadzadi et al. "few hip loading data presently exist for posterior-dislocation-prone activities such as stooping, leg crossing, or rising from a low seat such as a toilet " and "there are no motion data whatsoever for anterior-dislocation-prone activities" [45]. Since there are several possible motions that should be included in a motion capture study to provide clinicians information on ROMs, motion capture studies were reviewed to assess the need to study these particular motions.

Motion Capture Studies

Motion capture is used to record a person's movements and can be used to produce information on ROMs for motions using kinematic data. The kinematic data includes marker positions, joint angles, velocity and acceleration. Hip ROMs for ADLs can provide insight into why dislocation occurs as well as be useful to surgeons, PTs, and researchers focusing on computer modeling. Surgeons and PTs can use this information to help answer THA patients' questions about ADLs. Although Nadzadi et al. stated that there was a lack of data for ADLs related to dislocation [45], there are motion capture studies about the hip that should be reviewed.

These motion capture studies sought how the hip moves to assess back pain [46], [47], changes in movement due to obesity [48], provide information to doctors and implant companies [45], [49], and reveal motion techniques that could reduce incidence of dislocation [50]. These studies have produced information on one or multiple joints and ADLs as well as specific populations. Information on ADLs includes both which ADLs have been tested and if kinematics for these activities were reported. In trying to determine the amount of information that is lacking in motion capture studies, the studied ADLs, joints, and sample population are summarized below before any current results are discussed.

Studied ADLs, Joints, and Sample Populations

Reviewing the ADLs, joints, and sample populations already studied will help to determine which ADLs have yet to be studied and to what extent. The joints of interest are the hip, knee, and ankle. The other two lower body joints, the ankle and knee, can influence hip motion, which is why it is helpful to know if a study included them. Sample populations are primarily age-based, but can be dependent on a group's background or lifestyle [49], [51], [52]. However, when studies are narrowed to particular populations and specific ADLs, gathering a complete general picture of the hip becomes difficult. In Tables 1.2 and 1.3, the activities and joints studied in current motion capture studies are listed. The first table lists studies that reported the kinematics for all planes (i.e., sagittal, frontal, and transverse). The second table includes the studies that did not report all kinematics. Images of some of the ADLs follow the tables along with details the studies provided about the setup of these activities. Later, a summary of the number of activities, repetitions of the activities, and participants are provided along with the average age of the population, if it was available, per study.

Table 1.2. Activities and lower body joints included in current motion capture studies with reported kinematics.

Activity	Ref. Numbers	Tested for the Knee	Tested for the Hip	Tested for the Ankle
High ROM: Squatting	[49], [51]	X	X	X
High ROM: Kneeling	[49]	X	X	X
High ROM: Sitting Cross-Legged	[49], [52]	X	X	X
Self-selected walking	[51]	X	X	X
Jogging	[51]	X	X	X
Standard Chair Sit to Stand	[48]	X	X	X

Table 1.3. Activities and lower body joints included in current motion capture studies without reported kinematics.

Activity		Ref. Numbers	Tested for the Knee	Tested for the Hip	Tested for the Ankle
Sit to Stand	Low Chair Sit to Stand	[45]		X	
	Erectly seated leg crossing	[45]		X	
	Seated while Reaching for the floor	[45]		X	
Forward bending (about the hip)		[46], [47]		X	
Automobile Ingress/Egress		[53]		X	
Flexing forward to pick up an object between the feet		[50]		X*	
Flexing to pick up an object lateral to the foot		[50]		X*	
Squatting to pick up an object between the feet		[50]		X*	
Kneeling on one knee to pick up beside the knee		[50]		X*	
Standing while turning upper body away		[45]		X	
Lying Supine		[45]		X	
Rolling Over		[45]		X	

* The study used a 3D magnetic tracking system and did not report abduction and adduction values for the motions tested.

Six ADLs have kinematics reported for the hip in all planes, and they are high ROM squatting, high ROM kneeling, high ROM sitting cross-legged, self-selected walking, jogging, and a standard chair sit to stand (STS). Both walking and standard chair STS are commonly studied, but they are not associated with a high risk for dislocation. In some cases, an ADL was covered by two studies. Out of these motions, the high ROM ADLs would be the most related to dislocation because the amount of flexion involved would exceed 90°. Since the motion requires a lot of flexion, having kinematic data for these activities is valuable. In addition to the hip, the ankle and knee joints were studied for the high ROM activities. Overall, based on the small number of studies that did report kinematics for the hip for a limited variety of ADLs, there is a lack in available motion data for all three planes of motion.

The studies that did not report kinematics covered several ADLs. Four of the five studies in the second table are journal articles while the last one, by Rasmussen et al., is an abstract. Of the four studies that did not report all kinematics, Nadzadi et al.'s study included several activities [45]. Unlike Nadzadi et al.'s study, Shariff et al.'s study reported kinematics for flexion, extension, and rotation [50]. It is missing abduction and adduction. The studies by Esola et al. and Pal et al. focused on back pain in one plane of motion, and were not activities that would be high risk for dislocation [46], [47]. Both Nadzadi et al. and Shariff et al.'s studies had participants complete activities that are related to anterior and posterior dislocation risk. Rassmussen et al.'s abstract mentioned an activity involving a participant getting in and out of a car that would be related to dislocation risk. However, the methods for the motions were not included within the abstract and the data was sent directly to a computer model. Altogether, a variety of ADLs have been tested in a limited number of studies, but not all of the activities have published kinematics because these studies are answering other questions about motion. Despite the lack of kinematic data, the studies are valuable for the methods they produced for ADLs. The methodological information includes how researchers determined a starting and stopping point for activities, chair heights, and other similar details.

Each study developed their own methods for the activities tested. These methods focus on standardizing the motions between participants and can be based on a population's lifestyle. By standardizing the motions, the researchers can more easily compare motions between participants.

One of the studies that produced data on high ROM ADLs was conducted by Hemmerich et al. in hopes of influencing THA implant design [49]. There were two things that Hemmerich et al. had the participants do in order to achieve the right motion during the high ROM activities. First, they had the participants practice the motion to be comfortable. Second, the participants held the endpoint of the squatting motions for 2 seconds, which is when the person has settled into the squat. By having the participants complete both, the motion should be consistent and include the full ROM for the activity.

Shariff et al. studied retrieving an object from the floor in four different ways (Figure 1.11) to determine which technique was less at risk for hip dislocation [50]. The four techniques were picking up the object between the feet, picking up the object to the side of the feet, squatting to pick up the object, and kneeling to pick up the object. They used standardized foot and object placements standardized within their lab.

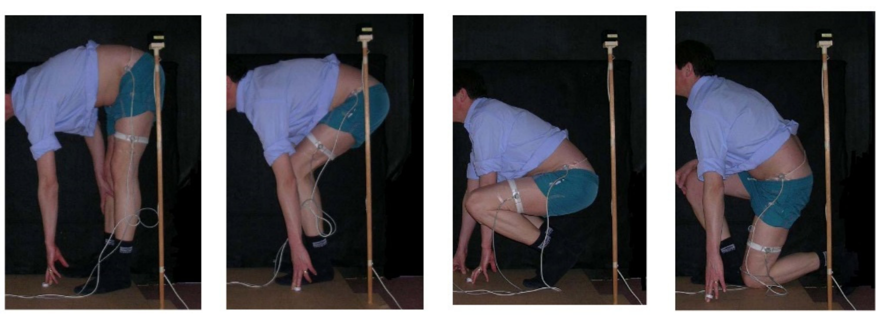

Figure 1.11. Shariff et al.'s images of the four techniques to pick up an object up from the floor [50]. From left to right: picking up the object between the feet, picking up the object to the side of the feet, squatting to pick up the object, and kneeling to pick up the object are displayed. These images are licensed under the Creative Commons Attribution License. © Shariff et al; licensee BioMed Central Ltd. 2011

Nadzadi et al. studied seven motions in 10 volunteers with the purpose of collecting information to be used in a computer model to detect impingement within the same article. The seven motions were a low STS, normal STS, seated leg cross, shoe tying, stooping down to reach an object, pivoting, and rolling in bed. These motions cover activities related to both posterior and anterior dislocation. Additionally, Nadzadi et al. included specific details related to the chair heights for the STS activities as well as details for the other motions. For the normal STS activity, a volunteer would be asked to stand up from the chair that was set to 46 cm [45], which is the height of a standard chair. On the other hand, the chair would be set to a height of 39 cm for the low STS [45]. During the low STS activity, the hip would be bent more than 90°, which is not recommended for THA patients. However, a common ADL that would require this amount of flexion is when using a low toilet.

Additionally, the seated leg cross and shoe tying activities used the standard chair height [45]. Images for the other activities can be found in Figure 1.12. The starting placement of the feet for stooping and pivoting was stressed to participants [45]. Researchers desire motion capture trials to be comparable among a group of individuals, which is achieved through controlling the start and end of a motion. Similar to controlling the feet placement for stooping and pivoting, the participants were instructed to relax their right leg when turning their upper body during the rolling activity [45].

By sending the motion capture data through a computer model, Nadzadi et al. found that there was a high incidence of dislocation for all seven of these activities, but that risk was dependent on the activity [45]. For example, a patient is six times more likely to dislocate from a low STS activity than from stooping to pick up an object. Although Nadzadi et al. did not report the kinematics for this study, their results are valuable in showing that there is motion-based dislocation risk.

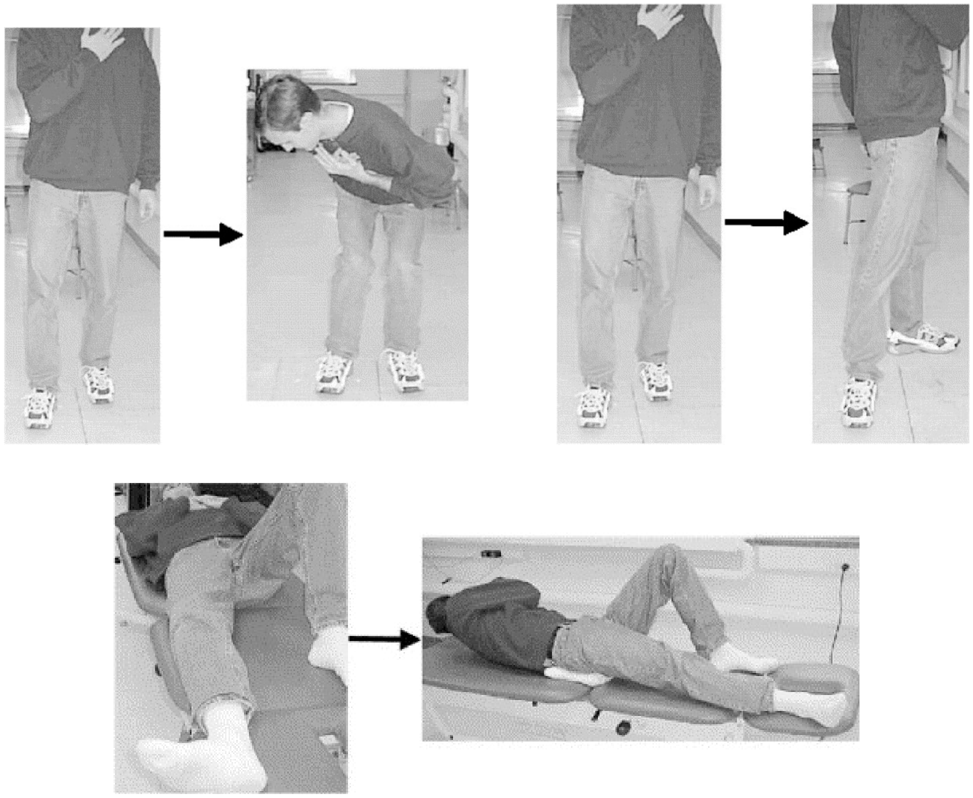

Figure 1.12. Nadzadi et al.'s images for stooping (top left), pivoting (top right), and rolling in bed (bottom) [45]. The starting placement of the feet for the activities displayed on the top row was stressed to participants. In the ROLL activity, the relaxed leg was kept relaxed as the participant used their upper body to turn.

A summary of the number of activities, repetitions of the activities, and participants are provided along with the average age of the population, if it was available, per study in Table 1.8. From Huffman et al.'s study only the healthy controls are included in Table 1.8. The number of activities ranged from one to seven with three to ten repetitions. The only exception to the number of repetitions was the study by Nadzadi et al. that had an unnamed number of repeats. Nadzadi et al.'s study continued for three sessions and the activities were collected as the participant progressed, leading to uneven numbers of repeated activities [45]. There were between 10 and 40 subjects in a study. Studies tended to have either younger or older participants. When a study had a larger sample population, there were typically younger participants involved. A comparison of motion based on age could provide insight into dislocation, especially since retrospective studies highlighted age as a risk factor. In order to make this comparison a study that includes all ages needs to be completed.

Table 1.4. Number of activities, repetitions, and volunteers per study reviewed.

Author	Ref. Numbers	Number of Activities	Number of Repetitions	Number of Volunteers	Average Age of Volunteers (years)
Nadzadi et al.	[45]	7	Repeatedly	10	49.7
Shariff et al.	[50]	4	3	25	>18
Esola et al.	[46]	1	3	21	27.5
Pal et al.	[47]	1	5	20	20.6
Hemmerich et al.	[49]	5	6	30	48.2
Han et al.	[51]	3	6	40	-*
Zhou et al.	[52]	1	6	40	23.8
Huffman et al.	[48]	1	10	10	24.9

* Han et al. stated that their population was students and faculty from the university, but did not provide an average age.

The above information has provided insight into the size of current motion capture studies, including the number of activities and participants. It appears common to study between one and seven activities for 10 or more participants. Additionally, the various studies provided descriptions of setup information about the ADLs that is valuable. This includes chair heights and stressed start and endpoints. Overall, due to the small number of studies that reported kinematics, there is a shortage of hip ROM data for motions related to total hip dislocation. Published ROM values are discussed below.

Published ROMs

Six studies produced ROM values for six activities (Table 1.9). Some of the ADLs in the table would be primarily risky for just patients receiving the posterior THA.

Both squatting and sitting cross-legged produced the greatest amount of flexion, which would be considered risky for patients. Kneeling had a smaller amount of flexion, and it had external rotation. The combination of flexion and internal rotation would put a patient at risk, not external rotation. That suggests that kneeling would possibly be safe for patients to do. Walking, jogging, and standard chair STS are activities that are not seen as high risk for dislocation, but these activities have been extensively studied and included for completion of the table.

Table 1.5. Hip ROM values for six activities from three studies.

	Squatting	High ROM Kneeling	Sitting Cross-Legged	Self-Selected Walking	Jogging	Standard Chair STS
Sagittal	95.4-180.2°	73.9°	85.4-101.7°	35.0°	35.8°	79.9°
Frontal	22.4-28.2°	25.3°	36.5-43.2°	9.0°	9.9°	8.4°
Transverse	15.8-25.7°	28.1°	36.4-40.3°	5.0°	9.3°	10.0°
Reference	[49], [51]	[49]	[49], [52]	[51]	[51]	[48]

Altogether, there is a need for more published ROM data for ADLs for participants of all ages. The current ROM table comprised of the ROMs from six different studies does not represent all ADLs. On the other hand, methods have been developed for several ADLs that can be used as needed in a new study of motion focused on the hip. In order to perform ADLs, muscle strength is required. Therefore, it is important to study strength when studying motion. Additionally, surgery can alter muscle strength, which also influences motion.

Muscle Strength Testing

Before and after surgery, doctors and other clinicians are concerned about THA patient’s muscle strength. THA patients will commonly have muscle asymmetries or weakness that need to be monitored during recovery [54], [55]. The asymmetry or weakness is generally caused from having a painful or weak hip, which causes the patient to favor one leg to another or to exercise less. After surgery, the hope is that patients will return to their previous strength, but asymmetry and weakness can persist if the patient does not use both legs equally or complete their rehabilitation. Monitoring isokinetic hip strength using a dynamometer is commonly used to screen for hip strength deficits both between limbs and between subjects in studies with younger athletes and patients [56]–[63]. Isokinetic tests are tests performed over a person's full ROM at a constant speed and variable resistance to isolate the desired muscle groups and to find the maximum peak torque.

However, in a research setting, there is a need for standard practices to be formed for studying hip muscle strength, which a few researchers have begun to address. So far, all researchers use a 60 °/s test speed for isokinetic hip strength testing [56]–[63], but a standard testing position for both sagittal and frontal planes is not fully established. One study by Julia et al. tested the reproducibility of isokinetic peak torque measurements for flexion and extension in 10 healthy adults [64]. The participants completed one set of tests every week for three weeks with the same researcher [64]. Tests were completed at 60 °/s and 180 °/s [64] with participants in a supine position. The testing device was the CON-TREX isokinetic dynamometer [64]. The dynamometer has two securing straps, one for the upper body and the second for the hips. Julia et al. found that their results showed good to very good reproducibility for the hip flexors and extensor muscles (ICC of 0.94) [64]. Additionally, Julia et al. found no difference between right and left hip values for the healthy participants.

A later study by Meyer et al. studied isokinetic hip strength in 18 healthy participants for the non-dominant hip in order to develop a standardized test setup for both sagittal and frontal planes. In order to establish reliable methods, the participants completed two identical test sessions one week apart and the same researcher was present [65]. The testing device was the Biodex isokinetic dynamometer, which enabled testing for both sagittal and frontal planes using test speeds of 60 °/s and 120 °/s (Figure 1.13) [65]. In addition to the Biodex's securing straps, Meyer et al. used a brace to prevent undesired motion of the hip. Comparing the hip's measured torque values from both sessions, Meyer et al. found that their results showed a moderate to high repeatability (ICCs of 0.92 for flexion and 0.83 for abduction) [65]. The test setup details from Meyer et al. and Julia et al. are helpful to future studies in hip muscle strength. Additionally, Meyer et al.'s results are comparable to Julia et al.'s.

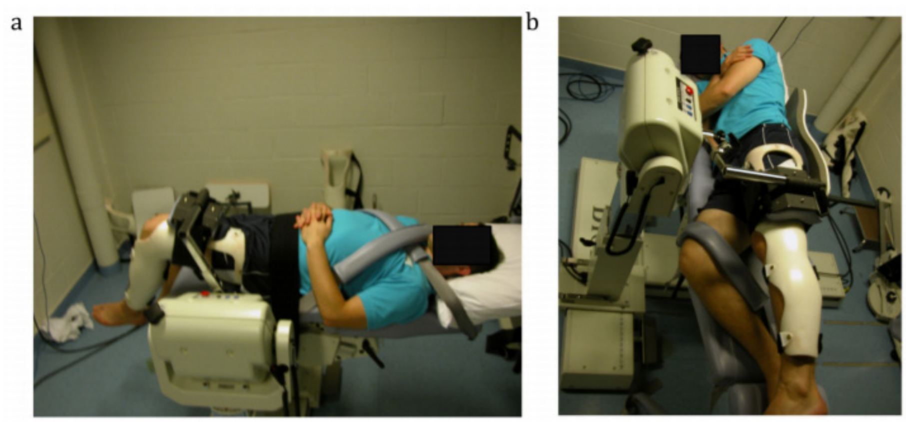

Figure 1.13. Meyer et al.'s two testing positions for the sagittal (a) and frontal (b) planes [65]. The braces were used to reduce compensatory motion when a participant completes the tests. These images are licensed under the Creative Commons Attribution License. © 2013 Meyer et al.

Although the Biodex dynamometer and other mechanized dynamometers are the gold standard for testing hip isokinetic muscle strength, the Biodex was not primarily built for studying hip. The Biodex's main intended use is testing the knee. The Biodex is still capable of testing the hip. However, opposite from Meyer et al.'s methods, the Biodex's manufacturer actually recommends hip tests be performed standing in their video tutorial. Standing positions could minimize the pain and injury risk, but there are questions about the repeatability of this position in terms of obtaining reliable and repeatable hip muscle strength measurements.

In a research setting, these tests are commonly performed with the patient supine since it provides a repeatable and rigid fixation of the patient with respect to the machine [57], [60], [62]. However, this supine position typically requires the patient to hang their leg over the side of the chair to obtain an accurate leg weight measurement and to allow the patient to achieve a full ROM while performing the test. This position places the hip in extension while supporting the weight of the leg, which could cause discomfort and place patients at risk for dislocation. Additionally, when a patient works to complete a test, they will generate enough force during flexion to be worrisome for THA patients who received a posterior THA.

Although Julia et al. and Meyer et al. completed reliability studies and shown fully developed methods for testing the hip, neither the supine nor the standing position provide an optimal testing position for THA patients. Developing a new testing position in order to test THA patients' hip muscle strength would be necessary in addition to collecting motion capture data for ADLs.

In Summary

Dislocations are a complication from THA. Factors that cause or are related to dislocation risk have been thoroughly studied from a surgical and demographic level in retrospective review and computer modeling studies. Retrospective review studies were used to show that the anteversion angle of the cup is an important surgical factor, a larger femoral head size should be utilized in at-risk patients, and at-risk patients include those who are older or have a history of cerebral dysfunction. Computer modeling studies were used to confirm that larger femoral heads would reduce dislocation, but they also highlighted implant types that were exceptions to the findings from retrospective reviews. Additionally, when combining the study of dislocation and motion in computer modeling, it was found that activities, such as sitting on a low chair or standing, have their ROMs influenced by implant positioning, which in turn might impact dislocation risk. These studies have led to an understanding that flexion and internal rotation is a risky motion combination for those treated with a posterior approach, and extension and external rotation is risky for those treated with an anterior approach. Several studies of hip motion and muscle strength have been completed, but information for clinicians is still needed. Surgeons and PTs are often asked by their patients if they can still do various ADLs, such as rising from a sofa, golf, gardening, and more. However, there is not enough general information available to surgeons and PTs for them to clearly answer these questions. New motion capture studies focusing on ADLs and the hip are needed, but before involving THA patients, healthy individuals should be involved. An understanding of the dislocation risk for particular ADLs needs to be established before THA patients can be brought into motion capture studies.

In addition to the motion capture studies that need to be performed, hip muscle strength needs to be tested for all participants. Surgery affects strength, and in turn, strength affects motion. The effected hip strength of THA patients could be why particular ADLs are placing patients at risk. However, there is not a testing position for hip muscle strength that is safe and secure enough for THA patients. Similar to performing motion capture on healthy participants to gather enough information on risky motions, there needs to be a study to develop a new testing position for at-risk populations. In order to develop the new testing position, a study with healthy individuals needs to be completed first.

Altogether, in order to further knowledge about dislocation and motion, two major studies need to be completed with healthy persons, one for muscle strength and one for motion capture. Additionally, for the motion capture, preparation of code is required. For muscle strength, two methods currently exist for testing isokinetic hip muscle strength. The supine position is not reasonable to ask THA patients to complete due to the extension when at rest and the force the patients must overcome during flexion tests. Alternatively, the standing position may not provide enough fixation. A possible future testing position would be a fixed standing position. Additionally, all testing positions that are safe enough for THA patients also need to produce consistent results. Thus, the purpose for this study is to determine the repeatability of hip flexion and abduction measurements between days with the subject in three different positions (supine, standing, and fixed standing) and identify a safe testing position. This purpose will be achieved through the testing of the following hypotheses:

1. Flexion measurements will be less repeatable with the subject standing (free or fixed) as compared to supine.
2. Abduction measurements will be less repeatable with the subject standing (free or fixed) as compared to supine.

As for motion capture, the required preparation of the code will be discussed separate from the study. For the study, motions that put THA patients at risk need to be put into quantitative terms before a decision can be made to include or exclude them from motions that can be reasonably tested with THA patients. Additionally, when put into numerical terms some motions may be of such a low dislocation risk that it would be best to give priority to other motions. Since motion capture studies involve people, time is normally limited and not everything can be included. As noted above, several studies focused on particular groups. Although THA is a surgery typical of an older population, there are a large number of both young and old THA patients, making it important to study and include all ages [66]. Thus, the purpose of this motion capture study is to test ADLs with healthy individuals of all ages to determine if they are safe enough for a THA patient to complete and which activities would be the most useful to test. This purpose will be achieved through the two project aims:

1. Produce normative data for healthy individuals
2. Study how age influences hip and trunk motion during ADLs in a healthy population of older and younger participants

CHAPTER TWO

Isokinetic Hip Muscle Strength Study: Standing versus Supine Repeatability

Muscle weakness and asymmetry are common in THA patients before and after surgery [54], [55]. Due to this weakness or asymmetry, a patient's muscle strength should be monitored during a motion capture study as it could influence a patient's motion. Julia et al. and Meyer et al. tested hip muscle strength reliability in a supine position using isokinetic muscle strength tests [64], [65]. Reliability refers to whether or not the results produced from the tests are consistent. Isokinetic tests are performed to isolate the desired muscle groups and to find the maximum peak torque over a person's full ROM at a constant speed and variable resistance. The two studies found that the results produced in the supine position were consistent [64], [65]. However, this position can place THA patients at risk for dislocation and pain because the start of the tests would place THA patients in extension with rotation. Additionally, when overcoming the starting position, THA patients would have to use flexion and rotation, making this position risky regardless of surgical approach. The current alternative is to complete tests with the THA patient standing, which is recommended in the manufacturer's video tutorial. However, this testing position may not be as reliable because the hip's muscles are not isolated and there is not a way to secure THA patients during a test. Currently, there is not a position that is safe and reliable for THA patients.

In this muscle strength study, there are three positions tested for reliability: supine, free standing, and fixed standing. The supine position is standard in literature

[64], [65] while the free standing position is suggested by the company that manufactures the Biodex Dynamometer in their tutorial video. The new fixed standing position, the method developed for this study, prevents unnecessary body movement while providing safety. These three testing positions are used with isokinetic testing, which is commonly used to screen for hip strength deficits both between limbs and between subjects [62]–[69]. In order to determine the repeatability of hip flexion and abduction measurements between days with the subject in three different positions (supine, standing, and fixed standing) and identify a safe testing position the following hypotheses will be tested:

1. Flexion measurements will be less repeatable with the subject standing (free or fixed) as compared to supine.
2. Abduction measurements will be less repeatable with the subject standing (free or fixed) as compared to supine.

The results below will show that all of the subject positions will produce reliable isokinetic muscle strength data using a gold standard muscle strength dynamometer on the condition that those collecting the data are consistent and clear in all instructions, especially when a person is in the free standing position. Furthermore, fixed standing will be shown to combine the best of both the free standing and supine positions. With a fixed standing position, the risk for THA patients being in a position that places them in extension and external rotation during flexion tests is removed and allows for tests that isolate the hip better than a free standing position.

Muscle Strength: Methods

The study was approved by Baylor University Institutional Review Board (IRB). For every participant, the same lead researcher and assistant collected all the data for this study to ensure consistent testing conditions. Both the researcher and assistant were present to provide strong verbal encouragement, consistent positioning, and clear instructions.

Ten (10) healthy test subjects (3 F, 7 M) aged between 20 and 23 participated in the study. Only subjects with healthy hips were enrolled to reduce the risk of hip injury from the supine position. All isokinetic tests were completed on a Biodex System 3 (Biodex Medical Systems, Inc., Shirley, New York). All participants completed three test sessions that were three to five days apart. Once a participant was properly positioned in the Biodex, they were required to practice by completing three submaximal practice repetitions [65]. The sub-maximal practice tests were used to warm up the participants, ensure participants were properly connected to the Biodex, and checked the participants' alignment with the rotational axis of the dynamometer. All participants had at least a two minute rest period between maximal exertion tests [65]. The individual tests for right hip flexion and abduction were maximal exertion isokinetic testing completed at 60°/s, which is considered to be a strength speed [56]–[63], in the three different positions: supine, standing, and fixed standing (Figure 2.1).

Figure 2.1: Overview of the three Biodex testing positons: Standard position in literature is the supine position. The standing position is mentioned in the Biodex tutorial. The fixed standing position is achieved by strapping the patient to the back of the Biodex chair using a custom back support pad and two straps across the torso.

For all testing types, the leg was strapped to a hip attachment bar that can be locked in place to obtain various measurements. One measurement is the anatomic zero reference, which occurs when the hip is in a neutral position. This reference zero was then used as the zero value for the built in goniometer on the Biodex's computer, which affects the angle used for the leg weight measurement. The leg weight measurements were recorded in newton meters through the Biodex after the participant's leg was secured at a set angle and rested all their leg's weight onto the secured hip attachment bar. All leg weight measurements were taken at the same angle from the neutral position. This measurement is used to correct hip strength values by removing the leg weight when the participant is raising their leg against gravity or adding the leg weight when the participant is lowering their leg with gravity. This correction produces hip strength values that show only the participant's effort to raise and lower their leg.

For the supine position, the setup followed the methods of Meyer et al. with the test subject positioned lower on the reclined chair so that the leg weight could be properly obtained [65]. The lowered positioning on the reclined chair causes the test subject's thigh that is covered in the testing strap to hang over the edge. The leg overhang allows the researcher to correctly set the anatomic zero reference. Instead of using a foam wedge or pillows to bridge the gap between the chair cushions, the manufacturer provided a custom pad. Figure 2.2 below shows more images of the supine position for both flexion and abduction tests. In the images, it is clear there are a few inches of space between the knee and the bottom of the hip pad, which was in accordance with Meyer et al.'s methods. Additionally, from the images it is clear that the participants would start in extension during the flexion tests.

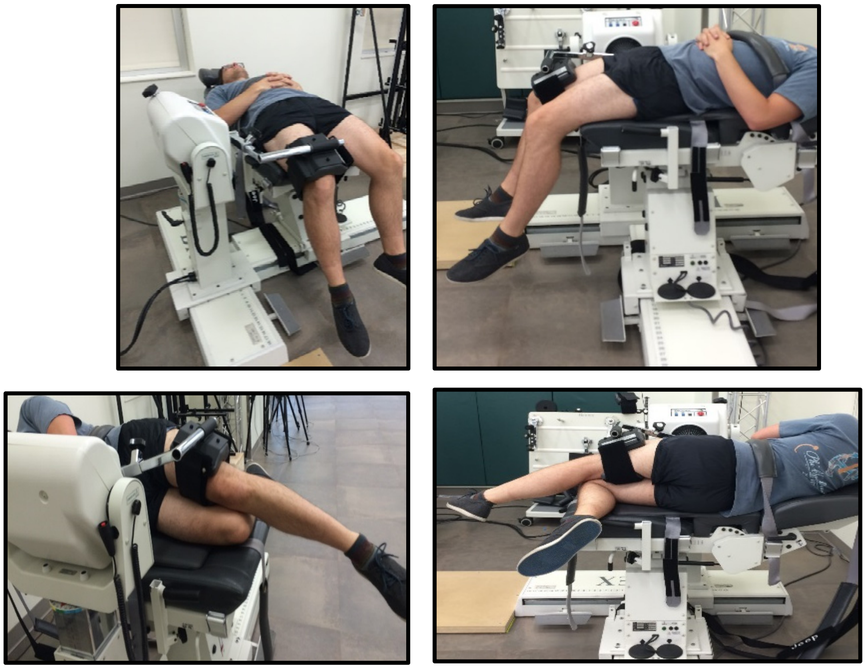

Figure 2.2. Supine positon setup for flexion (above) and abduction (below). There are two views for flexion and abduction. In the images of flexion, it is visible from the side that the person is experiencing extension. Their foot is also partially turned out.

For the free standing position, the setup followed the manufacturer's tutorial instructions with an added platform (Figure 2.3). When planning for this study, it was noted that the participants shorter than roughly 1.7 meters (5 feet 6 inches) would not be tall enough for their hip center to be aligned with the dynamometer's head, making it necessary to have an elevated starting point for all. During these tests, participants were told to look straight ahead. If they started to look elsewhere, they were reminded to look ahead. Additionally, they were reminded not to press into the dynamometer head (i.e., the point of attachment for the hip bar easily seen in Figure 2.3), where they were allowed to place their right hand for balance during the flexion measurements. For abduction, they were allowed to use both hands for balance and again reminded not to press into the dynamometer head. They were also told to keep their upper body straight.

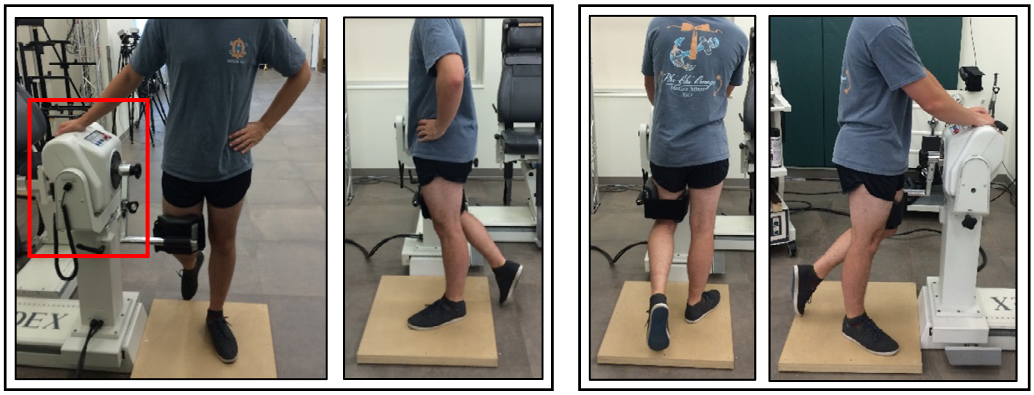

Figure 2.3. The free standing positon for flexion (left) and abduction (right). Having a set position for both hands at all times, helped the participant remember to remain upright during the tests. On the other hand, reminders were needed for the participant to not press into the dynamometer head, which is the point of attachment for the hip bar to the rest of the device. The dynamometer head is best seen in the image on the far left (boxed)

The fixed standing position, the method developed for this study, focused on safety and repeatability through positioning and comfortable securing (Figure 2.4). Additionally, this position allowed for an easy transition between flexion and abduction setups just like the previous two positions. For both flexion and abduction, the custom pad from the supine position was modified to attach onto the back of the chair. New straps were also attached to the Biodex on the headrest. For flexion, the straps crossed the body. For abduction, a single strap crossed the body, which was similar to the supine position's abduction test. Additionally, there was a space at the top of the "T" platform that a block filled, as seen below in Figure 2.4. The space was where people most naturally placed their untested foot during abduction, so filling the space was necessary.

During the positioning of the subject for both standing positions, the most important item that the researcher and assistant worked together on was to properly tighten the leg strap to prevent it from slipping. When the participant was standing, the leg's muscles were engaged, making the leg slightly thicker. On the other hand, when the participant completed the testing motion, not all of the same muscles were engaged, so the leg strap would slide, which would cause inaccuracies. To prevent this slippage, the researcher and assistant had the participant lift their leg slightly when tightening the strap.

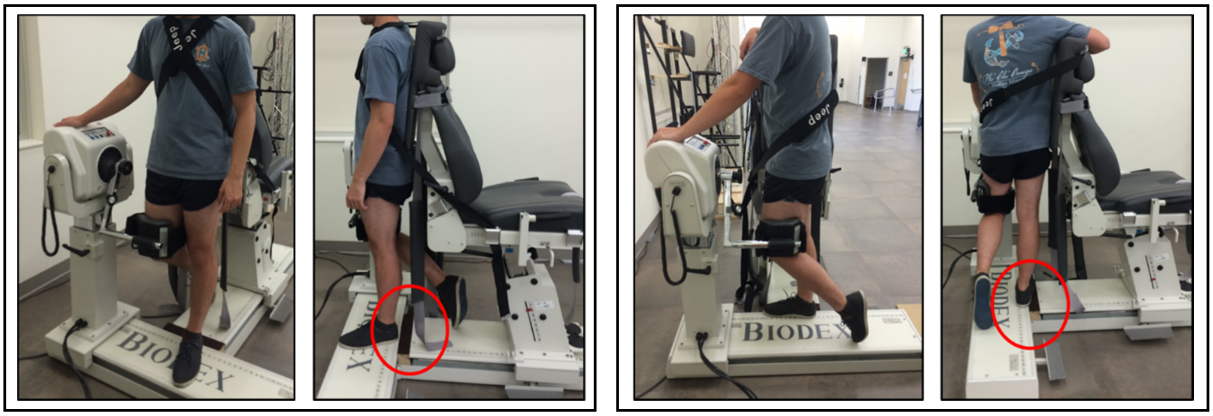

Figure 2.4. The fixed standing positon for flexion (left) and abduction (right). The block circled in red helps to fill the space at the top of the “T” in the platform. Two new straps were attached to the Biodex to secure the participant in a similar manner to the supine position. Both straps are used during flexion while just one is needed in abduction.

Preparing for analysis, the data was processed with a custom Matlab (Mathworks Inc., Natick, Massachusetts) program that filtered the data and obtained maximal muscle torques for each trial. The Biodex’s manufacturer recommended the three filters that were used on the data. First, the data was sent through a low pass filter in order to smooth the data. Then, the data was passed through a degree cushion filter, which removed data points that were close to when participants decelerate and change directions during a test. When a participant decelerates and changes directions, some of the data points generated are artificial spikes, which is why the Biodex’s manufacturer recommends this filter. Lastly, the data passed through an isokinetic window, which is used to remove data points that are not close enough to the actual testing speed.

For the analysis for both hypotheses, the repeatability of the data was tested in two ways using SPSS (IBM Corporation, Armonk, New York). First, the between days repeatability for abduction and flexion was evaluated by intraclass correlation coefficients (ICCs). ICCs that were less than 0.80 were labeled insufficient, between 0.80 and 0.90 were moderate, and those above 0.90 were high [65]. Second, the average between session leg differences were compared using t-tests. To explain, for a single participant and one test type, the average from each session was subtracted from one another, which means there was a difference value for Sessions 1 and 2, Sessions 1 and 3, and Sessions 2 and 3. Once all of these difference values were obtained, they were averaged to produce a single value for the test type. The differences per test type were then compared with a t-test to see the difference between positions. For example, if a person had session values of 40, 42, and 39 Nm, then they would have session differences of 2, -1, and -3 Nm. The average between session leg difference would then be 2 Nm.

Muscle Strength: Results

Before detailing the results, as a reminder, the purpose for this study is to determine if standing positions are as repeatable as the supine position during isokinetic muscle strength exercises in order to find a viable testing position for THA patients. This purpose was investigated by testing the following hypotheses:

1. Flexion measurements will be less repeatable with the subject standing (free or fixed) as compared to supine.
2. Abduction measurements will be less repeatable with the subject standing (free or fixed) as compared to supine.

Hypothesis 1: Flexion Results

The average peak flexion torque for the right leg per session and per test type is displayed below in Figure 2.5. By visual inspection, it is clear that the averages per test type are grouped. For the supine, free standing, and fixed standing positions, the ICC values of 0.955, 0.962, and 0.955, respectively, are high. These values agree with Meyer et al.'s result of an ICC of 0.92 for a supine position with a unique bracing technique to prevent extra motion of the hip during the tests [65]. Additionally, the values agreed with Julia et al.'s result of an ICC of 0.94 for a supine position without a brace [64].

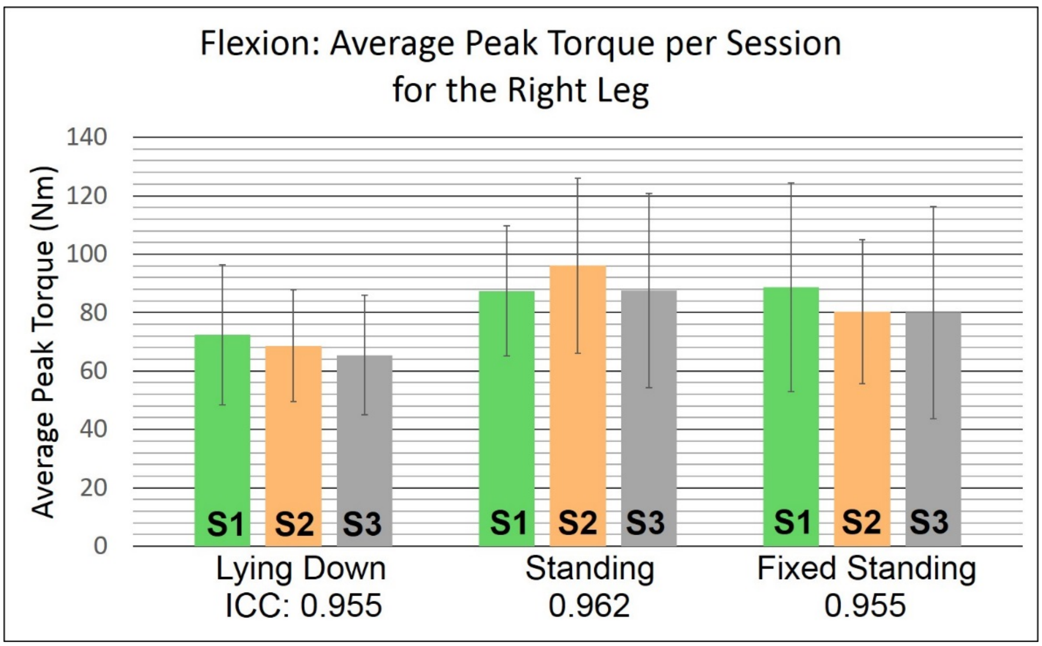

Figure 2.5. Average peak torque for hip flexion per session for the right leg at the isokinetic speed 60 °/s. The session number is distinguished by "S1", "S2", and "S3" in chronological order. The error bars are the standard deviation for each session.

From the information presented in Figure 2.5, the average between session differences were determined (Table 2.1). Again, these values represent the difference between all sessions for all participants, and this representation provides an idea of how tightly or loosely grouped all of the individual session values are to one another. The difference for the supine position was the smallest. Although standing and fixed standing had larger differences than the supine position, they were also small. There was not a significant difference between the position differences.

Table 2.1. Flexion average between session differences (no significant differences).

	Supine (Avg ± St Dev)	Standing (Avg ± St Dev)	Fixed Standing (Avg ± St Dev)
Average between session difference (Nm)	8.57±6.11	10.68±8.46	12.89±10.48

To recap, flexion measurements were repeatable with all positions. Between sessions, the supine position had a lower average and standard deviation than either standing or fixed standing, making the supine position the most repeatable. However, both standing positions were reasonable, which is important to note for the aim of finding a viable testing position for THA patients that is both safe and reliable.

Hypothesis 2: Abduction Results

Similar to the flexion results, Figure 2.6 displays the average peak abduction torque for the right leg per session and per test type. Once again, by visual inspection, it is clear that the averages per position are grouped, suggesting that the results are consistent among the different sessions. However, the standing positions look more closely grouped together than the supine position. For supine, the ICC value of 0.890 is still moderately high. For free and fixed standing the ICC values of 0.954 and 0.945, respectively, are high. Julia et al. tested only flexion and extension, so the only comparison available is to Meyer et al.'s results for a braced supine position, which was an ICC of 0.83 [65]. The ICC values produced from this study are in agreement with Meyer et al.'s results.

From the information presented in Figure 2.6 the average between session differences are determined (Table 2.2). The difference for the free standing position was the lowest this time. There was not a significant difference between the position differences.

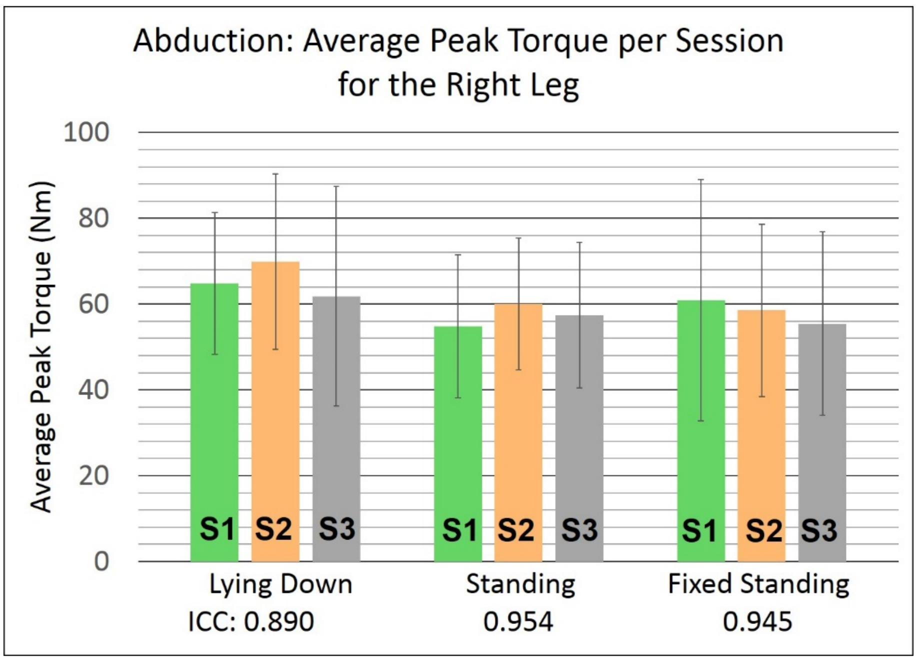

Figure 2.6. Average peak torque for hip abduction per session for the right leg at the isokinetic speed 60 °/s. The session number is distinguished by "S1", "S2", and "S3" in chronological order. The error bars are the standard deviation for each session.

Table 2.2. Abduction average between session differences (no significant differences).

	Supine (Avg ± St Dev)	Standing (Avg ± St Dev)	Fixed Standing (Avg ± St Dev)
Average between session difference (Nm)	12.33±9.86	6.39±5.38	9.47±8.10

To recap, abduction measurements were repeatable with all positions with the most repeatable being free standing followed closely by fixed standing.

Muscle Strength: Discussion

To summarize the results, flexion measures were repeatable with all positions. Based on the average between session differences, the supine position was more repeatable than the two standing positions, but the two standing positions were still reasonable. Abduction measurements were repeatable with all positions with the most repeatable being free standing. Overall, based on the high ICC values for repeatability, all three positions were found to be usable for reliably collecting hip flexion and abduction isokinetic measurements.

The results for all of the positions showed high ICC values that were comparable to Meyer et al.'s flexion and abduction results for the supine position with a brace to prevent extra motion of the hip [65] and to Julia et al.'s flexion results for the supine position without a brace [64]. From this comparison, it appears to be possible to obtain reliable results without the use of a brace to prevent extra motion of the hip during testing when the researchers are careful about proper participant positioning on the Biodex and providing constant instructions. In fact, for the standing positions, these comparable values are highly attributed to the researchers' ability to properly position participants and provide constant instructions. Instructions were based on common tendencies of participants that had been gathered during preparation for this study. Participants in the standing position had a tendency to crunch or press into the dynamometer head to aid their hip muscles. By reminding the participants to maintain their proper position throughout the tests, they appeared to complete the test with only their hip muscles. The fixed standing position did appear to provide stability and participant positioning consistency.

Another point of interest is that the Biodex is the gold standard, not for the hip, but for knee strength testing. Reliability studies have been conducted for the knee with methods solidly established that do not require the need of extra braces or careful instructions because the machines were designed primarily for knee tests. These studies take a similar form to the few reliability studies completed for the hip. Sole et al. tested 18 participants (7 F, 11 M) for their knee strength for flexion and extension at 60 °/s on two different occasions a week apart and compared the sessions [67]. There was only one examiner, which is similar to the current study presented in this thesis and the other studies examining hip strength [64], [65]. All tests were performed on a Kinetic Communicator 500H. Sole et al. reported ICC values of 0.93 for flexion and extension when examining the max values [67]. The majority of the ICC values produced from the study in this thesis are greater than Sole et al.'s values, which suggests that the repeatability of the measurements for the hip is similar to the repeatability of the measurements for the knee. This is reassuring for researchers seeking to investigate hip strength using methods developed for the Biodex that has only been known as the gold standard for knee strength.

Upon studying Figure 2.5, it is clear that the supine position during flexion tests produced smaller average peak torques than either of the standing positions. The starting position for the supine position is with the participants slightly extended. Before being fully able to flex their hip, the participants would have to overcome the extension. Several of the participants noted that it took a lot of their strength to overcome the starting position. It is possible that the overall decrease in average peak torque is due to participants having to focus their energy on overcoming the starting position. Although this reduced the overall average peak torque, it did not reduce the consistency of the tests for the supine position.

Surprisingly, the supine position was not the most repeatable position for abduction measurements. When supine, abduction isolates the gluteus maximus and medius muscles. This isolation might cause a higher activation level for those muscles [68] when a person is trying to raise their leg. The majority of the participants in this study were of average activity level with a few participants working out more regularly. For those who viewed themselves as more average, it is possible that the isolated use of these muscles was difficult for them, which showed up in the results for the supine abduction test through a lower ICC value. Although this ICC value was lower, it was not significantly lower than the standing ICC values.

In contrast to the supine position, the standing positions had a larger average peak torque during flexion and were more consistent than the tests completed in the supine position during abduction. During flexion tests, participants would have to be reminded to not bend forward while standing. This issue was solved through the fixed standing position that offered a more stable standing position. Although reminders were provided to not crunch against the straps, more instructions could be focused on encouragement. Alternatively, the standing position without fixation would be the quickest set of tests to complete. Since the fixed standing position still requires the participant to be secured, it takes a similar amount of time as preparing a participant for a supine test. Between the two, only the standing position is recommended by the Biodex manufacturer. However, the standing position is not typically used in the research community, which is why a standing position that offers fixation would be a better alternative to the supine position.

Altogether, all the positions tested were repeatable for hip flexion and abduction. The ICCs produced from the data was comparable to other studies of the hip as well as a study of the knee, which is the joint most studied using a Biodex dynamometer. The supine position did produce lower average peak torques for flexion, which is possibly due to participants having to overcome the initial position. Additionally, the supine position was less consistent during abduction, which is most likely due to participants attempting to use isolated muscles that are not normally used in isolation. As for the standing positions, the free standing position offers a position that is quick and recommended by the manufacturer. However, the free standing position does not offer fixation to prevent unnecessary movement by participants.

Muscle Strength: Conclusion

Overall, this study indicated that standing positions are as repeatable as the supine position for obtaining isokinetic muscle strength values for hip flexion and abduction at a speed of 60 °/s. To achieve this, the researchers were meticulous and took great care with their instructions and positioning of participants. Of course, this study involved only healthy young individuals. With an older population or a person with a painful hip, there might be some concern with their ability to maintain the free standing position. Additionally, constant verbal instructions were needed with the younger population, especially with the free standing position. Alternatively, the supine position is a safety concern for THA patients because it places them in a position with extension and external rotation. Furthermore, during a flexion test in the supine position, a participant’s comfort is lower because of having to hang their leg over the side of the chair. Some of this study's participants have said that it strains their back to complete the flexion test in a supine position. Therefore, the fixed standing position might provide additional support to ensure the patient comfort and proper positioning throughout the muscle strength test.

With proper instructions, all of the testing positions are repeatable. This finding is valuable to both the BioMotion Lab at Baylor and the biomechanical community in general because it confirms Meyer et al.'s results for the supine position [65] and provides methods for a new testing position that is desirable for researchers studying older populations or populations with painful hips. Meyer et al. produced the methods for the supine position for the Biodex and showed that their position with a special brace had a high or moderately high level of repeatability. Additionally, without the brace our results were comparable to Meyer et al. and Julia et al.'s results. For the BioMotion Lab, this conclusion influences the methods for collecting hip strength data. When studying healthy individuals, the supine position or the fixed standing position will be equally desirable options for the lab. As for the motion capture study detailed in the next chapter that also involves healthy participants, the newly validated fixed standing position was adopted for taking hip muscle strength measurements so that future iterations of that study can include patients with THA. The decision to adopt the fixed standing position was based on that position providing a safe fixation regardless of age because in the future, data will be collected on THA patients who will be older and possibly have muscle weakness or asymmetry. For studies that are outside of the BioMotion Lab at Baylor that involve patients with painful or compromised hips, the fixed standing position might be the position they adopt to conduct their hip muscle strength tests as well.

CHAPTER THREE

Motion Capture: Preparation of Motion Capture Processing Code

Setting up the Baylor BioMotion Lab involved placing and troubleshooting the camera system, selecting the various marker sets to be used in the lab, and developing the necessary software codes in order to process the motion capture data. In the Baylor BioMotion Lab, the Full Body Point Cluster Technique (PCT) marker set was selected to be the standard lab setup to be used with the Vicon Nexus 2 motion capture collection software. The PCT marker set will be further described in Chapter 4. The code needed to facilitate the use of this PCT marker set through the Vicon Nexus 2 platform integration with Matlab was developed by updating several existing scripts. Early validation testing was performed to ensure that the coding updates were performed correctly. With these updated scripts, motion capture data processing has been streamlined and a new standard has been established for the BioMotion Lab. The study described in Chapter 4 was the first study to utilize this new data processing standard. Chapter 3 is dedicated to describing the software updates that were made to the PCT processing code integration with Nexus 2 and the early validation testing that was performed to ensure a correct and consistent output.

Preparation: Code Update

In the lab, the Vicon Vantage Cameras work with the Vicon Nexus program to collect motion data, which are the x, y, z coordinates for each reflective marker during a motion. Additionally, the Vicon Nexus program has the ability to communicate with third party software, such as Matlab, and other programs created from Vicon, such as Body Builder. The Body Builder program is similar to Matlab and is used for its built in functions that handle matrix transformations between body segments. Both the Matlab and Body Builder programs are used in the PCT marker set codes to process the motion data, which includes identifying joint centers, developing coordinate systems for body segments, and determining joint angles.

Altogether, the PCT code is comprised of 11 Matlab scripts and 4 Vicon Body Builder scripts. Chaudhari provided the scripts that were valid for use with the Nexus 1 software. The current version of Nexus is the second version, which now communicates with Matlab directly. This meant that the current Matlab code contains Matlab commands that are linked to a software or program that acted as an intermediate between Matlab and Nexus. All of these commands need to be removed and replaced for the code to be used with Nexus 2.

The researcher for this study took on the task of updating the scripts. Since the change from Nexus 1 to Nexus 2 was a change in communication with Matlab, only the lines of code that generate communication between the programs were altered. Examples of these alterations are included in Appendix B. However, this still required an in depth understanding of all lines of the code, which includes all mathematical operations. This level of understanding was required because the original commands that let Matlab communicate to Nexus did not provide a clear picture of the needed inputs and outputs, and in some cases, the outputs were arranged differently. All of these inputs and outputs had to be re-created with the newer commands so that the mathematical operations did not have to be altered. Additionally, there was not a command library available with detailed notes for the Matlab commands used for Nexus 1. The most information available came from the comments in the Matlab code and the lines of code handling the math.

After the researcher understood each script, the Nexus 2 commands could be selected for use in the updated scripts. Unlike Nexus 1, the Nexus 2 Matlab commands and help information was available within Matlab as well as in the user's manual for Nexus 2. This allowed the new commands to be understood as quickly as any other command native to Matlab. Furthermore, these new commands were created to accomplish specific and useful tasks, which increased the number of commands already available to the user. Thus, after the researcher understood what was required for a script and selected the necessary Nexus 2 commands, a script could be updated.

Once updated, the troubleshooting process started. Small edits were made to the script updated by the Vicon Support team. As for the other two scripts, it was quickly noted that the new commands did not always produce matrices in the same way as the old commands. For instance, what used to be a column matrix was now transposed and some variable types were now not accepted by the new commands. In other places, the newer commands could not use the original inputs due to a variable structure requirement by the newer commands. This was solved by finding what variables the commands accepted and re-creating the variable based on the acceptable variable structures. These small changes added up to days of work, but in the end, the troubleshooting of the Matlab scripts was completed. Most importantly, none of the math within the code was altered. Instead, all matrices were transposed to be used with the original equations and alternatives were found to fix the variable type issues, so the structure of the original code did not have to be altered drastically. Following the completion of the troubleshooting phase, the researcher created documentation for standard operating procedures and common problems for use in the lab (Appendix C).

Later, during an attempt to fully process a test trial, a new problem was discovered with the Body Builder codes. The researcher, although unfamiliar with the scripting language, was able to learn about the program and was able to discover the source of the problem. With the problem identified, the researcher was able to correct the issue and verify the results against a standard test trial provided by Chaudhari.

Preparation: Code Validation

Since the actual calculation code was not altered, these results should be the same with the new code. However, we did a visual validation while an outside party from Auburn University is completing a more comprehensive validation. To do this validation, walking trials produced from the study for hip flexion/extension (Figure 3.1), ab/adduction (Figure 3.2), and rotation (Figure 3.3) were compared to Kadaba et al.'s published results [78].

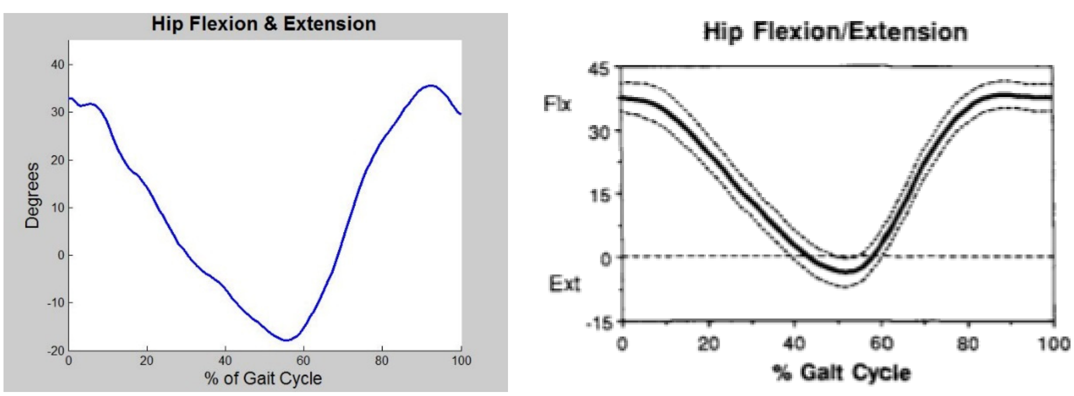

Figure 3.1. Flexion/extension: the processed walking trial from the BioMotion Lab next to Kadaba et al.'s graph was reproduced with permission from Wiley. Copyright © 1990 Published by John Wiley & Sons Inc.

For flexion, the published results shows an average peak flexion of 40° occurring between 80 and 90% of the gait cycle [78] and the walking trial shown in the figures has a max peak flexion of 35° during a similar point in the gait cycle. The peak extension point is approximately 5° in the published data occurring around 50% of the gait cycle and 17° in the trial occurring around 55% of the gait cycle. Although the amount of extension from the trial seems excessive, the published results showed a standard deviation that could approach 10°. Furthermore, the peaks and valleys occur at similar times for the trial and published data, suggesting that there is good agreement between the two.

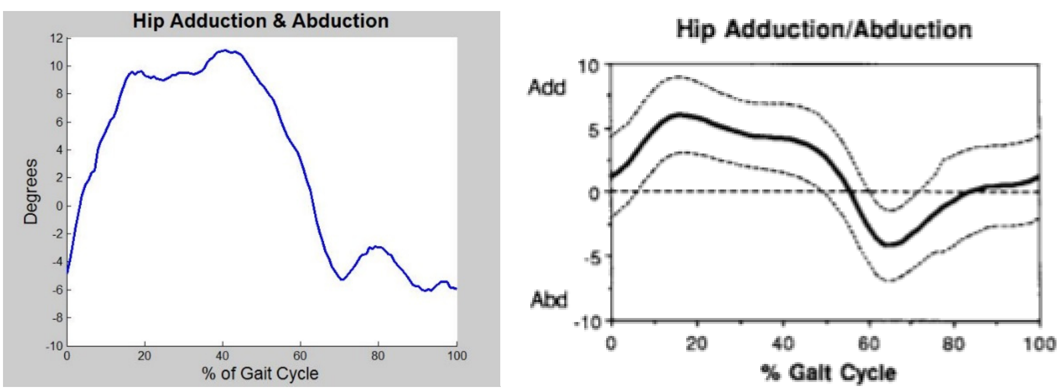

Figure 3.2. Add/Abduction: the processed walking trial from the BioMotion Lab next to the published data. Kadaba et al.'s graph was reproduced with permission from Wiley. Copyright © 1990 Published by John Wiley & Sons Inc.

For adduction, the published results show an average peak of approximately 6° [78] and the walking trial shown in the figures has a max peak adduction of about 11°, which is close to within the standard deviation pictured. The abduction point is approximately 5° in the published data and almost 5° in the trial. Both of the peak abduction points are occurring within 60 and 70% of the gait cycle. Although the trial from the study shows more adduction, the graph retains the correct shape and general ROM for adduction and abduction.

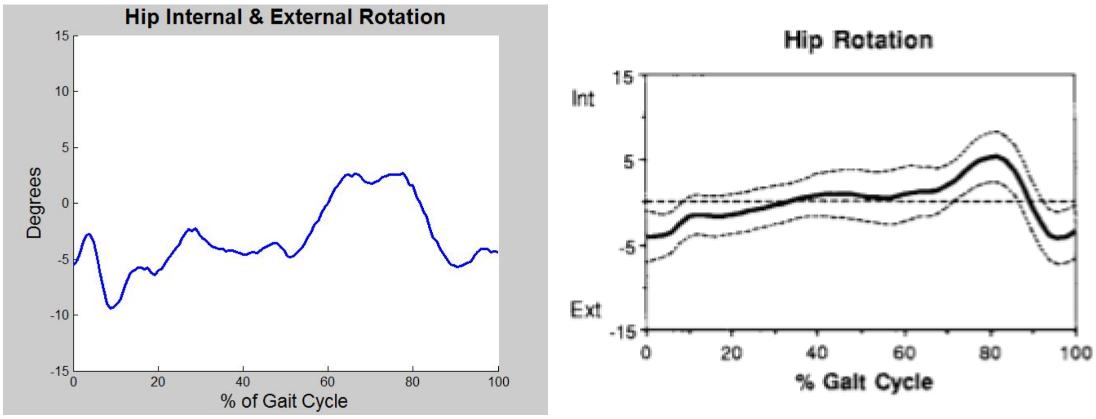

Figure 3.3. Rotation: the processed walking trial from the BioMotion Lab next to the published data. Kadaba et al.'s graph was reproduced with permission from Wiley. Copyright © 1990 Published by John Wiley & Sons Inc.

For internal rotation, the published results show an average peak of approximately 5° [78] and the walking trial shown in the figures has a max peak of 3°. Both peaks occur around 80% of the gait cycle. The peak external rotation point is approximately 5° in the published data and 6° in the trial with both occurring around 90% of the gait cycle. Additionally, with rotation there is more emphasis on the range than peaks. Thus, looking at the range, the trial has a 13° ROM, which is equal to the published curve's average 13° ROM. The similar shape and peaks along with the matching ROM suggests a decent match between the two.

Additionally, Kadaba et al. noted that embedded errors from the markers are small for flexion, but more pronounced in both ab/adduction and rotation [78]. This is clear from the larger standard deviation around the means for both ab/adduction and rotation in the published data. Kadaba et al. also cited that there is an error introduced due to uncertainty in defining the neutral axis, and thus to interpret angles with caution. With that, other subjects were viewed for visual validation and it appears that the joint angles are valid for all planes of motion.

The visual validation shows that the PCT codes were properly updated for obtaining hip kinematics. Now with the updated marker set in Nexus 2 and the updated code, completed collections could now be smoothly processed. Additionally, a more complete validation is being performed in collaboration with a lab at Auburn University and several other labs around the country are interested in the updated codes.

Preparation: Conclusion

Altogether, the PCT code was updated and quickly validated. The update did not alter any of the mathematical calculations within the core of the code, but did require an understanding of the calculations to complete the update. The quick validation showed that the Baylor BioMotion Lab produced results that match well with published data. The code is now part of the data collection and post-processing standard for the BioMotion Lab at Baylor and other labs around the country who utilize the PCT marker set.

CHAPTER FOUR

Motion Capture: Investigating the Influence of Age on Hip and Trunk Kinematics

Dislocation is a complication from THA that is currently being studied by surgeons, PTs, and biomechanists. The study of dislocation risk has recently lead to computer modeling studies that are used to investigate impingement during a simulated motion [35] and a few motion capture studies used to provide information to computer modeling studies [45] and improve implants [49]. In Nadzadi et al.'s study, he found a shortage of generally available motion data [45], which shows that furthering knowledge about hip movement will help to better define dislocation risk. Additionally, surgeons and other clinicians need published normative ROM data for ADLs so they can better treat their patients.

Currently, surgeons are unable to confidently answer their patients when asked about particular ADLs. Although the Hip Precautions are provided to THA patients, these guidelines are general and patients desire more specifics when they feel uncertain about a particular ADL. In order to provide surgeons and other clinicians the information they need to give better instructions to patients and improve post-op rehabilitation strategies following surgery, normative data needs to be collected from THA patients. However, before completing a study with patients, data needs to be collected on the ADLs with healthy individuals to provide "normal" values to establish when THA patients deviate from normal and to determine that the ADLs included in a THA study are reasonably safe and useful to the study.

Additionally, although retrospective studies have shown that older patients are not part of an at-risk population for dislocation, some researchers have noticed that dislocation rates for older individuals are higher than those for younger [23], [31]. Since this is true, concerns for older patients still exist. To further knowledge on age-based dislocation risk in THA patients, both younger and older participants are included in this study so that the ADLs can be examined for a relationship between age and kinematics in a group of healthy individuals. Both hip and trunk kinematics are compared between the age groups.

Additionally, hip muscle strength is important to monitor during recovery following THA, as patients will experience asymmetry or weakness before and after surgery [54], [55]. The patients' effected strength will in turn affect their motion, which could be why particular ADLs are placing patients at risk. For the current study that is handling healthy individuals only, there may be a relationship between strength and age. In order to study the possible effects of strength on motion, normative data from healthy individuals needs to be produced. Furthermore, if a relationship exists between strength and age as it pertains to motion, it may help explain why some older patients are more at risk.

This current motion capture study is used to establish the methods for a future THA patient study and to provide normative data for hip muscle strength and for hip motion during ADLs with healthy individuals of all ages. Additionally, this study is used to provide normative data for the trunk to further clarify hip motion as well as investigate the influence of age on motion. Several normative data tables are produced and the comparisons of younger versus older participants for particular activities of interest indicates that some hip movement strategies change with age.

Motion Capture: Methods

The Baylor IRB approved the study. There was one researcher for all study participants and occasionally an assistant that worked the collection computer. The researcher completed the consent process with the participants, markered the participants, and provided all instructions throughout the study for both the muscle strength testing and the motion capture. The consent process was completed in private with the participants. The BioMotion Lab in the Baylor Research and Innovation Collaborative (BRIC) was the location for all data collections (Figure 4.1). The lab has 14 Vicon Vantage Cameras (Vicon Motion Systems Ltd, Oxford, UK), making it a state-of-the-art motion capture lab.

Figure 4.1. The BioMotion Lab at the BRIC: Complete with 14 Vicon Vantage Cameras. The Biodex System 3 is in the left corner.

Twenty-three (23) volunteers (14 younger (ages 19-33), 9 older (ages 51-68)) completed the informed consent process and went forward with the study. The participants' demographics are summarized in Table 4.1.

Table 4.1. Motion capture participant demographics.

Group	Avg. Height ± Stdev (cm)		Avg. Weight ± Stdev (kg)		Avg. BMI ± Stdev (kg/m^2)		Avg. Age ± Stdev (years)		Female:Male
Younger	177.0	±10.9	75.2	±10.0	24.1	±3.3	23.1	±3.9	7:7
Older	172.2	±8.3	82.0	±13.5	27.6	±3.8	60.8	±6.4	5:4
All	175.1	±10.0	77.8	±11.7	25.5	±3.8	37.9	±19.4	12:11

Muscle strength data for hip flexion and abduction was collected using a Biodex System 3 (Biodex Medical Systems, Inc., Shirley, New York). Motion capture was completed with the 14-camera system collecting at 120 Hz. The Full Body Point Cluster Technique (PCT) Marker Set developed by Andriacchi at Standford University and Chaudhari at Ohio State was used [69], [70]. Fifty-two (52) motion variations were captured. Seven distinct activities have been selected for analysis for this thesis. These seven activities (Figure 4.2) include motions that are good for comparison with prior studies as well as activities related to posterior dislocation risk based on literature [43]. The seven activities include:

1. Picking up a ball on the right side of the body at a normalized distance away and moving it to the front at the same distance away
2. Normalized to leg length STS
3. Lower than normalized STS (38 cm)
4. Low soft chair (sofa) STS
5. Ascending stairs

6. Descending stairs

7. Tying shoes on the right foot (with the right foot placed on a raised bar)

Figure 4.2. A snapshot of the analyzed activities. Pictured is ball pick up (top left), STS (top center), sofa STS (top right), shoe tying (bottom left), and stair ascending (bottom right). Further descriptions of these activities are provided later in this thesis.

The complete list of activities and their variants can be found in Appendix D. Variants were collected because it would not add a significant amount of time to the collection and the approach to a task could alter ROM. If one of these variants reduce unwanted ROM, then PTs and surgeons would desire this information. However, an activity's risk for dislocation should be identified first before delving into the analysis of the different variations. The work to produce the 3D hip kinematics from each movement can be divided up into preparation, participant recruitment, collection, processing, and analysis steps.

Collection Preparation

The preparation for this study involved research to select activities, the selection of a marker set, and building of two small structures. The small structures are similar to stage props and were needed to help the participants of the study better understand how to perform some of the ADLs.

Activity list. The research performed on the ADLs generated a lengthy list of activities to be included in the study. To start, ADLs not thoroughly investigated were included, which means that any activity outside of picking up an object from the floor and high ROM kneeling was included. Then, the surgeons and clinicians at BS&W were consulted about activities they were often asked about from their patients. They provided a list of ADLs and activities that fell outside of the ADL category, such as sporting activities. Only the activities that fell into the category of ADLs were included.

The list generated from the literature and the doctors was large, so activities that were essentially duplicates were eliminated. This was done to keep the collections at a reasonable length of time (2-3 hours). From there, variations of the activities were added as the setup for variations would only require a new set of instructions. Once this list was determined, the doctors at BS&W reviewed and approved the list.

From the list of activities, descriptions for instructions per activity were generated. Through the instruction generation process a few activities were selected to have structures built as the activity would be difficult to complete without tangible support items (Figure 4.3). These activities were the sofa STS and shoes tying. Additionally, the structures built for these two activities were re-used for two activities on the larger list: getting in a car, out of a car, in a bath tub, and out of a bath tub. For the stairs, an existing structure was utilized in this study.

Figure 4.3. The sofa chair and foot bar. The sofa chair was mounted to a platform that could be easily rolled in and out of the capture volume, and when in use would not roll.

The other half of the instruction process was determining start points for all activities. For example, the height of the chair for the normalized STS activity was determined from the lower leg length [71], [72]. The goal was to set the height of the chair so that the hips and torso would make a 90° angle between them, which was achieved by finding the length of the lower leg by measuring from the knee markers to the floor. This method for normalizing the chair height was determined the best after reviewing other articles [73]–[76]. Additionally, the research completed on the normalized chair height showed that the ball pick up activities should be started and stopped at normalized locations as well. The ball pick up activities' start and end points were related to the initial and final placement of the ball, and they were placed at a distance 25% of the person's height away from their ankle. Between the start and end, the participants were instructed to bring the ball to stomach height.

Marker set. The marker set used for this study was the PCT, pictured in Figure 4.4, developed by Andriacchi at Standford University and Chaudhari at Ohio State [69], [70]. The PCT marker set was developed to minimize error associated with soft tissue artifact. The marker set uses clusters of markers on the lower and upper legs to remove some of the non-rigid body segment behavior. The average distance a cluster (i.e., all markers in a cluster) crosses between two time points is used to remove changes in individual marker locations that are too large or too small. When the change is too large or too small, the marker would follow a trajectory not fitting of a rigid body in motion. The methods behind this error minimization were tested in a simulation and compared to an *in vivo* study using intra-cortical bone pins, and these comparisons showed that it was a method that more closely approached the *in vivo* results than other methods [77]. Since this study included older individuals who might possess more soft tissue, this was the preferred marker set.

The PCT marker set is a marker set that works with all body types, which further motivated its selection because it does not require participants to fit in a body suit. Body suits are needed when the markers require a power source and wires. The suit is used to contain the electrical components and markers. However, the suit can add to the error from soft tissue artifact because it is another layer that will move either in the same or opposite direction as the soft tissue.

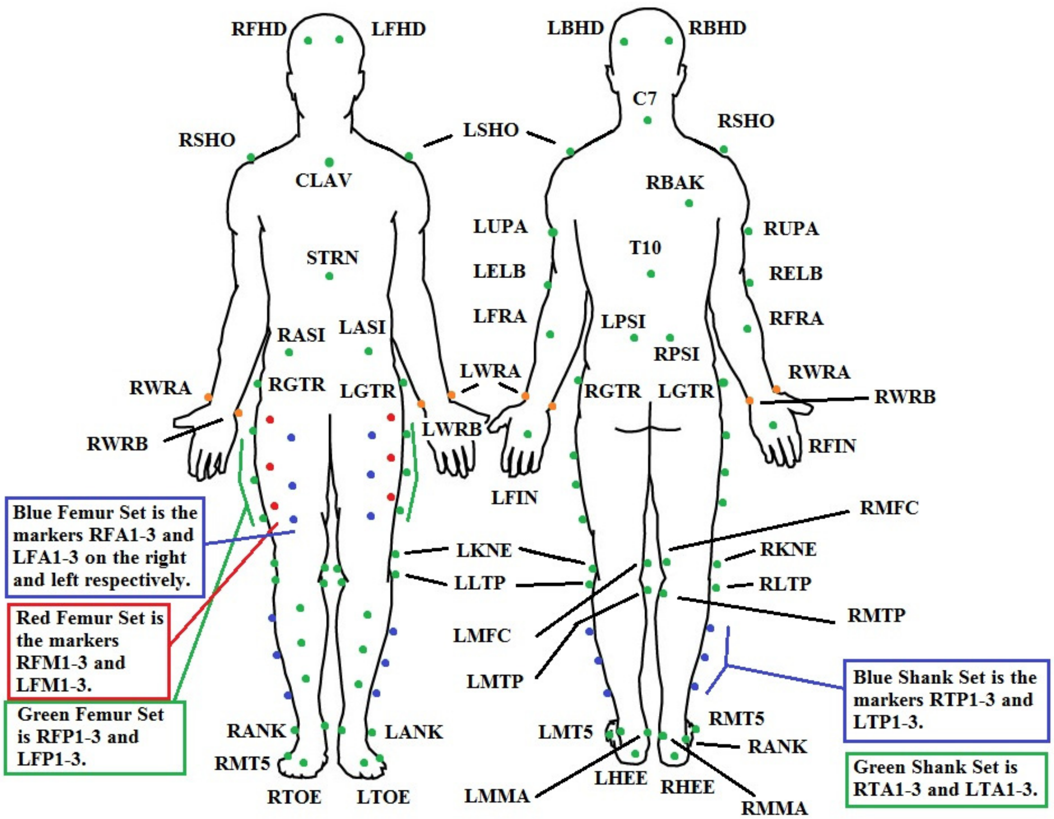

Figure 4.4. The PCT marker set: has 77 markers placed about the body with a high density of markers around the thigh. This image was generated by the author of this thesis for use in the Baylor BioMotion Lab.

Overall, the PCT marker set was selected for use in this study because it works with all body types and is used to minimize soft tissue artifact.

Participant Recruitment

Participant were recruited to the study via flyers. The flyer, which was approved with the study protocol by the IRB (Appendix E), was posted on social media and in public places both on Baylor's campus and at local Waco, TX YMCAs. The details of the study were also spread by word of mouth. If interested, a person would contact the BioMotion Lab. When contacted by a potential subject, details about the study were shared and any questions were answered. If still interested, then a time would be setup for a study visit at the BRIC. The details of how long a collection took, how it was handled, and other information is discussed below.

Collection Details

Collection details refers to the different portions completed during a study visit and the amount of time it takes to complete the visit. Before a study visit, some time was needed to prepare the lab. During a study visit, a volunteer was led through the informed consent process, demographic information collection, and data collection. After the collection, the lab was cleaned. Altogether, a study visit would take about two to three hours to complete.

Preparation of the lab simply included turning on all computers, completing a calibration of the motion capture system, and having the markers prepared for a participant. Calibration was completed with a wand that had markers at known locations on the wand. The marker preparation involved placing double-sided tape on the back of all 77 markers.

The first step the volunteer completed was the informed consent process, which was completed with the volunteer privately before any demographic or data collection. The IRB approved documents that were filled out were the eligibility check and the consent form. These documents made sure that volunteers were healthy enough and were fully informed of the tests involved in the study. If the volunteers passed the eligibility check and agreed to the study via the consent form, they would then be participants and moved onto the next step.

The second step was the demographic information collection. This information included name, date, time, height, weight, gender, race, age, lower limb injury history, and for women if they have had a child. Collecting the lower limb injury history after completing the eligibility check was an extra measure to ensure that participants were healthy.

The last step was the data collection, consisting of muscle strength testing and motion capture. The muscle strength testing was completed on a Biodex System 3 following the methods developed for the fixed standing position in Chapter 2 at 60 °/s for flexion and abduction. Fixed standing was chosen so that future iterations of this study that involved THA patients could use the same methods. Motion capture was used to collect data on 52 motion variations. For all activities, the collection was completed at 120 Hz with the PCT marker set, using the collection software, Nexus 2. All participants wore shorts that were rolled and taped up, and then they also had the option of wearing a shirt rolled and taped up. The option was available for women as long as they had a sports bra and were comfortable. These clothes allowed for all of the markers to be placed on the skin. For the seven activities included in this study for analysis, how they were achieved will be described below.

Side to front ball pick up (Figure 4.5): This activity was completed with a normalized setup. All participants started with their feet about shoulder width apart and the ball a measured distance away from their right side. The measured distance was 25% of the participant's height and was measured from the participant's ankle to the desired location of the ball's start and stop. They would then bring the ball to their stomach and then place it down on the floor at a measured distance in front of them.

Figure 4.5. The four steps followed to complete the side to front ball pick up activity from left to right. The ball was placed to the side of the right foot (far left) for the start of the activity. The distance the ball was placed away from the person was determined by a calculation used to normalize the ball placement. The participant would then pick up the ball (center left) and bring it to their stomach (center right) before placing it before them (far right). The place where the participants would place the ball was marked for them using tape.

Normalized STS (Figure 4.6): The participant stood up from the chair with their arms away from their hips. The normalized height of the chair was based on the lower leg's length (measuring from the lower lateral knee marker to the floor) [71], [72]. The chair had adjustable notches at set heights, and the chair was adjusted to the height mark closest to the lower leg's length. If it fell in between adjustable notches then, out of the two notches, one would be selected that allowed for the back and hip to make a 90 degree angle (or close to 90 degree angle) starting point. Similarly, a 90 degree angle was desired at the knee for the start.

Low STS: The participant followed the same instructions as the normalized STS activity, but the chair was set to its lowest height of 15 inches (38 cm).

Figure 4.6. The normalized STS activity is completed using an adjustable chair. The low STS activity uses the same chair, but on the lowest possible setting, which increases the initial amount of hip flexion.

Soft STS (Figure 4.7): The chair was a salvaged car seat put on a movable platform. The car seat had an angle to it similar to a sofa that would increase the angle at the hip, which was the desired starting point. Similar to the previous STS activities, the participant would stand up from the chair with their arms held away from the hip.

Shoe tying (Figure 4.8): The foot rail structure that was described earlier was used. The starting point was with the subject’s right foot on the rail while standing up straight. They would then put a loop that simulated a sock or shoe over their shoe. They would then return to the starting point for the ending point, so after the subject completed putting the loop on they would return to standing with a straightened back.

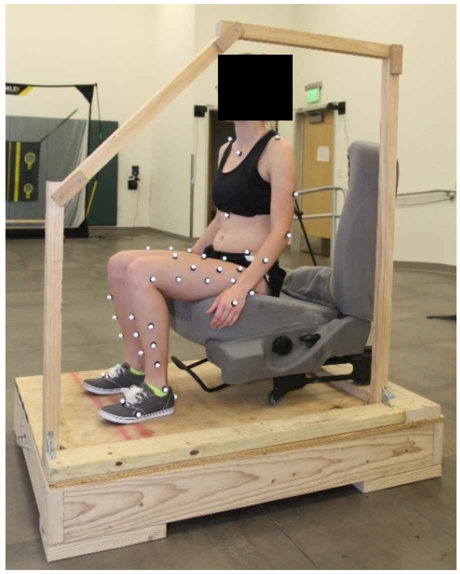

Figure 4.7. The starting position of the sofa STS activity. The participant would stand up from the chair to complete the activity, similar to the other STS activities.

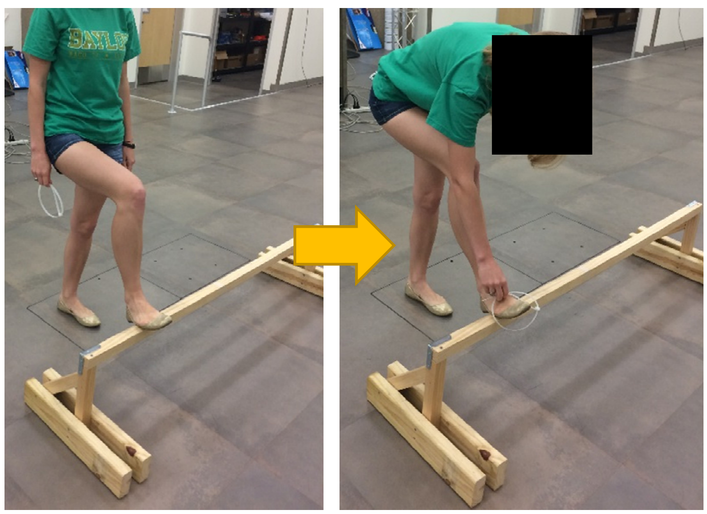

Figure 4.8. The shoe tying activity is completed with the foot bar. The participants all started with their foot on the bar and their torso straight (left). Then they would place the loop over their shoe (right). The size of the loop is large enough to fit over any shoe. All participants were instructed to return to the initial position for the next trial.

Ascending and descending stairs (Figure 4.9): A movable three step structure was secured to two AMTI force plates (Advanced Mechanical Testing, Inc., Watertown, MA). To provide participants a safe and easy place to turn around, a platform that had already been made for the lab was used as a landing. The starting point was before the first step of the stairs while the ending point was the platform.

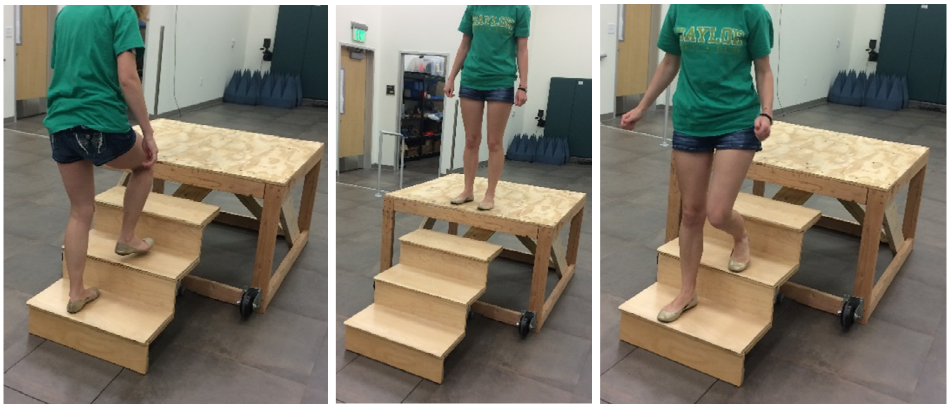

Figure 4.9. Images of stair ascending (left), the platform being used in between ascending and descending (center), and stair descending (right).

Outside of these activities, the participants completed all of the others listed in Appendix D. Some of the activities, such as getting out of the bath tub, were altered or dropped for older subjects who could not comfortably complete the activity. The activities included in the analysis do not include those that were altered. Additionally, the activities that are not covered in this study will be studied in the near future and described at that time. Once all of the activities were completed, the markers were removed and the subject was allowed to leave. The equipment and markers were cleaned thoroughly.

Processing Trials

Processing trials of motion capture data involved labeling the trajectory data for all 77 markers used in the PCT marker set and gap filling. Gap filling is the process of adding trajectory information to frames with missing markers, typically by linear or spline interpolation. In some cases, the marker’s trajectory could reconstructed using other markers' trajectories if they are on a segment of the body that can be assumed to be a rigid body, such as the pelvis.

First, trials were labeled and then gap filled using Vicon Nexus 2. Generally, the pelvis and head were filled using the rigid body fill while all other parts of the body were spline filled. Whenever the spline fill was unavailable, the pattern fill was used as is recommended by Vicon. Lastly, the PCT code determined the joint angles per trial.

After the joint angles were calculated, the angle data in all planes of motion for both sides of the hip was exported with a custom Matlab script.

Analysis Steps

Custom Matlab code was written for all steps to find ROM values and to conduct analysis on the kinematics to determine if there are differences between younger and older participants. The trunk joint angle was added to the analysis to be used as supporting results because people will use either the hip to compensate for the trunk or the trunk to compensate for the hip [79], [80]. In this study, the trunk joint angle is defined as the thorax relative to the pelvis. To start, for the hip and trunk joint angles, the ROM, max, and min per plane of motion (i.e., sagittal, frontal, transverse planes), trial, activity, and participant were calculated. For each joint angle, the subject averages of the ROM, max, and min per plane of motion and per activity was then calculated. From there, activity averages and standard deviations were calculated. The activity averages for the ROM, max, and min for both the hip and trunk joint angles were sent to Excel sheets to produce normative data tables for flexion/extension, abduction/adduction, and internal/external rotation.

From the Excel sheet, the averaged data was visually checked to make sure values were within a reasonable range. From this point, an objective data validation was then completed for data from both legs. Outliers were identified, and any that were the result of errant data collection were omitted. The tables were then updated for all participants in general and for each of the two age groups. The younger (Y) group contained those between 19 and 33 years old, and the older (O) group contained those between 51 and 68 years old. From the updated information, general observations were made and motions that fell into the risk category for dislocation (i.e., more than 90° of flexion and internal rotation for patients receiving a THA via the posterior approach and extension with external rotation for patients receiving a THA via the anterior approach) [43] were noted. Additionally, differences between the Y and O groups were extracted and compared for hip flexion/extension, abduction/adduction, and internal/external rotation.

Hypotheses to test the Y and O group differences were derived from literature and observations from the normative data tables. The average ROM for the planes of motion and activities of interest were compared individually between the Y and O groups per joint. In order to compare groups, an unpaired t-test was used after the distribution and variances of the data were checked. All groups of data had a normal distribution and equal variances. After the t-tests, a simple regression per activity was completed to determine if there was a linear relationship between age and ROM to be used as supporting results.

For hip strength, the Y and O data was averaged separately with female and male subgroups, so there was an average produced for all females in the Y group and all males in the Y group and the same for the O group. These averages were then tabled.

Motion Capture: Results

As a reminder, the purpose of this motion capture study was to test ADLs with healthy younger and older individuals to establish normative data, identify age effects with movement, and to determine which activities are safe enough for a THA patient to complete and which activities would be the most useful to test. This purpose will be achieved through the two project aims:

1. Produce normative data for healthy individuals
2. Study how age influences hip and trunk motion during ADLs in a healthy population of older and younger participants

Aim 1: Normative Data Tables

Normative data tables for ROM, max, and min were developed for the seven analyzed ADLs: side to front ball pick up, normalized STS, lower than normalized STS, sofa STS, stair ascending, stair descending, and shoe tying. Both the hip and the trunk tables are provided. The trunk angle was included to possibly reveal compensatory mechanisms [79], [80]. Additionally, a normative table for hip strength was produced that shows average peak torque for the Y and O groups according to gender. Observations are noted for all tables.

Hip ROM, max, and min tables for ADLs. The normative tables fulfill the first aim of this study, to produce normative data for a range of ages. The first three tables below show the average amount of flexion and extension (Table 4.2), adduction and abduction (Table 4.3), and internal and external rotation (Table 4.4) for the Y and O groups. The tables were produced for the separate portions of the ROM because dislocation is associated with both magnitude and direction of movement. Additionally, the left hip data for the shoe tying activity is included in the tables because the two hips were completing different tasks in the activity. The left hip was supporting the body while the right hip was flexed and the shoe was being "tied".

Table 4.2. Hip – average amount of flexion and extension per age group in degrees.

ACTIVITY	Flexion (Max)			Extension (Min)	
	Y Norm (Stdev)		O Norm (Stdev)	Y Norm (Stdev)	O Norm (Stdev)
Ball Pick Up	106.1 (7.7)		110.7 (5.5)	-3.2 (4.7)	0.2 (6.5)
Normalized STS	88.6 (7.9)		84.3 (15.4)	-1.1 (5.1)	1.8 (6.8)
Lower STS	95.1 (8.5)		91.6 (13.2)	1.1 (8.8)	1.9 (6.2)
Sofa STS	97.4 (9.1)		97.4 (16.1)	-0.6 (5.0)	2.4 (6.3)
Stair Ascending	65.1 (4.3)		73.6 (8.2)	-3.5 (4.9)	1.2 (6.9)
Stair Descending	42.8 (4.0)	*	52.1 (7.1)	-3.5 (5.5)	0.8 (7.0)
Tying Shoes (Right Flexed Hip)	99.6 (7.8)		109.1 (4.5)	70.6 (5.8)	74.9 (7.0)
Tying Shoes (Left Stance Hip)	35.0 (8.4)	*	46.8 (5.9)	-5.0 (5.2)	-4.3 (6.7)

Note: All positive values indicate flexion and negative values indicate extension. For t-tests, * indicated a significance at $p < 0.05$ for comparisons between the Y and O groups.

For the Table 4.2, the right hip during the ball pick up and shoe tying activities produced the greatest values in flexion. The ball pick up activity was 16° on average greater than the 90° of flexion that is deemed safe according to the Hip Precautions and literature [35], [41]–[43]. The shoe tying activity was about 10° on average greater than the limit of 90° of flexion. These activities were followed by the lower and sofa STS activities, which produced more than 5° on average over the flexion limit. Not many of the activities listed will produce a large amount of extension, which is evident from the table's small negative values. Additionally, when an activity has a large positive value in the extension column, it shows that the hip was still flexed during the activity and had become slightly less flexed. An example of this can be seen in the right hip during shoe tying. Conversely, the left hip during shoe tying showed the greatest amount of extension. Following the left hip for shoe tying, the greatest amount of extension appears in the ball pick up and stairs activities for both the Y and O groups. Differences between younger and older individuals in flexion are the greatest for the normalized sit to stand, lower STS, stair descending, and shoes tying activities.

Table 4.3. Hip – average amount of adduction and abduction per age group in degrees.

ACTIVITY	Adduction (Max)				Abduction (Min)			
	Y Norm	(Stdev)	O Norm	(Stdev)	Y Norm	(Stdev)	O Norm	(Stdev)
Ball Pick Up	4.0	(4.7)	5.4	(3.8)	-15.6	(7.8)	-14.7	(8.9)
Normalized STS	-0.2	(2.7)	5.4	(6.7)	-11.2	(5.1)	-2.4	(8.3)
Lower STS	-0.6	(2.0)	4.6	(6.3)	-10.9	(4.9)	-5.0	(8.0)
Sofa STS	0.9	(2.4)	3.5	(5.1)	-13.1	(6.2)	-7.1	(8.8)
Stair Ascending	7.4	(4.1)	10.7	(6.2)	-9.3	(2.6)	-6.3	(3.7)
Stair Descending	8.1	(3.2)	9.0	(5.3)	-11.2	(2.8)	-9.9	(4.4)
Tying Shoes (Right Flexed Hip)	0.0	(5.9)	-1.0	(7.4)	-8.0	(7.9)	-9.9	(7.5)
Tying Shoes (Left Stance Hip)	5.0	(2.8)	7.1	(4.2)	-1.2	(3.6)	1.0	(3.6)

Note: All positive values indicate adduction and negative values indicate abduction.

For the Table 4.3, the stair ascending, descending, and ball pick up activities produced the greatest values in adduction. For abduction, the ball pick up activity has the greatest values. Although adduction and abduction are not included in the mechanisms for dislocation, observations are included here for completion. Additionally, it may be possible that differences in the Y and O groups stem from changes in adduction and abduction. There is at least a 5° difference between Y and O groups for adduction for normalized STS and low STS. All of the STS activities show at least a 5° difference between Y and O groups for abduction.

Table 4.4. Hip – average amount of internal and external rotation per age group in degrees.

ACTIVITY	Internal Rotation (Max)					External Rotation (Min)			
	Y Norm	(Stdev)		O Norm	(Stdev)	Y Norm	(Stdev)	O Norm	(Stdev)
Ball Pick Up	11.7	(7.7)		7.0	(5.9)	-9.0	(7.6)	-14.3	(6.6)
Normalized STS	9.1	(8.8)		5.0	(6.9)	-4.7	(8.8)	-7.3	(6.7)
Lower STS	10.4	(9.7)		5.4	(6.5)	-4.6	(8.5)	-7.8	(6.1)
Sofa STS	13.2	(11.1)		7.3	(9.0)	-6.5	(8.8)	-8.6	(6.3)
Stair Ascending	10.5	(8.1)		8.2	(6.2)	-8.5	(8.8)	-9.8	(5.5)
Stair Descending	9.8	(9.2)		8.5	(6.5)	-9.8	(9.6)	-13.4	(5.6)
Tying Shoes (Right Flexed Hip)	7.4	(8.9)	*	5.0	(12.3)	-0.7	(8.2)	-6.3	(10.8)
Tying Shoes (Left Stance Hip)	5.6	(8.3)		7.1	(7.1)	-3.1	(8.3)	-0.8	(8.3)

Note: All positive values indicate internal rotation and negative values indicate external rotation. For t-tests, * indicated a significance at $p < 0.05$ for comparisons between the Y and O groups.

Unlike for flexion, there was not a specific amount of internal or external rotation mentioned in the literature [41]–[43]. Thus, activities with more than 10° of internal or external rotation will be considered as activities with high amounts of rotation. Setting the limit to 10° might be a conservative guess, but the guess is informed by the Hip Precautions [41], [42] cautioning their patients against turning their toes in. From Table 4.4, the Y group had the greatest amount of internal rotation during the sofa STS activity and the greatest amount of external rotation during stair descending. The O group had the greatest amount of internal rotation for stair descending and the greatest amount of external rotation for ball pick up. Looking at the differences between ages, internal rotation is greater for Y group in most activities while the O group tended to have greater external rotation. However, the age differences in rotation should be taken with some caution as Kadaba et al. suggested that there is uncertainty from defining the neutral axis [78]. It is possible that both groups have similar amounts of both internal and external rotation due to this uncertainty. Additionally, when a THA patient is not in bed, flexion or the combination of flexion and internal rotation is what can cause a dislocation if they have received a THA via the posterior approach. With this in mind, the ball pick up activity that involves a high amount of flexion would be risky for THA patients to complete because it also involves rotation.

The next two tables show the average flexion, adduction, and internal rotation for all participants (Table 4.5) and the average extension, abduction, and external rotation for all participants (Table 4.6). The tables below are for just the right leg except for the shoe tying activity that has data for both hips.

Table 4.5. Hip – average amount of flexion, adduction, and internal rotation all ages in degrees.

ACTIVITY	Flexion Norm (Stdev)	Adduction Norm (Stdev)	Internal Rotation Norm (Stdev)
Ball Pick Up	107.9 (7.2)	4.5 (4.3)	9.9 (7.3)
Normalized STS	85.6 (11.3)	2.0 (5.3)	7.4 (8.2)
Lower STS	93.7 (10.4)	1.4 (4.9)	8.5 (8.8)
Sofa STS	97.4 (12.0)	1.9 (3.8)	10.9 (10.5)
Stair Ascending	68.2 (7.2)	8.6 (5.1)	9.6 (7.4)
Stair Descending	46.2 (7.1)	8.4 (4.0)	9.3 (8.2)
Tying Shoes (Right Flexed Hip)	103.3 (8.1)	-0.4 (6.4)	6.5 (10.1)
Tying Shoes (Left Stance Hip)	39.7 (9.5)	5.9 (3.5)	6.2 (7.7)

Note: All positive values indicate flexion, adduction, and internal rotation while negative values indicate extension, abduction, and external rotation.

Similar observations to the earlier tables can be made for the tables that include all participants. In Table 4.5, the ball pick up and shoes activities have the greatest amount of flexion while ball pick up, stairs, and shoe tying (left hip) have the greatest for adduction. In Table 4.6, the ball pick up, stairs, and shoe tying (left hip) have the largest extension while the ball pick up activities have the greatest abduction. The ball pick up and sofa activities have the greatest internal and external rotation.

Table 4.6. Hip – average amount of extension, abduction, and external rotation all ages in degrees.

ACTIVITY	Extension Norm (Stdev)	Abduction Norm (Stdev)	External Rotation Norm (Stdev)
Ball Pick Up	-1.9 (5.6)	-15.3 (8.1)	-11.1 (7.5)
Normalized STS	0.1 (5.9)	-7.6 (7.7)	-5.6 (8.0)
Lower STS	1.4 (7.7)	-8.6 (6.8)	-5.8 (7.6)
Sofa STS	0.6 (5.6)	-10.7 (7.8)	-7.3 (7.8)
Stair Ascending	-1.8 (6.0)	-8.2 (3.3)	-9.0 (7.7)
Stair Descending	-1.9 (6.4)	-10.7 (3.5)	-11.1 (8.5)
Tying Shoes (Right Flexed Hip)	72.3 (6.5)	-8.7 (7.6)	-2.9 (9.5)
Tying Shoes (Left Stance Hip)	-4.7 (5.7)	-0.3 (3.7)	-2.2 (8.2)

Note: All positive values indicate flexion, adduction, and internal rotation while negative values indicate extension, abduction, and external rotation.

Several tables have been presented for the hip. A concise table of hip ROMs can be found in Appendix F. The ROM, as mentioned, is the difference between the max and min during an activity. Although the first aim is completed with the presentation of the normative hip data, the tables produced for the trunk are helpful for those studying the hip as the data could possibly reveal compensatory mechanisms [79], [80] and help explain changes in hip motion with age.

Trunk ROM, max, and min tables for ADLs. People may use their trunk to compensate for a lack of hip motion [79], [80], which is why these tables are included. Additionally, normative data for a range of ages for a joint angle close to the hip further helps to characterize the hip, which supports the first aim of this study. In this study, the trunk joint angle is defined as the thorax relative to the pelvis. Table 4.7 shows the ROMs for all activities per age group while Table 4.8 shows the ROMs for all activities for all participants.

Table 4.7. Trunk – average ROM for all planes of motion per age group in degrees.

ACTIVITY	Flex/Extension			Add/Abduction			Int/Ext Rotation	
	Y Norm (Stdev)		O Norm (Stdev)	Y Norm (Stdev)		O Norm (Stdev)	Y Norm (Stdev)	O Norm (Stdev)
Ball Pick Up	60.6 (7.6)		51.3 (6.4)	18.5 (4.6)	*	14.4 (3.7)	11.3 (2.6)	7.9 (2.0)
Normalized STS	37.4 (10.6)		28.0 (7.6)	5.5 (2.2)		4.6 (1.4)	4.1 (1.0)	2.8 (1.2)
Lower STS	41.7 (8.8)	*	31.2 (8.7)	5.7 (2.0)		5.1 (2.1)	4.9 (2.1)	3.6 (1.7)
Sofa STS	47.4 (12.9)		41.1 (7.6)	6.7 (1.6)		7.5 (3.0)	5.4 (1.9)	4.9 (2.5)
Stair Ascending	12.1 (2.4)		10.6 (3.8)	16.8 (4.4)		16.8 (3.8)	9.8 (2.3)	8.8 (2.7)
Stair Descending	11.4 (2.1)		9.5 (2.1)	14.5 (4.1)		16.1 (4.3)	9.7 (2.7)	6.6 (1.9)
Tying Shoes	51.1 (8.2)	*	41.2 (6.4)	12.5 (4.7)		10.4 (4.3)	13.3 (4.3)	13.4 (3.8)

Note: All positive values indicate flexion, adduction, and internal rotation while negative values indicate extension, abduction, and external rotation. For t-tests, * indicated a significance at $p < 0.05$ for comparisons between the Y and O groups.

Table 4.8. Trunk – average ROM for all planes of motion all ages in degrees.

ACTIVITY	Flex/Ext Norm (Stdev)	Abd/Add Norm (Stdev)	Int/Ext Rot Norm (Stdev)
Ball Pick Up	58.4 (8.2)	16.9 (4.6)	10.3 (2.9)
Normalized STS	33.7 (10.4)	5.1 (1.9)	3.6 (1.2)
Lower STS	37.6 (10.1)	5.4 (2.0)	4.4 (2.0)
Sofa STS	44.9 (11.4)	7.0 (2.2)	5.2 (2.2)
Stair Ascending	11.6 (3.0)	16.8 (4.1)	9.4 (2.4)
Stair Descending	10.7 (2.3)	15.1 (4.2)	8.6 (2.8)
Tying Shoes	47.2 (8.9)	11.7 (4.6)	13.4 (4.0)

From Table 4.7, the ball pick up activity had the greatest amount of combined average flexion and extension out of all seven activities for both Y and O groups. Additionally, the Y group had a larger sagittal plane ROM than the O group for all seven activities. During ball pick up, normalized STS, lower STS, and tying shoes the difference was approaching 9°. For combined average adduction and abduction, ball pick up had the largest value for the Y group while stair ascending had the largest value for the O group. The values between Y and O were similar. The shoe tying activity had the greatest amount of rotation on average in the trunk for both Y and O groups. Similar to adduction and abduction, the values between Y and O for rotation were not different.

Regardless of age, the ball pick up activity has the largest ROM in two of the three planes of motion, sagittal and frontal, as can be seen in Table 4.8. Additionally, the ball pick up activity had the second largest ROM in the transverse plane for the trunk. All three of the STS activities have a similar amount of sagittal, frontal, and transverse ROM. Stair ascending and descending involved a fair amount of combined adduction and abduction as they followed the ball pick up activity by less than 2°. Shoe tying had a similar ROM profile to the ball pick up activity in that it had large ROMs in all three planes of motion.

Overall, the ball pick up and shoe tying activities required moderate amounts of combined flexion and extension in the trunk for both groups. These two activities also required large amounts of flexion in the hip for both groups in order to be completed. Additionally, there appeared to be an age difference in ROM for the sagittal plane during ball pick up, normalized STS, lower STS, and shoe tying with the Y group using more flexion and extension. On further review of the hip tables, the ball pick up and shoe tying activities showed that older participants had an increased amount of hip flexion when compared to younger participants while the STS activities revealed that the older participants had a decreased amount of hip flexion when compared to the younger participants. When trunk flexion was at moderate amounts, the older participants tended to increase hip motion, which can be seen with the ball pick up activity.

Hip strength tables. As mentioned, THA patients may experience muscle weakness or asymmetry in the hip before and after surgery [54], [55]. In order to understand THA patient muscle strength as it compares to healthy individuals, the participants in this study were tested to produce normative data tables for hip muscle strength. Both flexor and abductor muscle strength was tested. Additionally, there may be a difference in hip strength between Y and O groups in the healthy participants. Table 4.9 summarizes the participants' average peak hip torques for flexion and abduction according to age group and gender as well as for both genders combined.

Table 4.9. Hip strength – average peak torques per age group and gender for flexion and abduction.

Age	Gender	Flexion Peak Torque (Nm)	Abduction Peak Torque (Nm)
Younger	Female	82.7 ± 21.2	63.3 ± 25.7
	Male	148.4 ± 37.0	105.2 ± 22.2
	Both	113.01 ± 44.2	82.7 ± 31.8
Older	Female	73.7 ± 17.9	56.4 ± 18.9
	Male	116.8 ± 29.6	93.2 ± 17.3
	Both	92.8 ± 31.7	72.8 ± 25.8

Comparing Y and O for both genders combined, there is a 20 Nm difference (19.6% difference) in hip strength for flexion and about a 10 Nm difference (12.7% difference) for abduction. In both cases, the Y group was on average stronger than the O group. Additionally, the males in both the Y and O groups are on average stronger than the females in both the Y and O groups for both flexion and abduction. For the Y group, there was about a 66 Nm difference in hip strength for flexion in between genders and about a 42 Nm difference in abduction between genders. For the O group, there was about a 43 Nm difference in hip strength for flexion in between genders and about a 37 Nm difference in abduction between genders.

Aim 2: How Age Influences Hip and Trunk Motion during ADLs

A greater occurrence of dislocation was found for older patients as opposed to younger in two retrospective review studies [23], [31]. Although this greater occurrence of dislocation was not found to be significant, these findings encourage surgeons to remain aware of patients who are older because they might be at risk for hip dislocation following a THA. Surgeons have guessed that greater occurrence of hip dislocation is possibly related to the older patients having a limited ROM or lack of strength. In order to develop an understanding of age and motion as it relates to dislocation, normative hip kinematic data for several ADLs have been presented above and they will be further analyzed below for age affects in particular activities of interest. Activities of interest are identified from literature and from activities requiring strength, and include ball pick up, shoe tying, low STS, sofa STS, stair ascending, and stair descending. These two classifications led to two groups of hypotheses, one group (Hypotheses 1 through 4) defined by literature and the other group (Hypotheses 5 through 6) defined by activities requiring strength.

During risky activities based on literature. Literature from surgeons and the Hip Precautions have provided information on the mechanisms of dislocation, which include more than 90° of flexion with or without internal rotation for a posterior THA [41], [42]. Additionally, from motion capture studies it is known that picking up an object [50] and high ROM activities, such as squatting and kneeling [49], [51], [52], are of interest in hip dislocation studies. During Aim 1 of this study, activities were identified that had high amounts of flexion and internal rotation. It is possible that these activities will be influenced by age and thus be associated with a greater risk for hip dislocation. In addition to testing the hip for statistical differences, the trunk will likewise be tested because the participants may have used their trunk to compensate for a lack of hip motion [79], [80]. Therefore, the following hypotheses will be tested:

H1: (A) Ball pick up will require more flexion and internal rotation from the hip from older participants than it will from younger participants, and (B) this activity will require less flexion and abduction from the trunk from older participants than it will from younger participants.

H2: (A) Low STS will require less flexion and internal rotation from the hip from older participants than it will from younger participants, and (B) this activity will require more flexion from the trunk from older participants than it will from younger participants.

H3: (A) Sofa STS will require less flexion and internal rotation from the hip from older participants than it will from younger participants, and (B) this activity will require more flexion from the trunk from older participants than it will from younger participants.

H4: (A) Shoe tying will require more flexion and internal rotation from the hip from older participants than it will from younger participants, and (B) this activity will require less flexion from the trunk from older participants than it will from younger participants.

To test these hypotheses, the activities were individually tested with unpaired t-tests. The results were indicated in the previously displayed Tables 4.2 and 4.4 for the hip and Table 4.7 for the trunk. Additionally, the average ROMs of the activities that had significant results were reviewed to ensure that the averages between age groups were different.

For Hypothesis 1, hip flexion, hip internal rotation, and trunk flexion were found to be not different between the Y and O age groups during ball pick up. Trunk flexion was approaching significance (p-value: 0.08) with the Y group having the larger ROM by a little more than 9°. Additionally, the Y group had significantly more trunk abduction, which was as hypothesized.

For Hypothesis 2, hip flexion and internal rotation were found to be not different between the Y and O groups during low STS. The Y group had significantly more trunk flexion by approximately 10°, which was opposite of what was hypothesized.

For Hypothesis 3, hip flexion, hip internal rotation, and trunk flexion were found to be not different between the Y and O age groups during sofa STS.

For Hypothesis 4, both the right and left hip were tested for shoe tying. As a reminder, the left hip was the support hip and the right hip was the flexed hip. Left hip flexion, right hip rotation, and trunk flexion were all found to be different between the Y and O age groups during shoe tying. For flexion in the left hip, the O group had the larger ROM by approximately 11°. For rotation in the right hip, the O group had the larger ROM by approximately 4°. For trunk flexion, the Y group had a ROM that was almost 10° greater than the O group's ROM.

To further understand the observed significant results for ball pick up and shoe tying, regressions between the hip and trunk and age were completed. No significant findings of a direct relationship between age and hip ROM was identified for ball pick up and shoe tying. Regression p-values for shoe tying approached significance. Unlike the hip, there was a significant correlation between the trunk ROM and age during the low STS activity (r^2 value: 0.348; p-value: 0.003). Trunk flexion in low STS tends to decrease with age.

Overall, the results for each hypothesis were different per activity, suggesting that age effects are activity dependent. The results from Hypotheses 1 and 2 suggested that age differences would be noticed in the trunk and not the hip for the ball pick up and low STS activities. Additionally, the differences in the trunk for the low STS activity was opposite from expected because the Y group had the larger amount of trunk flexion. The results from Hypotheses 3 suggested that this activity was performed in a similar way regardless of age, which was different from anticipated. The results from Hypotheses 4 suggested that age differences would be noticed in both the hip and trunk for shoe tying. Additionally, the age differences in the hip for shoe tying were as expected with the O group having the larger ROM for left hip flexion and right hip rotation. Conversely, the age differences in the trunk were opposite than expected (i.e., the Y group had the larger ROM in the trunk), which was similar to the results from Hypotheses 1 and 2.

The ball pick up and shoe tying activities fell into both activity categories of being interesting based on prior literature findings with regard to dislocation risk as well as being activities that would require greater amounts of hip strength. There are two other activities (stair ascent and descent) analyzed in this study that fall into the greater hip muscle strength category only. Although these two activities are only in the strength category, the results from these hypotheses might still provide insight into age differences and thus dislocation.

During risky activities based on greater hip strength. Since there is a hip muscle strength difference in the age groups in this study, activities that are viewed as requiring greater hip strength, such as stair climbing, were tested for age effects. It is possible that the strength difference will result in altered hip kinematics. Additionally, THA patients that will be included in future iterations of this study may have muscle weakness or asymmetry before and after surgery [54], [55]. Patients might alter their hip kinematics in a similar way to a healthy weaker population, which makes the study of age effects on activities requiring greater hip strength in healthy individuals useful to the study of hip dislocation. Out of the four activities that appear to require greater hip strength (i.e., ball pick up, shoe tying, stair ascending, and stair descending), stair ascending and descending have yet to be analyzed. Therefore, the following hypotheses will be tested:

H5: (A) Stair ascending will require more flexion from the hip from older participants than it will from younger participants, and (B) this activity will require the same amount of trunk flexion from both younger and older participants.

H6: (A) Stair descending will require more flexion from the hip from older participants than it will from younger participants, and (B) this activity will require the same amount of trunk flexion from both younger and older participants.

Similar to the previous set of hypotheses, these two activities were individually tested with an unpaired t-test and the significant results from these tests can be viewed in Tables 4.2 and 4.4 for the hip and Table 4.7 for the trunk.

For Hypothesis 5, hip and trunk flexion were found to be not different between the Y and O age groups during stair ascending. The lack of difference between age groups for trunk flexion was as expected.

For Hypothesis 6, hip flexion was found to be different between the Y and O groups during stair descending with the O group having the larger ROM by approximately 5°, which agreed with the hypothesis. No significant differences between age groups for trunk flexion was observed, which was as expected.

Similar to the previous set of hypotheses, a regression between the hip and age was completed to further understand the observed significant results for stair descending. Although the p-values for the regression were approaching significant levels, there was not a significant finding for a direct relationship between age and hip ROM for stair descending.

Altogether, significant differences in hip kinematics were observed between the Y and O groups during shoe tying and stair descending. Significant trunk kinematic differences between the Y and O groups were observed for the ball pick up, low STS, and shoe tying activities. Specifically, during the ball pick up activity, significant differences for trunk abduction and a trend in trunk flexion was observed between the Y and O groups. The low STS activity had significant differences for trunk flexion between the Y and O groups. Additionally, a significant correlation between the trunk ROM and age during the low STS activity was observed. This correlation suggested that trunk flexion in low STS tends to decrease with age. During shoe tying, significant differences for hip flexion on the left side and hip rotation on the right side were observed as well as differences in trunk flexion. The O group had a larger ROM for left hip flexion and right hip rotation during shoe tying. Additionally, the O group had the larger ROM for both hips when descending stairs. The Y group had the larger ROM for trunk abduction during ball pick up, trunk flexion during low STS, and trunk flexion during shoe tying.

Overall, when differences in the hip were observed the O group generally had the larger ROM, and when differences in the trunk were observed the Y group generally had the larger ROM. However, the results for each hypothesis were different per activity, suggesting that age effects are activity dependent. These results suggest that older individuals in general have a reduced trunk ROM and the more strenuous the activity the more the individual has to increase their hip ROM, which was seen in stair descending and shoe tying.

Motion Capture: Discussion

The two project aims of producing normative data and studying how age influences hip and trunk motion were achieved through the presentation of both tables and statistical data in the previous results section. The results of this study will now be discussed.

Aim 1: Normative Data Tables

In order to characterize hip motion, normative data tables were produced for the hip joint angle, the trunk joint angle, and hip muscle strength. All three sets of tables have valuable information about age as it relates to motion and dislocation risk. The hip and trunk joint angle tables had information from the seven analyzed ADLs. This information is discussed at length in the following sections.

Hip ROM, max, and min tables for ADLs. From the tables, the ball pick up activities have the largest amount of ROM in all planes of motion. It is a complex motion, which can put people at risk for dislocation. When a person turns to pick up a ball from the side of their body, they are pivoting and stooping. The pivot is considered risky for a patient who received a THA via the anterior approach [43] while stooping is considered risky for a patient who received a THA via the posterior approach [43]. Following the ball pick up activity, the low STS, sofa STS, and shoe tying activities have a high level of flexion, which is greater than the 90° that the Hip Precautions (Appendix A) warn against for posterior dislocations [41], [42]. Additionally, these same activities have a moderate amount of internal rotation, which when combined with flexion is a risky combination [41], [42]. For all of these activities, THA patients learn to alter their motion strategy or their environment to make the activities safe. This involves reducing hip flexion on the operated leg, raising chairs and seats for STS activities, and using assistive devices for tying shoes.

Additionally, both of the stair activities had a large amount of extension, but this extension was not large enough to be risky for patients with an anterior approach. Similarly, the stairs did have a moderate amount of internal rotation, but the rotation was not coupled with a large amount of flexion, making it reasonably safe for patients receiving a THA via the posterior approach.

In addition to comparisons made to the Hip Precautions, comparisons can be made to computer modeling studies. Patel et al.'s impingement simulation work that was mentioned in Chapter 1, determined that bony impingement could start at 118.8° of flexion for one of the standard implants and positioning of that implant (i.e., a 28 mm head with the cup at 45° of inclination and 20° of anteversion) [35]. Adjusted for soft tissue impingement, impingement would start at 98.8° of flexion based on Woerner et al.'s 20-degree reduction for flexion [44]. Comparing the tables' values with Patel et al.'s values adjusted by Woerner et al.'s soft tissue adjustment, the ball pick up and shoes activities might cause soft tissue impingement in some individuals following THA.

Additionally, the low STS and sofa STS activities are approaching the peaks in flexion that might cause soft tissue impingement.

A study by Shariff et al. produced hip sagittal plane kinematics for an object pick up activity from the lateral side of the foot [50], which is similar to the ball pick up activity presented in this thesis. Altogether, Shariff et al.'s version of object pick up produced an average 80° ROM in the sagittal plane [50], which is smaller than the 109.8° sagittal plane ROM produced for the ball pick up activity in this thesis. However, the object in Shariff et al.'s study was smaller and the amount of flexion at the hip seemed to be minimized to achieve the activity. Although Shariff et al.'s activity was completed to minimize hip flexion, it helps to show that the regular activity's ROM can be effectively reduced by 20° with an altered motion strategy, which is a goal shared by PTs.

A study by Huffman et al. collected kinematic data in healthy individuals to compare against obese individuals. Huffman et al. reported the average hip ROMs for a standard STS activity as 79.9°, 8.4°, and 10.0° in the sagittal, frontal, and transverse planes, respectively [48]. Huffman et al.'s values are similar to those reported in this study for the STS activity when the chair height was based on the leg length of the subject. The values for hip ROM reported in this thesis are 89.7°, 11.0°, and 13.7° in the sagittal, frontal, and transverse planes, respectively. The ROMs produced from this study are slightly larger, which is to be expected since the normalized chair height in this thesis would be slightly lower than that used in the Huffman study. Unlike the previously discussed activities, there is not a clear comparison in the literature for the shoe tying activity. Nadzadi et al. studied a shoe tying activity, but the kinematics were not reported and the activity was performed in a seated position [45]. The shoe tying activity reported in this thesis was performed with the participants standing, a position that is commonly used in the real world.

Trunk ROM, max, and min tables for ADLs. The trunk is connected superiorly to the pelvis that is part of the hip, causing the hip and trunk to be commonly linked in a kinematic chain. Therefore, alterations in hip movement can lead to compensatory motions in the trunk, which is why trunk movements were included as part of Aim 1. The primary finding relating the trunk and hip is that older participants tended to increase hip motion during activities requiring moderate amounts of trunk flexion while activities requiring below moderate amounts of trunk flexion revealed that older participants tended to decrease hip flexion.

For the activities that showed a high amount of hip flexion and internal rotation, the trunk did have a moderate amount of flexion in the Y and O groups. For example, the resulting trunk flexion for the ball pick up and shoe tying activities fell between 41.2°-60.6° trunk flexion. Additionally, based solely on the kinematics tables, the O group had more hip flexion than the Y group during these two activities. Although trunk flexion is not a specific indicator of risk for hip dislocation, it is possible that activities with a moderate to high amount of trunk flexion will be indicative of a motion with a corresponding high amount of hip flexion, which can place THA patients at risk for hip dislocation.

Parkinson et al. studied the lumbar spine during STS activities [80]. The trunk flexion ROM results presented by Parkinson et al. of 31.8° for females and 41.7° for males [80] were similar to the trunk flexion ROMs for the STS activities that fell between 28.0°-47.4°. Parkinson et al. had stated there might be differences in younger and older age groups in the trunk, but they were not able to confirm this because their study only included younger individuals. This observation by Parkinson et al. appears to be supported by the increased amount of trunk flexion observed in the Y group as compared to the O group in this thesis. This increased amount of trunk flexion in the Y group might be related to younger participants completing activities improperly or it could be related to a reduced usage of the trunk by the older participants [79]. An example of improperly completing activity can be seen during ball pick up, if the younger participants use their back more instead of lifting with their legs. Additionally, the older participants might be experiencing stiffness in the back, which is leading to a decrease in trunk motion.

During the STS activities, there was an expectation that older participants would have more trunk flexion as they might use the momentum of their upper body to rock out of the chair. However, this was not observed in the O group, possibly due to the healthy nature of the volunteers. If participants had been suffering from back pain or stiffness, according to Sung, the participants would increase hip flexion while minimizing trunk flexion as a compensatory mechanism [79]. Studying how older THA patients differ in hip and trunk angles from older healthy individuals during STS will possibly reveal patients using a compensatory mechanism and possibly shed light on why some STS activities could be risky for THA patients to complete.

Hip strength tables. As mentioned, THA patients might suffer from muscle weakness or asymmetry following surgery [54], [55], and there has been speculation that age may impact hip muscle strength. Thus, learning about healthy individuals' hip muscle strength is important for identifying these weaknesses and asymmetry in THA patients. The normative data tables for hip strength revealed that the average peak hip torques recorded for the older participants in this study were smaller when compared to younger participants for both flexion and abduction. This was true regardless of gender. Age differences from hip motion could be linked to hip muscle strength differences in the age groups. Additionally, this age difference in hip muscle strength could exist in a population of THA patients as well as be more severe.

In order to compare peak hip torques with other studies outside of the BioMotion Lab, the average peak hip torques were converted to normalized values. For both men and women, the normalized average peak flexion torque was 1.53 Nm/kg for the Y group and 1.15 Nm/kg for the O group. The normalized average peak abduction torque was 1.13 Nm/kg for the Y group and 0.90 Nm/kg for the O group.

Judd et al. studied hip muscle strength from older healthy participants to be compared against THA participants [54]. The average age of the healthy participants from Judd et al.'s study was 60 years old and the average mass was 79.53 kg [54]. These demographic values are similar to the values for the older participants from this thesis who were on average 60 years old and had an average mass of 82.0 kg. The healthy individuals from Judd et al.'s study produced a normalized average peak flexion torque of approximately 1.2 Nm/kg and a normalized average peak abduction torque of approximately 0.85 Nm/kg [54]. These values are similar to the normalized average peak flexion torque of 1.15 Nm/kg and the normalized average peak abduction torque of 0.90 Nm/kg of the O group from this thesis. Judd et al. found that the THA patients that were compared against the controls did have reduced muscle strength. Therefore, if muscle strength differences were found to significantly influence hip motion during ADLs, this would be another reason why some ADLs would place THA patients at greater risk for dislocation.

Altogether, the tables from Aim 1 have led to insights into motions that would be risky for patients receiving a THA, which includes the ball pick up and shoe tying activities. The low STS and sofa STS activities are over the 90° hip flexion range, which makes these activities also risky for THA patients. Additionally, the hip and trunk ROM values appear to agree with available published results. The trunk tables revealed an age difference as did the hip muscle strength tables. All of this information has so far fallen under the category of Aim 1, which was to produce normative data about the hip. The following is a discussion about the hypotheses tested in Aim 2.

Aim 2: How Age Influences Hip and Trunk Motion during ADLs

Several hypotheses were tested regarding how age influences hip and trunk ROM for common ADLs. The activities being tested with these hypotheses were divided into two categories. Category one activities were based on literature, which detailed the mechanisms of dislocation or ranges of motion identified from simulations as when bony impingement would start. Category two activities were based on activities requiring greater hip strength, which is related to activities similar to ball pick up, shoe tying, and stair navigation. The results from testing these hypotheses revealed insights about how hip motion changes with age.

During risky activities based on literature. The literature used to identify motions of interest came from PTs, surgeons, and biomechanical researchers. PTs and surgeons have provided information on the mechanisms of hip dislocation, which include more than 90° of flexion with or without internal rotation for a THA via the posterior approach [41], [42]. Previous studies have identified that object pick up [50] and high ROM [49], [51], [52] activities, such as squatting and kneeling, are of interest in hip dislocation studies. The activities that matched these parameters were used in the Hypotheses 1 through 4, which individually tested age differences for hip flexion, hip internal rotation, and trunk flexion for ball pick up, low STS, sofa STS, and shoe tying. Trunk abduction was additionally tested during ball pick up because the motion required the use of the hip abductor muscles, making the researcher wonder about compensatory mechanisms of the trunk during hip abduction.

The trunk was included in the hypotheses to attempt to clarify differences in hip motion between the two groups. Differences in the hip kinematics between the two age groups were identified for only the shoe tying activity while differences between the age groups for the trunk kinematic results were identified in the ball pick up, low STS, and shoe tying activities. Since only particular activities showed differences in kinematics based on age groups, it is clear that dislocation risk will be activity dependent just as Nadzadi et al. suggested [45]. The O group had the smaller amount of hip ROM or flexion for several activities, which is contrary to what was expected based on the hypotheses. This reduction in motion would likely place this group at a lower risk for hip dislocation if the definition for dislocation were solely based on kinematics. This O group was identified as having a reduction in hip strength, so it is possible that the kinematic differences based on age identified in motion are caused by decreased hip strength. If this is true of THA patients, this might explain why these high ROM or flexion-based motions place some older THA patients at risk for hip dislocation.

Additionally, although most of the results were contrary to the expectations placed in the hypotheses, when examining the results closer and considering the motions being completed, the results make sense. To further develop this idea, each activity of interest will be further discussed.

The ball pick up activity did not have significant results for the hip, which upon further examination of the results, should have been expected. All participants, younger and older, were healthy individuals. Alternatively, if the healthy individuals were not so healthy, it is possible that the motion would have had significant differences in the hip between age groups, as it would have been likely that participants with painful hips would try to reduce their hip motion on the painful side. Additionally, although all participants had to pick up a ball from the floor, which will require similar amounts of bending at the hip, there were still observed nuances in the motion between all participants. Once the participants have bent down to pick up the ball, a clear difference is introduced in the trunk, which can help reveal how the two age groups approached the task. Furthermore, how participants reached for the ball appears to be different. It appears that for the younger participants they reached while turning their back to the side while for the older participants they tried to remain more squared. This led to the almost 10° difference in trunk abduction with the Y group having the larger ROM. The way that the older participants reached for the ball is more proper and better for the back, which would suggest that the younger participants, if they were THA patients, would be more at risk for hip dislocation. Of course, THA patients would likely alter how they approached this task, making it safe to complete either through the use of an altered motion strategy or a device.

The results for the sofa STS activity, which did not have significant results for the hip or trunk, are still surprising. The clinician team that helped develop this study mentioned that getting out of a sofa is a particularly risky and difficult activity for a patient following a THA. However, this study only included healthy individuals without join pain and it is possible that the car chair that was used to represent a sofa chair did not provide a low enough position or a cushioned enough seat to see unique statistical results between the age groups.

The low STS activity had significant differences in trunk flexion between groups, with the Y group having approximately 10° larger ROM than the O group. The trunk flexion result was initially surprising only in its direction, meaning that it was surprising that the O group did not have the larger ROM. As mentioned, there was an expectation that the older participants would possibly need to rock themselves to rise from the sofa chair. However, this compensatory motion was not observed since the participants were all healthy. Furthermore, there appeared to be a relationship between age and trunk flexion, which was shown in the significant r^2 value for the regression analysis between age and trunk flexion. However, as noticed in the regression results, the r^2 value is only 0.348, suggesting that age is only a minor contributor to the differences observed in trunk flexion.

Shoe tying was the only activity that mostly fit with expectations. There were significant results for kinematic differences in both hips as well as for trunk flexion when comparing the Y and O groups. The results for the hip matched expectations while the results for the trunk were opposite, meaning that the O group had the larger ROMs for the hip results and the smaller ROMs for the trunk. Additionally, it was slightly surprising that hip flexion was not significant in the right hip (i.e., the flexed hip) because that leg experienced a similar ROM no matter the strategy, but changes would have been more noticeable. It appears that since the participants were all healthy, they completed the activity in a similar enough way to not produce different kinematic results based on age for right hip flexion. Now, the hip flexion result in the left hip was expected. Although everyone had to bend over to put the loop over the shoe, some participants used their hip more while others leaned forward with their trunk more. In some cases, the people adjusted their left hip to complete the motion, which may have caused the hip rotation result in the right hip. Additionally, if the participant bent at the knee, this would further increase hip rotation. Altogether, this motion would be possibly safe for patients to complete, but they would only be able to complete the activity for the non-operated leg as the right flexed hip and this would need to be confirmed with a surgeon or PT. This method of putting on shoes would not be recommended for the implanted hip simply because of the amount of flexion. Additionally, the positioning adjustment in the hip that the older participants make during ball pick up needs to be further studied. Determining why the older participants make this adjustment could also deepen understanding of hip motion. For example, if the older participants made this adjustment because they felt unstable otherwise, this would most likely be true of older THA patients and could help inform the selection of activities to study in future iterations of this study.

Altogether, although the results were different from expected for these risky activities, the ROMs and results clarified hip movement during these activities.

During risky activities based on greater hip strength. Since there were observed differences in hip muscle strength between age groups, activities that require greater strength to perform, such as stair climbing, became activities of interest. Additionally, THA patients that will be included in future iterations of this study may have muscle weakness or asymmetry before and after surgery [54], [55], which increases the need to learn about strength and motion as it relates to age before enrolling patients in a similar study. Therefore, Hypotheses 5-6 were developed to individually tested age differences for hip flexion and trunk flexion for stair ascending and descending.

Age differences in the hip were identified for only the stair descending activity, which indicated that older participants had a 5° larger ROM in the sagittal plane for both hips. This observation might be partially supported based on previously published work by Qu et al. that investigated the effects of lower limb muscle fatigue on stair gait.

Although muscle weakness and fatigue are not exactly the same thing, fatigue leads to reduced muscle strength. The older group in this study had overall weaker hip muscles than the younger group and therefore could be a reasonable comparison to the fatigued movement conditions in the Qu et al. study. Qu et al. found that between the two testing conditions, not fatigued and fatigued, that stair ascending kinematics remained unaffected by the two conditions while stair descending showed differing kinematic results for the hip [81]. Qu et al. was surprised by the lack of significant results for stair ascending. Qu et al. added that the differences noticed in stair descent could be related to the participants not being able to control their motion. With older individuals in general, there is a greater concern for tripping and falling, especially on stairs. When descending stairs, a concerned individual would want to ensure that the heel of their foot clears the edge of the step or to lean forward to watch their feet to make sure they clear the step.

This would alter the ROM for the sagittal plane by increasing the hip ROM, which was the result found in this study for the O group.

Additionally, during stair ascent, it is possible that the body is already moving as efficiently as possible up the stairs. The stairs are all one set height and the mind knows it must clear the steps to achieve the task, which might place a pre-targeted minimum on the ROM for stairs ascending.

For both stair ascending and descending, it is possible that the results for THA patients will be different. In addition to being concerned about falling, THA patients will be weaker than these healthy participants, and they will be more similar to the fatigued participants in Qu et al.'s study that had less control on their motion. Although not tied to hip dislocation risk, studying this activity could reveal other insights into patient strength that are unobtainable through the category of activities defined as risky by literature.

Strengths and Weaknesses of this Study

All studies have strengths and weaknesses. The strengths of this study includes the number of motions that were captured in a single session by a single researcher. Even though the study visit was lengthy, there were 23 willing participants that completed this study. Additionally, several of these activities are ADLs associated with hip dislocation risk for both posterior and anterior surgical approaches. Although the seven activities analyzed in this study were primarily related to posterior dislocation, the ball pick up activity can be related to anterior dislocation through the pivoting motion that occurs during the activity. Another strength is that in addition to the motion data collected, hip muscle strength data was collected. Aim 2 of this study is focused on age and its influence on hip and trunk motion, but differences in motion caused by age were based in motion and hip muscle strength. With the hip muscle strength data, this study can more effectively study hip motion as it relates to hip dislocation.

One potential weakness of this study is in relation to the limited sample size of the O group, which other studies have faced [48]. A study by Huffman et al. that was examining STS in healthy and obese participants was only able to get 10 healthy participants and 9 obese participants, which is similar to this thesis's 14 younger participants and 9 older participants. Studies focused on patient populations or specific demographics tend to have a smaller grouping of the desired population, which is why having close to 10 participants per group is understandable. Furthermore, the O group was composed of older individuals that closely resemble the age groups commonly found in retrospective review studies, which is important for age matching with THA patients in future iterations of this study.

Another potential weakness of this study is in relation to the number of activities analyzed. Based on what was collected, more activities could have been included, but most studies publish with less than seven activities [46]–[52]. Additionally, there are a limited number of joints studied. The knee and ankle might give more insights into differences in motion, but the focus was the hip.

Overall, tables of normative data were produced for hip and trunk kinematics as well as hip muscle strength to help define and clarify hip motion during ADLs. These data tables included ROMs for ADLs that are considered risky for THA patients to complete as well as those requiring greater hip strength. From these tables, the ball pick up and shoe tying activities possess the highest amounts of flexion and internal rotation, which might make them more risky for THA patients who have received an implant via the posterior approach. Additionally, these activities are followed by low STS and sofa STS that have a little more than 90° of flexion, which is seen as risky for patients who received a THA through the posterior approach. In some of these activities, primarily the ball pick up, low STS, and shoe tying, trunk flexion was moderately high. The table produced from the healthy individuals for hip muscle strength showed an age difference with older individuals being on average weaker than younger individuals. In order to study the effects of age on hip and trunk motion, hypotheses were tested for age effects on ADLs of interest. The results for the first category of hypotheses showed that the age affects were activity specific, and that the hip was affected during shoe tying while the trunk was affected during the ball pick up, low STS, and shoe tying activities. Based on these age effects, a younger population would be at higher risk during the ball pick up activity while older individuals would be more at risk during shoe tying. As for the second category of hypotheses that were focused on activities requiring greater hip strength, the stair descending activity revealed an age difference for hip flexion with older individuals increasing their ROM to complete the activity.

Altogether, the study of these seven motions have started to identify potentially risky activities for THA patients. Within these seven analyzed motions, it has been noted that there are current methods for patients to avoid dislocation by altering their motion. These alternative motion strategies could be expanded upon by this current study to give THA patients further options on how to approach an ADL differently. Additionally, for patients that refuse to adopt the alternative motion strategies, the results from this and future motion capture studies could be used to encourage some of the non-compliant patients. With healthy individuals involved in this study it is possible to state that activities that required motion in two or three planes of motion as well as moderate amounts of trunk flexion, such as the shoe tying activity, influenced motion through age by increased hip and trunk flexion. Although trunk flexion is not a specific indicator of risk for hip dislocation, it is possible that activities with a moderate to high amount of trunk flexion will be indicative of a motion with a corresponding high amount of hip flexion, which can place THA patients at risk for hip dislocation. Studying how older THA patients differ in hip and trunk angles from older healthy individuals during STS will possibly reveal patients using a compensatory mechanism and possibly shed light on why some STS activities could be risky for THA patients to complete.

Additionally, from these seven analyzed activities, it is clear that age affects are dependent on the activity being performed and that hip muscle strength declines with age regardless of gender. Age differences from hip motion could be linked to hip muscle strength differences in the age groups. Additionally, this age difference in hip muscle strength could exist in a population of THA patients as well as be more severe, which would be another reason why some ADLs would place THA patients at greater risk for dislocation.

With age, there is a growing concern for falling, which was noted as a possible factor for kinematic differences in the stair descending activity between the two age groups. This concern would be heightened in THA patients, who would not want to fall and dislocate, which could possibly lead to altered hip kinematics.

Motion Capture: Conclusion

Before this study had been fully developed, surgeons were having trouble answering their patients' questions about specific ADLs. After a lengthy search of the literature resulted in little information regarding the role of hip motion during common ADLs, the need for this study to be completed was evident. As Nadzadi et al. had noted there was a need for more data on ADLs related to hip dislocation risk. The project aims were developed from this need as well as from the literature that showed patient demographics could influence dislocation risk. Out of all the demographics, age seemed to be the most influential for motion, which is why the project aims were to produce normative data for healthy individuals and to study how age influences motion through hypothesis testing. The normative data tables are needed for this study to advance into a future iteration with THA patients as risk needed to be quantified so that an informed selection of useful ADLs could take place. There are some activities, such as the sofa STS, that need to be adjusted and there are other activities, such as ball pick up, that would be helpful to continue but would need to be adjusted based on the activity being possibly risky for hip dislocation.

Additionally, a significant amount of time went into preparing the lab and developing methods. For measuring hip muscle strength, a separate study (detailed in Chapter 2) was required in order to fully develop the methods needed to test a patient population. As for the motion capture portion of the study, the activity list had to be developed, the code used for the marker set had to be updated and validated, and participants had to be recruited. All of the details were developed in order to have smooth and professional data collections that led to quality data. This data was processed and analyzed to produce the results that are presented in this thesis.

To summarize the results briefly, tables of normative data were produced for hip and trunk kinematics as well as hip muscle strength. Activities with more than 90° of flexion were the ball pick up, low STS, sofa STS, and shoe tying activities, which is seen as risky for patients who received a THA through the posterior approach. Additionally, both the ball pick up and shoe tying activities had internal rotation. In the ball pick up, low STS, and shoe tying activities, trunk flexion was moderately high. Hip muscle strength differences existed between age groups with the older participants being weaker than the younger participants are. Testing ADLs from two categories, one based on activities of interest from literature and the other based on activities requiring greater hip strength, the results showed that the age affects were activity specific. The hip was affected during shoe tying while the trunk was affected during the ball pick up, low STS, and shoe tying activities. During ball pick up, a younger population would be at higher risk of hip dislocation based purely on the hip movements that were measured while older individuals would be more at risk of dislocation during shoe tying. As for activities requiring greater hip strength, the stair descending activity revealed an age difference for hip flexion with older individuals increasing their ROM to complete the activity that was possibly related to concern for falling or tripping.

Main points from the discussion were that:

- Potentially risky activities for THA patients have started to be identified.
- There are current methods for patients to avoid dislocation by altering their motion, and these alternative motion strategies could be expanded upon by this current study to give THA patients further options on how to approach an ADL differently.
- Although trunk flexion is not a specific indicator of risk for hip dislocation, it is possible that activities with a moderate to high amount of

trunk flexion will be indicative of a motion with a corresponding high amount of hip flexion, which can place THA patients at risk for hip dislocation.

- Studying how older THA patients differ in hip and trunk angles from older healthy individuals will possibly reveal patients using a compensatory mechanism and possibly shed light on why some activities could be risky for THA patients to complete.
- Age affects are dependent on the activity being performed and that hip muscle strength declines with age regardless of gender.
- With age, there is a growing concern for falling, which was noted as a possible factor for kinematic differences in the stair descending activity between the two age groups. This concern would be heightened in THA patients, who would not want to fall and dislocate, which could possibly lead to altered hip kinematics.

These results help to inform surgeons and PTs about hip motion, which will allow them to start answering THA patient questions more confidently and directly. Additionally, through the use of the methods developed in this thesis, new strategies to decrease hip dislocation risk can be tested, which can be seen in the shoe tying activity that was designed from one of the many possible ways a person could approach shoe tying. The standing version was selected to have less hip flexion but still be natural, and test out if this would be a possible way for THA patients to tie their shoes if they were non-compliant towards the Hip Precautions. Although this activity would not be recommended for THA patients, other techniques can be evaluated through motion capture. These alternative techniques can be helpful for patients not likely to comply with the Hip Precautions (Appendix A) or use assistive devices. Additionally, having data to prove the need for following the Hip Precautions and using assistive devices might help convince patients to do so.

In addition to being useful to surgeons and PTs, the normative data tables with the ADLs' ROMs, maximums, and minimums are useful to biomechanists as baseline values that can be used in comparisons to other healthy controls or patients from THA or other surgical interventions to treat painful joints, such as those to treat femoroacetabular impingement. Besides using the tables for comparisons with healthy or patient populations, this data can be re-used in computer simulations similar to those described in the introduction. Other biomechanists can adopt the methods in this study for the ADLs in their studies. Additionally, this research may encourage motion capture researchers to publish or share the kinematic data they possess to further develop normative data tables.

Another valuable contribution of this study was the code for the PCT marker set. The marker set and code were developed by Andriacchi at Stanford University and Chaudhari at Ohio State University [69], [70]. The PCT marker set was developed to minimize error associated with soft tissue artifact. Since this code has been updated for this study by the researcher, several labs across the country desire to have and use the marker set and code. (All contributions the researcher has made to the lab are listed briefly in Appendix G).

Overall, the project aims for this study were achieved. Methods that are safe and a list of ADLs that are useful to study for hip dislocation risk in THA patients have been developed. Activities that are possibly risky for THA patients have been identified, and the influence of age on ADLs has produced some initial results. These results will be used for comparisons within the Baylor BioMotion Lab when THA patients are enrolled in a follow-up study. Additionally, surgeons, PTs, other clinicians, and biomechanists can use this information to answer questions and develop other future studies. Lastly, the code updated for this study has brought interest to the Baylor BioMotion Lab from other labs around the country.

CHAPTER FIVE

Future Work

The purpose of this thesis is to establish safe muscle strength testing protocols and establish normative hip kinematic data in younger and older healthy individuals for activities of daily living. This purpose was achieved through the muscle strength and motion capture studies that were described in the previous chapters. Methods for obtaining safe and reliable hip muscle strength measurements were validated. The update to the custom Matlab scripts for the PCT code described in Chapter 3 was validated. Normative data about the hip during selected ADLs was produced, and motions that would be risky for THA patients were identified. Risk for dislocation was based on literature, which showed that more than 90° of flexion by itself or paired with internal rotation was risky for THA patients with a posterior THA [41]–[43]. Additionally, for patients with an anterior approach, extension by itself or paired with external rotation was risky [41]–[43]. The seven activities included in the analysis were possibly risky only for patients that had a posterior THA. With this thesis's purpose achieved, the next steps involve completing the motion analysis for the rest of the current study, conducting a future study with THA patients, and expanding the scope of the current study. The future work on the current study needs to be completed before studying THA patients in a future study because the test protocol for the future study will depend on the results from the completed current study. These topics of future work will be discussed in detail below.

Completing the Current Study

Future work on the current study will be focused on processing more activities and analyzing the rest of the available data from these activities and the isokinetic hip muscle strength tests. Specifically, for the hip, the kinematics of the other activities, the muscle strength tests, and the kinetics of all activities that involved the force plates are available to study. Additionally, kinematics and kinetics for each exercise can be studied for other joints, including the ankle and knee.

Kinematics for Additional Activities

While there were several activities studied in this thesis, the other 44 activities of the motion capture study need to be analyzed and added to the tables. Some of the 44 activities are variations of motions, including instructed and uninstructed versions of the same activity that are used to compare motion strategies. The purpose of comparing the kinematics of similar versions of activities is to further understand how people naturally approach a task and how instructions will change their approach. While the uninstructed activities reveal the natural approach, the instructed activities fall into one of two categories: a standardized way to approach the task or a PT instructed strategy to safely approach a task. A PT instructed strategy comes from the Hip Precautions [41], [42], and they are the same strategies taught to THA patients to prevent dislocation during recovery. Although this current study did not include patients, having healthy controls complete the same tasks in the same manner as a THA patient provides baseline data that can be used to evaluate a THA patient's motion through comparison. Additionally, when comparing standardized with PT instructed activities, the effectiveness of the PT strategies at reducing flexion or other unwanted motion [41]–[43] with the operated leg can be quantitatively tested. For example, an uninstructed motion where a person picks up a ball in front of them might be different from the approach taught to THA patients. In this example, a ROM difference would not reveal a functional impairment, but it would reveal how well the instructed method appropriately reduces the ROM of an operated leg. Another desired benefit to standardized activities is that it makes comparisons among several individuals more straightforward.

Outside of the instructed and uninstructed activity variations, there are five unique activities that should be studied for kinematics and age differences. The five activities are walking, STS from a gardening chair, stepping in and out of a bathtub, entering and exiting a car, and getting in and out of a bed. While walking has been studied thoroughly, it needs to be analyzed for completion. On the other hand, the remainder of the activities can help reveal further risky motions for patients of both the posterior and anterior approach. Although all of the remaining activities are of interest primarily for the posterior approach, the getting in and out of bed activity is of interest for both surgical approaches as both have had patients dislocate in a bed [43]. These five activities need to be added to the tables that were generated in this thesis to further characterize the hip motion during ADLs as well as address a risky motion for anterior THA. Additionally, the results of these activities with the results from this thesis will determine which activities need to be included in the testing protocol of the future THA study.

Altogether, the results for these remaining 44 activities contain more insights about the hip kinematics that are needed before moving forward. To obtain these results, the analysis methods described in Chapter 3 using custom Matlab scripts can be used.

Isokinetic Hip Muscle Strength

Isokinetic hip muscle strength measurements for both hips for all subjects for flexion and abduction was produced from the current study. This data was collected following the methods that were validated in the first study described in Chapter 2. The data was processed and tabled, but still needs to be analyzed. For both studies, a project aim will be to determine the relationship between kinematics and muscle strength in order to evaluate a new theory on the risk of dislocation due to hip muscle strength weakness or asymmetry. The purpose behind this project aim would be to provide a way of identifying a poor functional recovery related to motion through the use of a device, such as the Biodex, that clinicians would already have. Exploring this project aim would include dividing test subjects into groups based on their muscle strength and comparing the ROM, max, and minimums of the ADLs among the different strength groups. In addition to establishing the relationship between strength and motion for healthy controls, normative muscle strength data would be produced from the current study. The healthy subjects' normative data will be used as a baseline comparison for the THA patients that could show asymmetries for all time points. Based on literature, it is most likely that the THA patients will show asymmetries and weakness at the pre-op and early post-op time points [54], [55]. The later post-op time point should show symmetry between legs and increased strength.

Hip Kinetics

Kinetics, in biomechanics, refers to the forces acting within the body that are generated from muscles contracting or lengthening to produce motion. Our data does not include electromyography, so these forces will refer to joint loading and not to specific muscles. For the current study, there are 12 activities without kinetics, and these activities are the sofa sit to stand and automobile activities. For the activities that do have kinetics, these results will be analyzed to provide insight into the relationship between joint loading and the risk of dislocation during ADLs. Dislocation risk is defined as more than 90° of flexion as it was in Chapter 1 [41]–[43]. Thus, in order to study the relationship of kinetics and dislocation risk, kinetics and kinematics of healthy individuals will be compared. Additionally, tables of normative data would be produced similar to the kinematics tables, and these tables would be used in future THA studies as a baseline comparison for THA patients' kinetics.

Another concern for THA patients is overstressing their healthy hip, which occurs when patients favor their healthy leg causing abnormal joint loading leading to joint damage and subsequently to surgery [82]. Abnormal joint loading is referring to asymmetric or overloading in the hips. Muscle asymmetry is common in THA patients even before surgery, and is monitored after surgery using muscle strength testing [54], [55]. The study of kinetics during ADLs could be used to study the risk of stress on the healthy hip by comparing pre and post-op kinetics from THA patients to healthy individuals that are matched for age, gender, weight, and height. Quantitatively defining the muscle asymmetry in relation to a healthy individual could reveal that at a level of asymmetry a THA patient should have an altered physical therapy to encourage more muscle rehab to prevent overstressing the patient's healthy hip.

Altogether, the results from the kinetics should be studied for their possible relationship to dislocation risk and stress on a THA patient's healthy hip, which can then be applied in the future THA study. To obtain the kinetics through Matlab, either the current study's custom code can be used or an alternate method can be developed. Methods for the analysis would need to be developed.

Other Joints

In this thesis, the hip was the focus and the trunk angles were brought in to help understand when the hip values differed between young and old. From the data collected, other joints are available to study. In keeping to the context of THA, the knee and ankle joints will be the most valuable. For describing the entire lower body during ADLs, the kinematics (i.e. the ROMs, maximums, and minimums) from the knee and ankle joints would be useful in a table with the hip kinematics. Not only would a table with the kinematics from the lower body's joints be in general useful, it would help PTs if a new strategy was needed for safely approaching a task. Currently, PTs take advantage of using alternative combinations of movement from the hip, knee, and ankle to make a task safe for THA patients. For example, PTs will instruct patients to get into a car by sitting down backwards into the car instead of stepping into the car, which uses more flexion at the knee than at the hip.

In summary, there are several motion variations to process and analyze, and there are other possible factors related to dislocation risk that need to be studied. These factors include hip muscle strength and kinetics. Completion of the current study will highlight areas of interest for understanding dislocation risk, and it is these areas of interest that will help define the testing protocol in a future THA study. Additionally, the completion of the current study involves the exploration of several project aims including:

1. Comparing uninstructed and instructed motion variations to better understand how the kinematics will change

2. Establishing the relationship between kinematics and isokinetic hip muscle strength in order to help identify poor functional recovery related to motion through the use of a device that clinicians would already have access to, such as the Biodex
3. Using kinetics to identify when a THA patient is overstressing a healthy joint which can lead to surgery

Preparing for the Future THA Study

The future THA study will involve the collection of isokinetic hip muscle strength and motion capture data similar to the current study. Instead of collecting this data from healthy controls, this will be collected from THA patients. This will further the thesis's larger purpose of improving post-op strategies and expand knowledge that impacts pre-op planning by adding and analyzing THA patient data for specific surgical approaches. Before starting this study, a new testing protocol needs to be developed based on the current study's results. Additionally, other study details need to be determined, such as what surgical approaches need to be included, how many time points before and after surgery need to be completed, and other devices that need to be involved.

Test Protocol Development

The current study's test protocol involved obtaining the consent of a volunteer, isokinetic tests, and then motion capture. The motion capture followed a list of activities that were selected before volunteers were recruited, and a study visit lasted between two and three hours. For the future THA study, the completed analysis of all 52 motion variations will be used to trim the activity list. Only the activities that are the most useful and are safe enough to be tested should remain on the list, but as a precautionary measure, a clinician on site might be required for some of the activities. The trimmed list should also shorten the time required for the testing protocol since THA patients are likely to become tired more easily. The goal would be a testing time of one to two hours [83], focusing on the most important activities.

Other changes to the testing protocol could involve re-arranging when the isokinetic hip muscle strength tests are completed or adding other devices. During the current study, the isokinetic tests were completed before the motion capture because these tests provided a chance for the volunteer to get comfortable as a test subject through interaction with equipment and the researcher. Additionally, the participant would be unfatigued and able to complete the tests properly at full strength at the beginning of the session. In the future, there might be a reason to move the isokinetic tests to later in the study visit and require several rest breaks to ensure the participant is at full strength.

Other devices, such as a marker replacement device, added to the testing protocol would need to simplify or cut time from the testing protocol. Any devices added to the testing protocol should be added in such a way to make the transition smooth for the participant as they move from device to device or test to test.

Surgical Approaches to be Included

As mentioned in Chapter 1, the most common activities related to posterior dislocation are sit-to-stand from a toilet, chair, erectly seated leg crossing, seated while reaching the floor, and standing while bending at the waist. Common anterior-dislocation-prone maneuvers include standing while turning the upper body away, lying supine and rolling over [43]. These activities cover a variety of ADLs. Although the

ADLs studied in the thesis consists of activities related to posterior dislocation only, the full list includes activities related to anterior dislocations. In general, there are more activities related to posterior dislocations than anterior dislocations [43], and this is reflected in the activity list for the current study. Thus, the future activity list will include activities related to both anterior and posterior dislocation, but will contain more activities related to posterior dislocations.

With the activity list containing motions related to both types of dislocation, the top choices of surgical approaches to study are posterior and anterior approaches. As mentioned in Chapter 1, when a THA patient experiences a dislocation following a posterior approach THA, then they are more likely to dislocate posteriorly. If they have had an anterior approach THA, then they are more likely to dislocate anteriorly. Additionally, these surgical approaches are desirable to study because the posterior approach is one of the most used surgical approach [84] while the anterior approach is a newer surgical approach and gaining popularity [85]. Both types of surgical approaches provide unique benefits, including a quicker recovery for the anterior approach and less risk for nerve damage with the posterior approach. Therefore, studying the posterior and anterior surgical approaches fits with the data currently being collected and will provide a large number of doctors with usable information.

Time Points to be Completed

When studying THA patients, it is common to collect information before and after surgery. These types of studies are prospective studies. A prospective study follows a group over time to determine through testing how factors unique to the group affect the outcome of the group. In the case of the future THA study, two groups will be followed over time. One group will have an anterior approach THA and another will have a posterior approach THA. Following these groups over time requires multiple testing time points in order to determine how the surgical approach will influence their recovery.

With the study having multiple time points, the timing of these data collections needs to be determined beforehand. Typically, there is at least one before and after. It would be best to get two post-op time points at three months and 12 months. The three months' time point would be the required post-op time point [86]. The last time point should be when the patient is fully recovered, but there is a chance that there is persisting lower limb gait abnormalities [83], [87].

Additionally, for a prospective study the same types of information are collected at every meeting. However, at the 3 months' time point it would be too early to have THA patients complete isokinetic hip muscle strength tests. Thus, this test would have to be excluded at the early post-op time point, but it would be collected at the pre-op and later post-op time points.

Other Devices to be Involved

Other devices that could be involved in a future THA study would need to make some portion of the testing protocol easier or shorten the time required to complete a study visit. Currently, a device that could improve a prospective study involving motion capture with multiple time points would be a marker replacement device.

Typically, a prospective study will take a few years to complete, which could involve several researchers, requiring different people to place the markers on a volunteer for the motion capture portion. Della Croce et al. has shown that obtaining precise marker replacement between researchers is less precise than intra-examiner marker placement for the pelvis and lower limbs [88]. The two solutions for this problem is to have one person place the markers, which may not be an option for the future study, or use a marker replacement device. A marker replacement device enables various users to place markers in the same place, removing the concern about precision in marker replacement. In the BioMotion Lab at Baylor, work is being currently done on a marker replacement device, but is not yet ready for use in a study. The device needs to be tested, which will be done in the following months.

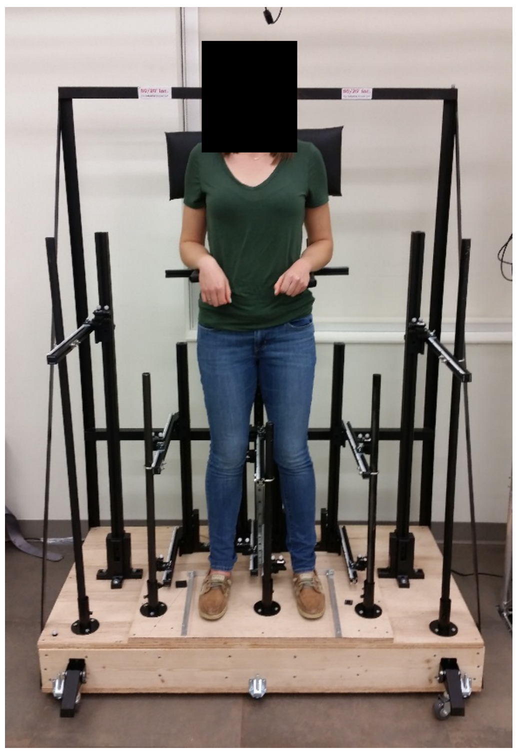

Figure 5.1. The Baylor BioMotion Lab's marker replacement device with a person standing in it for better visualization of the device in use. Lasers are situated on adjustable bars, and the location of the laser can be recorded from the bars. When a participant comes into the lab for a follow-up session, the lasers can be set to these recorded locations to place the markers where they had been during the first session.

In summary, once the testing protocol and other details are determined, the future THA study can be started. The details of the testing protocol involve determining the final list of activities, when to complete particular tests during a study visit, and the need of additional devices to aid with data precision. Additionally, other study details such as the types of surgical approaches and the number of time points to be completed need to be finalized before the start of the study.

Expanding the Scope of the Studies

Currently, the work put into these studies is focused on ADLs, activities that everyone will complete regardless of activity level or interests. Expanding the scope of the current study through a new motion study would involve expanding what activities are on the list as well as exploring other work that is contained within the data currently collected. Other work is referring to unique motions that might have been collected during an attempt of an ADL. The currently known example of a unique motion is when a participant stumbled on a stair ascending trial. The stumble is a valuable motion to study, but it does not fall into the ADL category. The expanded list of activities and the stumble will be discussed below.

Activities Outside of ADLs

When the list of activities for the study was being created, there were some activities mentioned by the doctors that were not a part of the ADL spectrum, like golfing and other sports related activities. Since these activities were not for a general enough population, they were not included in this study. However, a study focusing on active lifestyle activities would be desirable for various populations including the THA population. Several THA patients have an active life and are concerned about how surgery will affect their lifestyle. Beyond those sporting activities mentioned from the doctors, including an activity where the stairs are of not equal height would also be valuable to simulate hiking. Of course, the activities included would be based on individual THA patient's interests and not the general THA patient population. Thus, a specialized version of the future study that focuses on these sports related activities would be valuable to produce, especially for individualistic health and continuing collaboration between the BioMotion Lab and BS&W.

Stumble on the Stairs

Within the data collected for the motion capture, a stumble on the stairs was captured. It is not ethical to cause someone to trip without proper safety monitors and devices in place, but this was purely by accident and the individual was unhurt from the stumble. The participant did provide approval to study their data outside of the scope of the original study. This single trial will be valuable to process and analyze for a case study because the biomechanics behind a stumble with a person maintaining their uprightness can be applied to robotics. There are several robots that are built with a humanoid shape, and a primary concern is preventing these expensive machines from tipping over and causing damage to the electronics within them.

Summary of Future Work

Overall, the goals of the current study were met through the production of normative data and the validation of methods, which has led to several future work opportunities for the BioMotion Lab. A future study in the lab is already starting to take shape. Once the current study is completed, the details for that future study can be finalized. Some of the future work, including the future THA study, will continue collaboration between the lab and BS&W. All future work will contribute to the lab and the biomechanical community's knowledge of ADLs and their association to dislocation risk through the exploration of lower limb and trunk kinematics and kinetics for multiple activities. Additionally, the isokinetic hip muscle strength testing completing in the current study and the future study will help with understanding possible connections between muscle strength and risk of dislocation. There are other future work opportunities that have other applications, like the stumble on the stairs being applied to robotics.

APPENDICES

APPENDIX A

The Hip Precautions

The following images are of the handouts PTs provide to patients following either a posterior or an anterior THA.

POSTERIOR HIP PRECAUTIONS

DO NOT CROSS YOUR LEGS

DO NOT TURN TOES IN

DO NOT BEND HIPS GREATER THAN 90°

Blue foam wedge between legs when in bed.

R/L WEIGHT BEARING:___________

Figure A.1. Image of the posterior Hip Precautions handout from BS&W.

ANTERIOR HIP PRECAUTIONS

DO NOT CROSS YOUR LEGS

DO NOT TURN TOES OUT

DO NOT STEP BACKWARDS

Use a pillow between legs to roll in bed.

R/L WEIGHT BEARING:____________

Figure A.2. Image of the anterior Hip Precautions handout from BS&W.

APPENDIX B

Generally Helpful Matlab Code Update Information

The motion capture study involved the setup of a new lab, which would be using Vicon Nexus 2. In order to use Nexus 2 for processing of trials with the PCT marker set, the Matlab code for the PCT markers had to be updated so that Matlab and Nexus 2 could communicate. This update was driven by the desire to move from manually labelling trials to using the new auto-labelling feature that Nexus 2 offered. Since all changes in the code were focused on the communication between Matlab and Nexus 2, the mathematical operations that are the core of the code were not altered. This means that following the update, the code should produce the same results.

Outside of the BioMotion Lab at Baylor, several labs are manually labeling trials through the original Nexus 1 software, which is time consuming. With the new auto-labelling feature, there may be a greater desire by other labs to update to Nexus 2. Since the update was focused on lines of code calling for information from Nexus 2, these lines would be generally helpful for other motion capture researchers to have access to when they attempt to update. These changes are pictured and discussed below.

The Matlab code opening the communication between Nexus 1 and Matlab had to generate specific handles to access the trial's subject and trajectory information (Figure B.1). With the update, this is contained within the call to the ViconNexus object. After the ViconNexus object line is written into the code, access to information on the trial's subject and trajectory can be pulled out through specialized commands that were generated from the object. In the case of the PCT, there needed to be only one trial subject present, which meant that the number of subjects needed to be checked. The changes in variables used in this portion of the code are pictured in Figure B.2.

```
% Get hold of PECS (returns a handle to an ActiveX object)
hPECS = actxserver( 'PECS.Document' );

% Open the trial (returns a handle to an ActiveX object)
hTrial = get( hPECS, 'Trial' );

hProc = get( hPECS, 'Processor' );
```

```
% Create a vicon object to access vicon commands
vicon = ViconNexus();
```

Figure B.1. A screenshot of Matlab code that is handling the communication between Nexus 1 and Matlab (top) and Matlab code that establishes communication between Nexus 2 and Matlab as well as gives access to the new Nexus 2 commands (bottom). The code displayed in the top can simply be removed and replaced with the bottom.

```
nSubjects       = invoke(hTrial,'SubjectCount'); % If there are multiple subjects BodyBuilder won't run
if nSubjects>1,
    invoke(hProcessor,'Log','Too Many Subjects, Operation Failed',1);
    release( hTrial );
    release( hPECS );
    return
else
    hSubject = invoke(hTrial,'Subject',0);
    labelprefix = invoke(hSubject,'LabelPrefix');
    subjectname = invoke(hSubject,'Name');
    release( hSubject );
end
```

```
% check the number of subjects
nSubjects = length(vicon.GetSubjectNames()); % If there are multiple subjects BodyBuilder won't run
if nSubjects>1,
    error('Too Many Subjects. Operation Failed')
else
    S = vicon.GetSubjectNames();
    S = S{1};  % if there really is one subject this should be good
    % get the frame count
    [First_Frame,End_Frame]=vicon.GetTrialRegionOfInterest; %get frame range
    Frame_Range=End_Frame-First_Frame+1;
    Trial_Length=vicon.GetFrameCount;
end
```

Figure B.2. A screenshot of Matlab code communicating with Nexus 1 (top) and Nexus 2 (bottom) to pull the trial's subject information. In this image, the use of the ViconNexus object can be seen. All of the functions with "vicon." in front of them, such as vicon.GetSubjectNames, originate from the ViconNexus object. There are additional lines in the bottom image that show the code pulling the numbers for the first frame, last frame, and number of frames in total.

Following the check on the number of subjects, the code pulling the information on the trial's trajectories was updated. First, there were the lines of code finding the number of trajectories (Figure B.3). Then, there was the line of code pulling the actual trajectories (Figure B.4). In both places, new Matlab commands were needed and lines of additional code could be removed that communicated between Matlab and Nexus 1. Additionally, there was a function found in various places throughout the code that ended a process that had been initiated earlier. Lines of could with this function can be simply deleted as their functions are being assumed by the ViconNexus object or internally through other commands. An example of this function is pictured in Figure B.5.

Similar to opening trajectory information, the trajectories that need to be created and saved required updates. Three commands were used to accomplish this for Nexus 1, which for Nexus 2, can be done with one command (Figure B.6).

```
% Get total number of fields in the trial for marker data
nFields = invoke(hTrial,'VideoFieldCount');
nTrajectories = round(double(invoke(hTrial,'TrajectoryCount')));
```

```
markers = vicon.GetMarkerNames(S);
nMarkers = length(markers);
```

Figure B.3. A screenshot of Matlab code for pulling out the number of trajectories for Nexus 1 (top) and Nexus 2 (bottom). In trying to keep the naming convention in the updated code clearer, nTrajectories was renamed to nMarkers. This was changed throughout the code. Altogether, these images show explicitly the change from using the invoke function with a trial's handle name to using specific Matlab commands.

```
hTrajectory{ctr} = get(hTrial,'Trajectory',ctr-1);
```

```
[markx, marky, markz, marke] = vicon.GetTrajectoryAtFrame(S,mark_idx,i);
```

Figure B.4. A screenshot of Matlab code for pulling out the actual trajectories of the markers for Nexus 1 (top) and Nexus 2 (bottom). From Nexus 1 to Nexus 2, the trajectory information was outputted in the transpose. In order to keep the edits on the code simple, the trajectory information pulled using the Nexus 2 command was transposed to match the appearance of the output from the Nexus 1 command.

```
release(hTrajectory{ctr});
```

Figure B.5. A screenshot of Matlab code used for communicating with Nexus 1 that can be simply removed. This line was used to end the processes initiated from pulling trajectory information, which is now handled by the specialized commands internally.

```
eval([thandle '= invoke(hTrial,''CreateTrajectory'');']);
eval(['invoke(' thandle ',''Label'',''' [labelprefix tname] ''');']);
eval(['invoke(' thandle ',''Show'');']);
```

```
vicon.CreateModeledMarker(S, tname)
```

Figure B.6. A screenshot of Matlab code used for creating marker trajectories (i.e., the labels and trajectory values) with Nexus 1 (top) and Nexus 2 (bottom). When using the new command, a new issue is encountered. The command cannot be used to create a trajectory that already exists, so an if else statement is needed beforehand to check to see if the marker name will already exist.

Altogether, the update included several lines of code being altered or deleted entirely. Some of the newer functions will create output that may be transposed. When dealing with matrix equations, it will be simpler to transpose those outputs back. Additionally, when updating code for use with Nexus 2, exploring the original code line by line will help provide an understanding of what is needed regardless of understanding the commands used to communicate with Nexus 1. Exploring the code through Nexus 1 is not ideal, so it is recommended that the change shown in Figure B.1. be completed and the code explored through Nexus 2.

APPENDIX C

PCT Standard Operating Procedure

The following is the PCT Processing Protocol in its original format:

ORIGINAL AUTHOR(S)

Carley Fuller

MODIFIED BY

Jenny Tavares

PURPOSE

To provide instructions for processing the PCT Marker Set (called Baylor_Clusters in Nexus 2.x and FBPCT in Nexus 1.8.5 at Baylor University) as well as a troubleshooting guide for issues that may arise.

SUMMARY

Process trials in this order:

1. MOTOSTATIC
2. ROM
3. SAR & SAL
4. STATIC
5. Any Dynamic (walking, etc)

Make sure to save frequently!

MOTOSTATIC and ROM both teach Nexus about that subject's particular model and allows for Nexus to autolabel. SAR & SAL are for the Hip Joint Centers (HJC). The STATIC trial is used for generating the knee joint center, so not all of the knee markers need to remain. The Dynamic trials are those of interest to the researcher.

TIP: You can use ctrl+space to toggle marker labels

DETAILED PROCEDURE FOR DATA PROCESSING

> Note: Ensure all data is saved to the Vicon\ViconData\TKA_Tavares\ Subject Folder
>
> Matlab commands are shown in <Green Brackets>
>
> Body builder commands are shown in Blue

MOTOSTATIC trial:

1. Run "Reconstruct" pipeline (grey bubbles)

2. Make sure to have the Baylor_Clusters marker set attached (look to the left window)
    a. Fill in the advanced properties (should be done if the capture procedure was followed correctly)
    b. Check the advanced properties
    c. If a measurement appears wrong, then split the screen and ctrl select the markers that can be used to correct the measurement
3. In the tools tab (in the right window): Open the Motostatic Baylor Clusters Pipeline
4. Run "Autolabel Static Frame" (right click on it & select "run selected op")
5. Review markers – relabel where appropriate (Hit ctrl+space to view all markers at one time and have it set to Whole on manual labeling)
6. Delete any unlabeled markers (ghosts[1]). Keep the top of the pelvis markers
7. Run "Scale subject" and then "Marker-only Subject Calibration"
8. Save the file

ROM Calibration Trials (also used for dynamic trials):

1. Make sure the labeling is set to **Whole** at the top of the manual labeling window on the right), so that the next step looks at the whole trial.
2. Run "Reconstruct and Label" pipeline (blue bubbles)
3. Check the Quality tab on the bottom of the screen to see the number of gaps
4. Fill the gaps (have set to **Forward**[2] at the top of the manual labeling window on the right) by selecting the "Fill Next Gap" button. To fill the gaps use the following:
    a. Always use a rigid Body Fill on the Pelvis (when Rigid Body can't be used then use Pattern Fill before Spline)
    b. Use Spline Fill first and then Pattern Fill if Spline cannot be used on other locations
    c. Pattern Fill is preferred on the torso
5. Delete any unlabeled markers (ghosts) by selecting "Delete Marker Trajectory". Keep the top of the pelvis markers

SAR/SAL specific processing:

1. Repeat steps 1-5 from Section 4.2 (ROM Trial Calibration)
2. Remove the medial knee and ankle markers (RMFC, RMTP, RMMA, LMFC, LMTP, and LMMA)
3. Remove the bottom lateral knee markers (RLTP and LLTP markers)
4. Open the PCT_Pipeline_V2
5. Run "1) PECS STAR ARC" (1^{st} OP – a Matlab operation <HJC_Test_Final>)
6. Run "2) FBPCT_HJC" (2^{nd} OP – a Bodybuilder operation. Right click, select "Run Op")

Static trial specific processing:

1. Repeat steps 1-5 from Section 4.2 (ROM Trial Calibration)

---

[1] Ghosts are markers that do not actually exist as markers. These can be generated by people wearing glasses or anything reflective that will bounce the infrared light back to the cameras. The cameras will read those reflections as marker data even though it is not coming from an actual marker.

[2] When gap filling it is important to have the labeling setting set to Forward. If not, then when you re-label a marker it will do so for the whole trial, which continue to leave points in the trial where the marker is unlabeled.

2. Open the PCT_Pipeline_V2:
3. Run "3) PECS STATIC" (3rd OP – a Matlab operation <FBPCT_staticPECS>)
4. Run "4) FBPCT_static" (4th OP – a Bodybuilder operation, Right click, select "Run Op")
5. Run "5) OSU_STATIC" (5th OP – a Bodybuilder operation, Right click, select "Run Op")

Dynamic trial specific processing:

1. Follow the outline in Step 2 for ROM Calibration trials.
2. Remove the medial knee and ankle markers if they are still on the subject (RMFC, RMTP, RMMA, LMFC, LMTP, and LMMA)
3. Remove the bottom lateral knee markers (RLTP and LLTP markers)
4. Open the PCT_Pipeline_V2:
5. Run "6) PECS DYNAMIC" (6th OP – a Matlab operation, <FBPCT_dynamicPECS>, <vicon.SaveTrial(30)>)
6. Run "7) FBPCT" (7th OP – a Bodybuilder operation, Right click, select "Run Op")
7. If the trial is a walking trial,
    a. Run "8) Foot Traj PECS Plug-In" (8th OP – a Matlab operation, Right click, select "Run Op")
    b. Run "9) Detect Events from Forceplate" (9th OP – a Nexus operation, Right click, select "Run Op"). Should double check the calculated forces after this step
    c. Run "10) OSUSportsPIM" (10th OP – a Bodybuilder operation, Right click, select "Run Op")

Save all trials / processing

Under the PCT_Pipeline_V2 run "Save Trial – C3D + VSK" or press the floppy disk icon at the top left corner to save your work when solid progress has been made. (You never know when you will make a wrong step and need to start over).

DETAILED PROCEDURE FOR STATISTICS PROCESSING

Refer to the "Matlab Data Processing_HKA_README" text file for detailed instructions and commands. Line commands have been generated for each scenario and each subject group.

In general the following process will be followed

1. The hip, knee, and ankle angles will be extracted from Vicon using the <MO_HKA> command in Matlab
2. The <GenROMs_HKA> command will be used to generate the ROM, max, and min angles generated by each subject during the activity.
3. The <ROMavg_HKA> command will be used to average the data for each subject's trials, then each subject group.
4. Data validation will be performed using <AvROMval_HKA> to check for outliers. A manual check will be performed to determine what outliers should be excluded from the data.
5. The averaging commands will be re-run excluding the outliers
6. The equal variance and normal curve tests will be performed using <NormNEqualCheck_HKA>
7. The t-test will be performed on the data using <AvEvalttest2_HKA>

NOTES

1. Upper extremity markers
    a. A is thumb
    b. B is pinky for hand components
    c. Blue should be on the medial / thumb side for arm markers
2. Bodybuilder files
    a. Bodybuilder files should be kept in a folder on the desktop. They should not be kept within the subject file.
    b. All Bodybuilder files need a .mod and an .mp file to operate correctly.
3. When running a Matlab or bodybuilder process or when saving if Nexus freezes allow it time to catch up. Sometimes it only needs a minute or two, and when it is shut down and reopened it may still lag. If you have waited a while and no change occurs, then you can shut it down, but give the program time before you reopen it. (Additionally, this problem may only exist with those processing on the work laptops).

TROUBLESHOOTING

These follow the same order as above (MOTOSTATIC, ROM, SAR/SAL, STATIC, Dynamic, and saving). If your issue is not present, then when you find a solution edit this SOP to enable future researchers to more easily solve their own problems.

1. MOTOSTATIC trial:

a. If there is just a black screen, no floor grid or anything:
    1. Look at the top left of the center window (your workspace) and set camera view to 3D perspective view

b. If the Reconstruct pipeline (grey bubbles) isn't present at the top of the workspace
    1. You can find this pipeline in the right hand window (Tools window) under the Pipeline tab (Gear icon). Go to the drop down menu and select "Reconstruct". You can then run the pipeline.

2. ROM:

a. If there is just a black screen, no floor grid or anything:
    1. Look at the top left of the center window (your workspace) and set camera view to 3D perspective view

b. If the Reconstruct and Label pipeline (blue bubbles) isn't present at the top of the workspace
    1. You can find this pipeline in the right hand window (Tools window) under the Pipeline tab (Gear icon). Go to the drop down menu and select "Reconstruct And Label". You can then run the pipeline.

3. SAR/SAL specific processing:

c. If there is just a black screen, no floor grid or anything:
    1. Look at the top left of the center window (your workspace) and set camera view to 3D perspective view

d. If the Reconstruct and Label pipeline (blue bubbles) isn't present at the top of the workspace

1. You can find this pipeline in the right hand window (Tools window) under the Pipeline tab (Gear icon). Go to the drop down menu and select "Reconstruct And Label". You can then run the pipeline.

e. Error Message:

"Too Many Subjects. Operation Failed."

1. Look under the "Subjects" tab to see if there is more than one marker set attached to this subject. If there is more than one, then it needs to be deleted. If the PCT has been edited and requires two marker sets then an edit to the code to allow for more than one marker set is required.

4. Static trial specific processing:

a. If there is just a black screen, no floor grid or anything:
   1. Look at the top left of the center window (your workspace) and set camera view to 3D perspective view

b. If the Reconstruct and Label pipeline (blue bubbles) isn't present at the top of the workspace
   1. You can find this pipeline in the right hand window (Tools window) under the Pipeline tab (Gear icon). Go to the drop down menu and select "Reconstruct And Label". You can then run the pipeline.

c. Error Message:

"Too Many Subjects. Operation Failed."

   1. Look under the "Subjects" tab to see if there is more than one marker set attached to this subject. If there is more than one, then it needs to be deleted. If the PCT has been edited and requires two marker sets then an edit to the code to allow for more than one marker set is required.

d. "4) FBPCT_static" Pipeline failure
   1. Add the following data to the subject data (left hand side). Note that all dimensions are in mm.
      1. UseOptimizedHJC
         a. Default and Value = 1
      2. OptimizedKJC
         a. Default and Value = 0
      3. Female
         a. 0 or 1 (depending on the subject)
      4. Marker Diameter
         a. 14

5. Dynamic trial specific processing:

a. If there is just a black screen, no floor grid or anything:
   1. Look at the top left of the center window (your workspace) and set camera view to 3D perspective view

b. If the Reconstruct and Label pipeline (blue bubbles) isn't present at the top of the workspace
   1. You can find this pipeline in the right hand window (Tools window) under the Pipeline tab (Gear icon). Go to the drop down menu and select "Reconstruct And Label". You can then run the pipeline.

c. Error Message:

"Too Many Subjects. Operation Failed."

1. Look under the "Subjects" tab to see if there is more than one marker set attached to this subject. If there is more than one, then it needs to be deleted. If the PCT has been edited and requires two marker sets then an edit to the code to allow for more than one marker set is required.

d. The PECS code fails and delivers the messages:

"Not a valid point."; "Frame in question is: ". (The "Frame in question is: " should provide a line number).

1. It means that a cluster marker does not exist at this point. Either re-trim the trial or (if in the middle of the trial) you should investigate to make sure you properly gap filled the trial.

e. PECS Code fails and delivers message:

```
undefined variable "rt_thighcs" or class "rt_thighs.origin"
Error in FBPCT_PECS (line125)
        Len = eval(['length('+CSname')']);
Error in FBPCT_dynamicPECS(line31)
FBPCT_PECS
```

1. Find the first frame where all cluster markers (thigh and shank) are visible, trim trial to that frame, run FBPCT_dynamicPECS, drag trimmed edge back to frame 1 and save.

f. If a marker is ever detached from a subject window on the right
   1. Right click on the subject and re-add the Baylor Clusters Model
   2. Re-run Matlab and bodybuilder files on all files.

g. FBPCT (pipeline 7) fails
   1. Rerun pipeline 3 and 4 for the static trial
   2. Rerun pipeline 7

6. Saving:

a. Nexus has frozen
   1. Wait for it to unfreeze. Sometimes it takes a while to think. I've sped up the thinking process before by clicking in the workspace window a few times

Calibration Activities:

CALIBRATION ACTIVITY	ABBREVIATION	DESCRIPTION
Static	STATIC	Subject stands straight with arms slightly forward and palms facing outward. (In anatomical position). The capture is an auto-capture of 2 seconds in length. Note: Make sure that ALL markers are visible during the two seconds.
Motorcycle Static	MOTOSTATIC	Short for motorcycle static, the Subject stands straight with arms raised (as if on a

		motorcycle). To get them to the proper position have them raise their arms to a t-pose. Then they will raise their forearms straight up before dropping the forearms forward (so that their hands are before them). The capture is an auto-capture of 2 seconds in length.
Motorcycle	MOTO	Short for motorcycle, the Subject stands straight with arms by their side (not obstructing the hip markers). They will then bring their arms up to a t-pose before raising their forearms straight up and then dropping their forearms to be in front of them as if they were on a motorcycle and holding the handle bars. The capture is of variable length (however long it takes).
Range of Motion	ROM	Short for Range of Motion, the Subject stands on force plate 2 facing the wall by the changing room. They will then raise their arms to a t-pose before raising their forearms straight up. They will then twist their body to one side and then the other. Then they can lower their arms (without obstructing the hip markers) and take two steps forward, turn, and then take two steps forward once more in the direction they came from. They will then bring one leg up and then the other. The capture is of variable length (however long it takes).
Star Arc Right	SAR	Short for Star-Arc Right, the Subject stands straight on force plate 2 with their arms raised (not obstructing the hip markers) facing the wall by the changing room. They will swing their right leg out in front of them, 45 degrees to the side, directly to their side, 45 degrees behind their side, and then straight back. They will then swing their leg back and all around.
Star Arc Left	SAL	Short for Star-Arc Left, the Subject stands straight on force plate 2 with their arms raised (not obstructing the hip

		markers) facing the wall by the changing room. They will swing their left leg out in front of them, 45 degrees to the side, directly to their side, 45 degrees behind their side, and then straight back. They will then swing their leg back and all around.

APPENDIX D

The List of All Motion Variations Captured

Figure D.1 shows a list of the 52 motion variations captured during the study visits. Details on how these motions were completed are available upon request. Any information provided on these motions should be provided from the standard operating procedure documents.

Activity Group	Walking	#
	self-paced walk	1
	self-paced slow walk	2
	self-paced quick walk	3
	self-paced fast walk	4
Activity Group	Ball Pick Up, Put Down, or Hold	
	Ball pick up from the front	5
	Ball put down from the front	6
	Ball pick up front to side	7
	Ball pick up side to front	8
	Ball hold while twisting	9
Activity Group	Instructed Ball Pick Up and Put Down	
	Squat for ball pick up from the front	10
	Squat for ball put down from the front	11
	Squat for ball pick up front to side	12
	Squat for ball pick up side to front	13
	THA ball pick up from the front	14
	THA ball put down from the front	15
Activity Group	Shoe Tying	
	Using shoe bar	16
	Seated with partial leg lift	17
Activity Group	Chair STS	
	Normalized STS	18
	Normalized sit down	19
	Lower than normalized STS	20
	Lower than normalized sit down	21
	Gardening chair STS	22
	Gardening chair sit down	23
	Simulated gardening	24
	Sofa STS	25
	Sofa sit down	26

Activity Group	Instructed Chair STS	#
	Controlled hands normalized STS	27
	Controlled hands normalized sit down	28
	Controlled hands lower than normalized STS	29
	Controlled hands lower than normalized sit down	30
	Controlled hands gardening chair STS	31
	Controlled hands gardening chair sit down	32
	Controlled hands sofa STS	33
	Controlled hands sofa sit down	34
	Used handrail normalized STS	35
	Used handrail normalized sit down	36
	Used handrail lower than normalized STS	37
	Used handrail lower than normalized sit down	38
Activity Group	Bathtub Related	
	Simulated getting out of a bathtub - front facing	39
	Simulated sitting in a bathtub - front facing	40
	Simulated getting out of a bathtub - side stepping	41
	Simulated sitting in a bathtub - side stepping	42
Activity Group	Instructed Bathtub Related	
	Simulated getting out of a bathtub - THA	43
	Simulated sitting in a bathtub - THA	44
Activity Group	Auto	
	Entering a car	45
	Exiting a car	46
Activity Group	Instructed Auto	
	Entering a car - THA	47
	Exiting a car - THA	48
Activity Group	Bed	
	Getting onto a raised bed	49
	Getting off a raised bed	50
Activity Group	Stairs	
	Ascending	51
	Descending	52

Figure D.1. A list of the 52 motion variations collected during the study visits.

APPENDIX E

IRB Documents: Protocol

The following is the Baylor IRB approved protocol for the motion capture study in its original format:

Characterizing Hip Motion During Activities of Daily Living

PRINCIPAL INVESTIGATOR:

Name: Jonathan Rylander
Address: One Bear Place#97356, Waco Texas 76798
Phone # x4193
Fax #
Email: jonathan_rylander@baylor.edu

CO- or SUB-INVESTIGATORS:

Name(s): Sara Pelayo
Institution(s): Baylor University
Address
Phone #
Email: Sara_Pelayo@baylor.edu

Name(s): Carley Fuller
Institution(s): Baylor University
Address
Phone #
Email: carley_fuller@baylor.edu

Name(s): Savan Patel
Institution(s): Baylor University
Address
Phone #
Email: Savan_Patel@baylor.edu

Name(s): Larissa Melling
Institution(s): Baylor University
Address
Phone #
Email: Larissa_Melling@baylor.edu

PROTOCOL VERSION: 06/01/2016 Version #2

Synopsis

Title	Hip Dislocation Risk for Activities of Daily Living
Protocol Date	Upon IRB Approval
Study Duration	2 years – Feb 2016-Feb 2018
Study location(s)	Baylor University: Baylor Biomotion Lab; BRIC
Objectives	To obtain early data to determine which daily activities cause hip dislocation after total hip arthroplasty.
Number of Subjects	40 healthy adults
Main Inclusion/Exclusion Criteria	Inclusion: • Must be between the ages of 18 to 80, inclusive. • Must have a BMI $\leq$ 30. • Must not have any condition or prior injury which would potentially alter normal motion, such as ACL tear, stroke, or lower back injury. • Must be able to maintain moderate, intermittent physical activity for an extended period of time Exclusion: • Subjects will not be excluded based on race or gender. • Subjects will be excluded for co-morbidities that could hinder hip muscle coordination or strength, such as stroke, movement or neuromuscular disorders, and prior lower extremity amputation. • Subjects will be excluded if they have experienced prior trauma effecting gait such as proximal femur or pelvic fractures. • Subjects will be excluded if they are pregnant. • No prisoners will be enrolled in the study

TABLE OF CONTENTS

1.0 BACKGROUND AND RATIONALE

In the United States alone, 332,000 people receive a total hip replacement (THR) each year [1]. Hip dislocation after total hip arthroplasty occurs in between 2% and 11% of patients and is estimated to cost at least $75 million per year [2]. Dislocations can occur posteriorly and anteriorly. According to literature, "posterior dislocations occur with flexion and internal rotation of the hip (as when sitting on a low chair or reaching for the foot), whereas anterior dislocations are the result of external rotation and extension (as was seen in this case, when the patient rolled over in bed)" [3]. According to the available literature, "few hip loading data presently exist for posterior-dislocation-prone activities such as stooping, leg crossing, or rising from a low seat such as a toilet. Moreover, there are no motion data whatsoever for anterior-dislocation-prone activities" [2]. The most common posterior-dislocation-prone maneuvers are sit-to-stand from toilet, chair, erectly seated leg crossing, seated while reaching floor, and standing while bending at the waist. Common anterior-dislocation-prone maneuvers include standing while turning upper body away, lying supine and rolling over [3]. Therefore, the purpose of this study is to explore the daily activities that can cause hip dislocation in THA patients so that clinicians can give better instructions to patients and improve post-op rehabilitation strategies following surgery. Our goal is to quantify the movement strategies employed to complete these common tasks and identify the motions that can make a person more vulnerable to hip dislocation. Only after a firm foundation for "normal" movements is developed can we start to further refine our understanding of mechanical dislocation mechanisms. We plan to collect kinematic and kinetic data at and around the hip joint during daily activities. Initially, we will look at theses activities in a group of healthy controls to look for normal variations in movement strategies. The "highest risk" activities will be identified and a later follow-up study will record the movement strategies in the target hip replacement patients under more strict clinical supervision.

2.0 STUDY OBJECTIVES

PRIMARY: To characterize hip mechanic strategies during activities of daily living with the purpose of identifying potential hazardous activities for hip dislocation.

SECONDARY: To identify the various range of movement strategies employed during standard activities of daily living and see if there are certain identifiers such as age or muscle strength, that might help explain the observed movement strategy.

3.0 SUBJECT SELECTION & RECRUITMENT

Data will only be collected from healthy control subjects. Potential subjects will be recruited by any member of the research team by word of mouth or through a flyer posted in approved locations around the Baylor campus (Appendix 1). Potential subjects will be approached about participating in the study; if the potential subject expresses interest in the study, a member of the research team will review the consent process with the subject. A written consent form will be provided to the subject and they will be given ample time to read and understand the consent form and any questions will be addressed at that time. Only after all concerns have been addressed and the subject agrees to sign the consent form will they be considered as an enrollee in the protocol. After consent is obtained, the subject will be screened by completing an inclusion/exclusion form (see appendices) to screen for medical conditions that may influence their motions.

Subjects from vulnerable populations: Students of the PI may be included in the study on a volunteer basis. A member of the research team unrelated to the class will initially approach the subject. Participation in or refusal to participate in this research will in no way impact their grade in the class.

Informed Consent: No study-specific procedures will be performed without a signed informed consent document. Those who do not demonstrate the ability to understand or the willingness to sign the written informed consent document will be excluded from study entry.

This study only requires that the subject attend one session in the BioMotion Lab at the BRIC, during which motion capture and muscle torque measurements will be collected. Subjects will be clearly notified that they are allowed to quit at any time and will have the opportunity to exit the study at any point. If they opt to remove themselves from the study, all collected data up to that point will be kept confidential.

3.1 INCLUSION CRITERIA

- Must be between the ages of 18 to 80, inclusive.
- Must have a BMI $\leq$ 30.
- Must not have any condition or prior injury which would potentially alter normal motion, such as ACL tear, stroke, or lower back injury.
- Must be able to maintain moderate, intermittent physical activity for an extended period of time

3.2 EXCLUSION CRITERIA

- Subjects will not be excluded based on race or gender.
- Subjects will be excluded for co-morbidities that could hinder hip muscle coordination or strength, such as stroke, movement or neuromuscular disorders, and prior lower extremity amputation.
- Subjects will be excluded if they have experienced prior trauma effecting gait such as proximal femur or pelvic fractures.
- Subjects will be excluded if they are pregnant.
- No prisoners will be enrolled in the study

The researcher will fill out the inclusion/exclusion form.

4.0 RESEARCH METHODS & PROCEDURES

This is a single-visit study to test the ROM, force, and torque of healthy subjects of various ages without a prior history of lower limb injury or pain. It will examine various daily activities that may increase the risk of hip dislocation in a total hip replacement patient such as walking, ascending and descending stairs, climbing into and out of bed, and climbing into and out of a bathtub.

Subjects will be asked to perform these tasks in the Bio-motion Laboratory at the Baylor Research and Innovation Collaborative facility while data is collected using non-invasive motion capture cameras recording the location of various reflective markers placed on the subject's body. These cameras pose no risk to the patient and only record the location of the markers. Standard video cameras will also be used to verify the motions. Data will be processed using the Vicon Nexus 2 software located in the BioMotion Laboratory.

5.0 STUDY VISITS

Only one visit will be required for inclusion in this study. Subjects will be briefed on the visit and informed consent will be obtained. Once consented, demographic information as well as other pertinent health information will also be recorded (age, height, weight, sex, [for women] if they have had a child or not).

Subjects will be instructed to sit on the Biodex dynamometer. Instructions will be given throughout the Biodex session to obtain isokinetic muscle strength values. Subjects will then have markers placed on their body using double-sided tape. The subject will then perform basic activities of daily living such as getting out of bed, bending over to pick something up off the floor, rolling over in bed, etc. Data will be collected for each performed activity. After this data collection, if there is still time then the subject will be fatigued using Biodex's isokinetic testing. Some markers may need to be removed during the isokinetic testing and then replaced afterwards. Once fatigued, the subject will then repeat some of the activities of daily living while fatigued. Lastly, the markers will be removed.

Each participant will only be required to participate in one, 3-hour session at the BioMotion Lab. Video recording and photography may be conducted during the visit. If video or photography are used in any presentation, the subjects will be de-identified by cropping or blurring out their face and they will have to agree ahead of time on their informed consent document.

6.0 RISKS & BENEFITS

Risks:

The subject may experience muscle strain or discomfort due to mock activities imitating everyday function. This may include hip strain on the thigh, inside of the hip joint, groin, outside of the hip joint and lower back.

The subjects will be asked on a repeated basis if they want to rest. If subjects have increased muscle fatigue/soreness and/or increased general fatigue, they will be encouraged to inform a member of the research team. At that time they will be allowed to rest until they are comfortable or decide to discontinue. We are not trying to measure the impact of fatigue on daily activities during the initial motion capture portion of this study. If time allows and participants are willing, a second motion capture session of a select group of activities will take place following a fatigue protocol using the Biodex dynamometer. The level of fatigue needed to do so, should not put the participant at risk. However, should the participant feel unwell (or they change their mind) during the fatigue protocol they will be allowed to stop.

Additionally, mild discomfort may be experienced during the removal of the double sided tape used to apply the reflective markers, similar to that experienced when removing a Band-Aid.

There is also a risk of discomfort or embarrassment due to the minimal amount of clothing required to ensure that all the markers are applied directly to the skin. Consistent with standard practice subjects will be able to discontinue participation in the study at any time.

Risks to subjects participating in the study will be low. We will, however, work to ensure confidentiality of all information gathered and subject safety during the execution of the study. Prior to participation subjects will be consented and screened to ensure they meet the inclusion and exclusion criteria of the study.

Any adverse event will be monitored and immediately reported to the Baylor IRB. If necessary, appropriate medical or professional intervention will be arranged by the principal investigator or a member of the research team.

Benefits:

- Subjects will be informed that there are no guaranteed benefits to participating in this study other than the satisfaction of helping with a scientific study that could help improve future healthcare.

7.0 STATISTICAL ANALYSIS

This is a characterization study to establish normal kinematic ranges for various common activities of daily living. The variables of interest are hip kinematics for flexion/extension, abduction/adduction, and internal/external rotation. Additionally, peak isokinetic torque data will be collected using a Biodex Dynamometer. Subject data may be grouped by age and muscle strength as identified by the Biodex dynamometer and comparisons between groups may be carried out. It is very possible that different people will respond differently to performing the activities. However, the primary objective of this study is to establish normal ranges of hip motion during common activities and to use that information to identify which activities pose the biggest threat to hip dislocation in patients who recently received a total hip replacement. Therefore, any statistical analysis outside of determining averages and standard deviations will be secondary. Therefore, no power analysis was performed. Instead, the target number of 40 enrolled healthy adults of various ages was identified based on the number of subjects we believe we can handle over the next two years.

Criteria for subject participation termination: each patient will be well-informed that they can quit the testing and/or study at any time. If a participant decides to quit the study at any time, all data collected for the participant in direct association with the study will be destroyed by permanently deleting all the files associated with the participant in the presence of the participant. Additionally, all paper forms other than the consent form will be destroyed via shredding.

8.0 DATA MANAGEMENT & PRIVACY/CONFIDENTIALITY

Data to be collected will be in the form of patient information, full body kinematics, and the Biodex Dynamometer data that records the muscle strength information. Subject information that will be collected includes: age (birthdate), sex, height, weight, and lower limb injury history. For female participants, we will also ask if they have given birth since pregnancy can alter hip anatomy and increase joint laxity. Biodex data will be in the form of maximum isokinetic torque peaks for hip flexion/extension, abduction/adduction, and internal/external rotation. Motion capture data will be collected (3D coordinates of the reflective markers) along with high-speed video recording during a single motion capture session. All identifiable data will be collected and accessible to only the members of the research team.

All subject records will be kept in the Biomotion Lab at the BRIC. Personal identifiable data will be confidential; stored on password protected standalone computers in locked rooms. Data from the motion capture sessions will be labelled and stored according to a code; a key matching each individual to the code will be stored on a password-protected computer and/or in paper format in a locked file cabinet separate from subject data. De-identified, coded data will be stored on password-protected computers as it is being processed. Access to the data will be limited to members of the research team.

Data will be kept indefinitely to be used in future extensions of similar research beyond the scope of the proposed research. Additionally, for the participants that don’t consent for their data to be used in further research their data will still be kept indefinitely.

9.0 DATA & SAFETY MONITORING

All identifiable, sensitive data will be kept on password-protected computers or in locked storage cabinets located in locked rooms. Only de-identified data will be removed from these locations to be analyzed at Baylor University by the research team. In this way, there will be no way to trace the removed data back to the individual patients should the removed data become compromised. The key for the de-identification code will also be stored on the password-protected computer located in a locked room. Only the members of the research team will know the password.

All members of the research team will be current on their required online safety training module to better ensure the proper care and handling of the patient data. The research team will act as the review board for the accuracy and appropriate storage of the data collected as part of this study.

In the event of an unanticipated adverse event, the research team member will alert the IRB coordinator immediately via email and/or by phone. The research team will also thoroughly document the circumstances surrounding the adverse event. The patient will be located in a hospital should a serious (and highly unlikely) event take place during testing and would be able to receive quick medical attention.

10.0 REFERENCES

[1] "FastStats: Inpatient Surgery." (2014, May 14). *CDC: The Center for Disease Control and Prevention.* [Online]. Available: http://www.cdc.gov/nchs/fastats/inpatient-surgery.htm
[2] Nadzadi M., et al. "Kinematic, kinetics, and finite element analysis of commonplace maneuvers at risk for total hip dislocation." 2003. Journal of Biomechanics 36: 577-591.
[3] Fillingham Y., et al. "Dislocation of a total hip arthroplasty: acute management in the ED." 2014. American Journal of Emergency Medicine 32: 1554e1-1554e3.

APPENDIX 1: Flyer

BAYLOR UNIVERSITY

RESEARCH PARTICIPANTS NEEDED

STUDY: Characterizing Hip Motion during Activities of Daily Living

LOCATION: BioMotion Lab – Baylor Research and Innovative Collaborative (BRIC)
(100 Research Pkwy, Waco, TX 76704)

Looking for: healthy individuals, between 18-80 years old, who can perform daily activities such as walking, jogging, getting out of bed, and rising from a low chair. To be eligible, you must be free of major lower limb injuries or surgeries that would hinder normal movement.

The underlying purpose of this study is to determine the normal ranges of hip motion during many different activities of daily living. These norms will then be used in a future study to reduce the risk for hip dislocation in patients with a total hip replacement.

Please contact Carley Fuller, the Lead Researcher, for more information or to volunteer at: Carley_Fuller@baylor.edu

APPENDIX 2: SUBJECT INCLUSION/EXCLUSION CRITERIA
(This form is to be completed by the researcher).

Characterizing Hip Motion During Activities of Daily Living	
Subject Number:	**Session Code:**
ENROLLMENT CRITERIA	

INCLUSION CRITERIA: *(To be eligible for study participation, the questions below need to be answered "YES")*

	YES	NO
• Must be between the ages of 18 to 80, inclusive.	☐	☐
• Must have a BMI $\leq$ 30.	☐	☐
• Must not have any condition or prior injury which would potentially alter normal motion, such as ACL tear, stroke, or lower back injury.	☐	☐
• Must be able to maintain moderate, intermittent physical activity for an extended period of time	☐	☐

EXCLUSION CRITERIA: *(To be eligible for study participation, the questions below need to be answered "NO or "N/A")*

	YES	NO
• Subjects will not be excluded based on race or gender.	☐	☐
• Subjects will be excluded for co-morbidities that could hinder hip muscle coordination or strength, such as stroke, movement or neuromuscular disorders, and prior lower extremity amputation.	☐	☐
• Subjects will be excluded if they have experienced prior trauma effecting gait such as proximal femur or pelvic fractures.	☐	☐
• Subjects will be excluded if they are pregnant.	☐	☐

Completers Initials:_________________

Date:_____________________________

APPENDIX F

All Other Tables

The following are the rest of the tables that were mentioned in the results section Aim 1: Normative Data Tables in Chapter 3. This includes the hip ROM tables per age group (Table F.1) and for all participants (Table F.2).

Table F.1. Hip – average ROM for all planes of motion per age group in degrees.

ACTIVITY	Flex/Extension				Add/Abduction				Int/Ext Rotation			
	Y Norm	(Stdev)	O Norm	(Stdev)	Y Norm	(Stdev)	O Norm	(Stdev)	Y Norm	(Stdev)	O Norm	(Stdev)
Ball Pick Up	109.3	(6.6)	110.5	(9.4)	19.6	(7.5)	20.1	(6.6)	20.7	(5.5)	21.4	(3.4)
Normalized STS	89.7	(9.6)	82.5	(18.3)	11.0	(4.1)	7.8	(3.0)	13.7	(5.5)	12.4	(4.7)
Lower STS	94.0	(13.6)	89.8	(16.0)	10.3	(3.8)	9.6	(2.8)	15.0	(5.6)	13.2	(4.6)
Sofa STS	98.0	(11.1)	95.0	(17.7)	13.9	(4.8)	10.6	(4.8)	19.6	(7.4)	15.9	(6.0)
Stair Ascending	68.5	(3.6)	72.3	(5.4)	16.7	(4.2)	17.0	(3.0)	19.0	(4.2)	17.9	(2.1)
Stair Descending	46.2	(5.4)	51.3	(4.9)	19.2	(4.1)	18.9	(1.9)	19.5	(4.9)	21.9	(3.9)
Tying Shoes	29.0	(8.0)	34.2	(8.1)	8.0	(3.0)	8.9	(3.5)	8.1	(2.6)	11.2	(3.6)
Tying Shoes (Left Hip)	40.0	(8.5)	51.1	(8.5)	6.3	(2.2)	6.1	(2.0)	8.7	(2.7)	7.9	(2.0)

Note: All positive values indicate flexion, adduction, and internal rotation while negative values indicate extension, abduction, and external rotation.

Table F.2. Hip – average ROM for all planes of motion all ages in degrees.

ACTIVITY	Flex/Ext		Abd/Add		Int/Ext Rot	
	Norm	(Stdev)	Norm	(Stdev)	Norm	(Stdev)
Ball Pick Up	109.8	(7.6)	19.8	(7.0)	21.0	(4.7)
Normalized STS	85.5	(13.8)	9.6	(4.0)	13.0	(5.2)
Lower STS	92.3	(14.4)	10.0	(3.4)	14.3	(5.2)
Sofa STS	96.8	(13.7)	12.6	(5.0)	18.2	(7.0)
Stair Ascending	69.9	(4.6)	16.8	(3.7)	18.6	(3.5)
Stair Descending	48.1	(5.7)	19.1	(3.4)	20.4	(4.6)
Tying Shoes	31.0	(8.3)	8.3	(3.1)	9.3	(3.3)
Tying Shoes (Left Hip)	44.3	(10.0)	6.2	(2.1)	8.4	(2.4)

APPENDIX G

Lab Contributions

The following are the contributions to the BioMotion Lab at the Baylor Research and Innovative Collaborative (BRIC):

- Helping to setup the lab with Dr. Jonathan Rylander, Larissa Melling (graduate student), and Savan Patel (honors undergraduate)
- Generating standard operating procedures for using the PCT
- Updating the PCT cluster code (Matlab and Bodybuilder) for use with Vicon Nexus 2 and providing instructions for transfer among computers
- Collecting data that can be examined through several different lenses
- Teaching undergraduates on how to use the Biodex System 3 and motion capture system
- Helping update various IRB document packages to continue research besides this study

REFERENCES

[1] CDC, “FastStats: Inpatient Surgery,” *Centers for Disease Control: National Center for Health Statistics*, 06-Jul-2016. [Online]. Available: http://www.cdc.gov/nchs/fastats/inpatient-surgery.htm. [Accessed: 09-Jul-2016].

[2] A. J. Arthursson, O. Furnes, B. Espehaug, L. I. Havelin, and J. A. Söreide, “Prosthesis survival after total hip arthroplasty--does surgical approach matter? Analysis of 19,304 Charnley and 6,002 Exeter primary total hip arthroplasties reported to the Norwegian Arthroplasty Register,” *Acta Orthop.*, vol. 78, no. 6, pp. 719–729, Dec. 2007.

[3] D. Kelmanovich, M. L. Parks, MD, R. Sinha, MD, and W. Macaulay, MD, “Surgical Approaches to Total Hip Arthroplasty,” *J. South. Orthop. Assoc.*, vol. 12, no. 2, pp. 90–94, 2003.

[4] L. D. Dorr, “Posterior Mini-Incision Approach for Total Hip Replacement:,” *JBJS Essent. Surg. Tech.*, vol. 6, no. 1, p. e5, Jan. 2016.

[5] K. Hardinge, “The Direct Lateral Approach to the Hip,” *Br. Editor. Soc. Bone Jt. Surg.*, vol. 64–B, no. 1, pp. 17–19, 1982.

[6] N. A. Christodoulou, K. P. Dialetis, G. K. Gouzias, T. C. Georgas, and A. Stavrianou, “Modified less invasive and bloodless lateral hip approach for total arthroplasty,” *Eur. J. Orthop. Surg. Traumatol.*, vol. 22, no. 2, pp. 167–174, Feb. 2012.

[7] M. S. Austin and W. J. Hozack, “Anterolateral approach for total hip arthroplasty,” *Semin. Arthroplasty*, vol. 15, no. 2, pp. 79–82, Apr. 2004.

[8] A. S. Unger, B. M. Stronach, P. F. Bergin, and M. Nogler, “Direct anterior total hip arthroplasty,” *Am. Acad. Orthop. Surg.*, vol. 63, no. 2014, pp. 227–238.

[9] H. Ito, T. Matsuno, A. Minami, and Y. Aoki, “Intermediate-Term Results After Hybrid Total Hip Arthroplasty for the Treatment of Dysplastic Hips,” *J. Bone*, vol. 85, no. 9, pp. 1725–1732, Sep. 2003.

[10] H. Ito, T. Matsuno, Y. Aok, and A. Minami, “Total hip arthroplasty using an Omniflex modular system: 5 to 12 years followup,” *Clin. Orthop.*, no. 419, pp. 98–106, Feb. 2004.

[11] J. Sanchez-Sotelo, G. J. Haidukewych, and C. J. R. Boberg, “Hospital Cost of Dislocation After Primary Total Hip Arthroplasty,” *J. Bone*, vol. 88, no. 2, pp. 290–294, Feb. 2006.

[12] Emma, “Hip dislocation after total hip replacement. Thread discussing Hip dislocation after total hip replacement,” *Patient*. 2013.

[13] R. S. Kotwal, M. Ganapathi, A. John, M. Maheson, and S. A. Jones, “Outcome of treatment for dislocation after primary total hip replacement,” *Bone Jt. J.*, vol. 91–B, no. 3, pp. 321–326, Mar. 2009.

[14] P. E. M. Beaule, T. P. Schmalzried, P. Udomkiat, and H. C. Amstutz, “Jumbo Femoral Head for the Treatment of Recurrent Dislocation Following Total Hip Replacement,” *J. Bone*, vol. 84, no. 2, pp. 256–263, Feb. 2002.

[15] J. Foran and S. Fischer, “Total Hip Replacement-OrthoInfo - AAOS,” *OrthoInfo*. [Online]. Available: http://orthoinfo.aaos.org/topic.cfm?topic=a00377. [Accessed: 18-Feb-2017].

[16] R. Bartlett, *Introduction to Sports Biomechanics : Analysing Human Movement Patterns*, vol. 2nd ed. Milton Park, Abingdon, Oxon: Routledge, 2007.

[17] C. VanPutte, J. Regan, A. Russo, R. Seeley, T. Stephens, and P. Tate, “Muscular System,” in *Seeley’s Anatomy & Physiology*, 10th ed., McGraw-Hill, 2014, pp. 345–355.

[18] F. Yoshimine, “The safe-zones for combined cup and neck anteversions that fulfill the essential range of motion and their optimum combination in total hip replacements,” *J. Biomech.*, vol. 39, no. 7, pp. 1315–1323, 2006.

[19] K.-H. Widmer and B. Zurfluh, “Compliant positioning of total hip components for optimal range of motion,” *J. Orthop. Res.*, vol. 22, no. 4, pp. 815–821, Jul. 2004.

[20] T. Scheerlinck, “Cup positioning in total hip arthroplasty,” *ACTA Orthop. Belg.*, vol. 80, no. 3, pp. 336–347, 2014.

[21] G. Lewinnek, J. Lewis, R. Tarr, C. Compere, and J. Zimmerman, “Dislocations after total hip-replacement arthroplasties,” *J. Bone Jt. Surg.*, vol. 60, no. 2, pp. 217–220, 1978.

[22] D. E. McCollum and W. J. Gray, “Dislocation after total hip arthroplasty: Causes and prevention,” *Clin. Orthop.*, no. 261, pp. 159–170, 1990.

[23] B. M. Jolles, P. Zangger, and P.-F. Leyvraz Prof., “Factors predisposing to dislocation after primary total hip arthroplasty: A multivariate analysis,” *J. Arthroplasty*, vol. 17, no. 3, pp. 282–288, Apr. 2002.

[24] M. A. Ali Khan, P. H. Brakenbury, and I. S. Reynolds, "Dislocation following total hip replacement," *J. Bone Joint Surg. Br.*, vol. 63–B, no. 2, pp. 214–218, 1981.

[25] Y.-H. Kim, Y. Choi, and J.-S. Kim, "Influence of Patient-, Design-, and Surgery-Related Factors on Rate of Dislocation After Primary Cementless Total Hip Arthroplasty," *J. Arthroplasty*, vol. 24, no. 8, pp. 1258–1263, Dec. 2009.

[26] M. Dudda, A. Gueleryuez, E. Gautier, A. Busato, and C. Roeder, "Risk factors for early dislocation after total hip arthroplasty: a matched case-control study," *J. Orthop. Surg. Hong Kong*, vol. 18, no. 2, p. 179, Aug. 2010.

[27] D. J. Berry, M. von Knoch, C. D. Schleck, and W. S. Harmsen, "Effect of Femoral Head Diameter and Operative Approach on Risk of Dislocation After Primary Total Hip Arthroplasty," *J Bone Jt. Surg Am*, vol. 87, no. 11, pp. 2456–2463, Nov. 2005.

[28] N. P. Hailer, R. J. Weiss, A. Stark, and J. Kärrholm, "The risk of revision due to dislocation after total hip arthroplasty depends on surgical approach, femoral head size, sex, and primary diagnosis," *Acta Orthop.*, vol. 83, no. 5, pp. 442–448, Oct. 2012.

[29] S. A. Paterno, P. F. Lachiewicz, and S. S. Kelley, "The Influence of Patient-Related Factors and the Position of the Acetabular Component on the Rate of Dislocation after Total Hip Replacement*," *J Bone Jt. Surg Am*, vol. 79, no. 8, pp. 1202–10, Aug. 1997.

[30] S. T. Woolson and Z. O. Rahimtoola, "Risk factors for dislocation during the first 3 months after primary total hip replacement," *J. Arthroplasty*, vol. 14, no. 6, pp. 662–668, Sep. 1999.

[31] R. M. D. Meek, D. B. Allan, G. McPhillips, L. Kerr, C. R. Howie, and F. the S. A. Project, "Late Dislocation after Total Hip Arthroplasty," *Clin. Med. Res.*, vol. 6, no. 1, pp. 17–23, May 2008.

[32] P. Maisongrosse *et al.*, "Obesity is no longer a risk factor for dislocation after total hip arthroplasty with a double-mobility cup," *Int. Orthop.*, vol. 39, no. 7, pp. 1251–1258, Dec. 2014.

[33] Jacob Elkins, N. Stroud, R. M. James, and T. Yuki, "The Capsule's Contribution to Total Hip Construct Stability - A Finite Element Analysis," *NIH Public Access*, vol. 29, no. 11, pp. 1642–1648, Dec. 2011.

[34] J. Nevelos, A. Johnson, C. Heffernan, J. Macintyre, D. C. Markel, and M. A. Mont, "What Factors Affect Posterior Dislocation Distance in THA?," *Clin. Orthop.*, vol. 471, no. 2, pp. 519–526, Feb. 2013.

[35] A. B. Patel, R. R. Wagle, M. M. Usrey, M. T. Thompson, S. J. Incavo, and P. C. Noble, “Guidelines for Implant Placement to Minimize Impingement During Activities of Daily Living After Total Hip Arthroplasty,” *J. Arthroplasty*, vol. 25, no. 8, p. 1275–1281.e1, Dec. 2010.

[36] M. Dastane, L. D. Dorr, R. Tarwala, and Z. Wan, “Hip Offset in Total Hip Arthroplasty: Quantitative Measurement with Navigation,” *Clin. Orthop. Relat. Res.*, vol. 469, no. 2, pp. 429–436, Feb. 2011.

[37] R. Y. Woo and B. F. Morrey, “Dislocations after total hip arthroplasty.,” *J Bone Jt. Surg Am*, vol. 64, no. 9, pp. 1295–1306, Dec. 1982.

[38] K. J. Stewart, D. R. Pedersen, J. J. Callaghan, and T. D. Brown, “Implementing capsule representation in a total hip dislocation finite element model,” *Iowa Orthop. J.*, vol. 24, no. Journal Article, pp. 1–8, 2004.

[39] W. Dihlmann and G. Nebel, “Computed tomography of the hip joint capsule,” *J. Comput. Assist. Tomogr.*, vol. 7, no. 2, pp. 278–285, Apr. 1983.

[40] T. Shoji, Y. Yasunaga, T. Yamasaki, S. Izumi, S. Hachisuka, and M. Ochi, “Low femoral antetorsion and total hip arthroplasty: a risk factor,” *Int. Orthop.*, vol. 39, no. 1, pp. 7–12, Jan. 2015.

[41] W. R. Frontera, J. K. Silver, and T. D. R. Jr, *Essentials of Physical Medicine and Rehabilitation*. Elsevier Health Sciences, 2014.

[42] C. J. Minns Lowe, K. L. Barker, M. E. Dewey, and C. M. Sackley, “Effectiveness of physiotherapy exercise following hip arthroplasty for osteoarthritis: a systematic review of clinical trials,” *BMC Musculoskelet. Disord.*, vol. 10, p. 98, 2009.

[43] Y. A. Fillingham, B. J. Erickson, G. L. Cvetanovich, and C. J. Della Valle, “Dislocation of a total hip arthroplasty: acute management in the ED,” *Am. J. Emerg. Med.*, vol. 32, no. 12, p. 1554.e1-1554.e3, Dec. 2014.

[44] M. Woerner *et al.*, “Soft tissue restricts impingement-free mobility in total hip arthroplasty,” *Int. Orthop.*, vol. 41, no. 2, pp. 277–282, Feb. 2017.

[45] M. E. Nadzadi, D. R. Pedersen, H. J. Yack, J. J. Callaghan, and T. D. Brown, “Kinematics, kinetics, and finite element analysis of commonplace maneuvers at risk for total hip dislocation,” *J. Biomech. Kidlington*, vol. 36, no. 4, pp. 577–91, 2003.

[46] Marcia A. Esola MS., Philip W. McClure MS, G. Kelley Fitzgerald MS, and Sorin Siegler PhD, “Analysis of Lumbar Spine and Hip Motion During Forward Bendi... : Spine,” *LWW*, vol. 21, no. 1, pp. 71–78, Jan. 1996.

[47] P. Pal, S. Milosavljevic, G. Sole, and G. Johnson, “Hip and lumbar continuous motion characteristics during flexion and return in young healthy males,” *Eur. Spine J.*, vol. 16, no. 6, pp. 741–747, Aug. 2006.

[48] K. D. Huffman, B. A. Sanford, A. R. Zucker-Levin, J. L. Williams, and W. M. Mihalko, “Increased hip abduction in high body mass index subjects during sit-to-stand,” *Gait Posture*, vol. 41, no. 2, pp. 640–645, Feb. 2015.

[49] A. Hemmerich, H. Brown, S. Smith, S. s. k. Marthandam, and U. p. Wyss, “Hip, knee, and ankle kinematics of high range of motion activities of daily living,” *J. Orthop. Res.*, vol. 24, no. 4, pp. 770–781, Apr. 2006.

[50] R. Shariff, S. Panchani, J. D. Moorehead, and S. J. Scott, “Kinematic assessment of hip movement when retrieving an object from the floor,” *J. Orthop. Surg.*, vol. 6, no. 1, p. 11, 2011.

[51] S. Han, G. Cheng, and P. Xu, “Three-dimensional lower extremity kinematics of Chinese during activities of daily living.,” *J. Back Musculoskelet. Rehabil.*, vol. 28, no. 2, pp. 327–334, Apr. 2015.

[52] H. Zhou, A. Liu, D. Wang, X. Zeng, S. Wei, and C. Wang, “Kinematics of lower limbs of healthy Chinese people sitting cross-legged,” *Prosthet. Orthot. Int.*, vol. 37, no. 5, pp. 369–374, Oct. 2013.

[53] J. Rasmussen, M. S. Andersen, R. Bichler, S. Carbes, and M. deZee, “B-5 Hip Joint Kinematics in Activities of Daily Living,” *J. Biomech.*, vol. 43, Supplement 1, p. S25, Jun. 2010.

[54] D. L. Judd, D. A. Dennis, A. C. Thomas, P. Wolfe, M. R. Dayton, and J. E. Stevens-Lapsley, “Muscle Strength and Functional Recovery During the First Year After THA,” *Clin. Orthop.*, vol. 472, no. 2, pp. 654–664, Feb. 2014.

[55] A. Rasch, N. Dalén, and H. E. Berg, “Muscle strength, gait, and balance in 20 patients with hip osteoarthritis followed for 2 years after THA,” *Acta Orthop.*, vol. 81, no. 2, pp. 183–188, Apr. 2010.

[56] A. Daneshjoo, N. Rahnama, A. H. Mokhtar, and A. Yusof, “Bilateral and Unilateral Asymmetries of Isokinetic Strength and Flexibility in Male Young Professional Soccer Players,” *J. Hum. Kinet.*, vol. 36, no. 1, pp. 45–53, 2013.

[57] S. R. Piva *et al.*, “Contribution of hip abductor strength to physical function in patients with total knee arthroplasty,” *Physical Therapy*, vol. 91, no. 2, p. 225+, Feb-2011.

[58] G. Mouzopoulos, R. Siebold, and M. Tzurbakis, “Hip flexion strength remains decreased in anterior cruciate ligament reconstructed patients at one-year follow up compared to healthy controls,” *Int. Orthop.*, vol. 39, no. 7, pp. 1427–1432, Feb. 2015.

[59] M. H. Arokoski *et al.*, “Hip Muscle Strength and Muscle Cross Sectional Area in Men with and without Hip Osteoarthritis,” *The Journal of Rheumatology*, 2002. [Online]. Available: http://jrheum.com/subscribers/02/10/2187.html. [Accessed: 03-Aug-2016].

[60] K. Masuda, N. Kikuhara, S. Demura, S. Katsuta, and K. Yamanaka, “Relationship between muscle strength in various isokinetic movements and kick performance among soccer players,” *J. Sports Med. Phys. Fitness*, vol. 45, no. 1, pp. 44–52, Mar. 2005.

[61] J. L. Brent, G. D. Myer, K. R. Ford, M. V. Paterno, and T. E. Hewett, “The Effect of Sex and Age on Isokinetic Hip-Abduction Torques,” *J. Sport Rehabil.*, vol. 22, no. 1, pp. 41–46, Feb. 2013.

[62] K. Masuda, K. Yamanaka, H. Takahashi, and N. Kikuhara, “The relationship between muscle cross-sectional area and strength in various isokinetic movements among soccer players,” *J. Sports Sci.*, vol. 21, no. 10, pp. 851–858, Oct. 2003.

[63] T. H. Nakagawa, E. T. U. Moriya, C. D. Maciel, and F. V. Serrao, “Trunk, Pelvis, Hip, and Knee Kinematics, Hip Strength, and Gluteal Muscle Activation During a Single-Leg Squat in Males and Females With and Without Patellofemoral Pain Syndrome,” *J. Orthop. Sports Phys. Ther.*, vol. 42, no. 6, pp. 491–501, Jun. 2012.

[64] M. Julia *et al.*, “Reproducibility of isokinetic peak torque assessments of the hip flexor and extensor muscles,” *Ann. Phys. Rehabil. Med.*, vol. 53, no. 5, pp. 293–305, Jun. 2010.

[65] C. Meyer *et al.*, “Test-Retest Reliability of Innovated Strength Tests for Hip Muscles,” *PLOS ONE*, vol. 8, no. 11, p. e81149, Nov. 2013.

[66] AAOS, “AAOS Online Newsroom | 2.5 Million Americans Living with an Artificial Hip, 4.7 Million with an Artificial Knee.” [Online]. Available: http://newsroom.aaos.org/media-resources/Press-releases/25-million-americans-living-with-an-artificial-hip-47-million-with-an-artificial-knee.htm. [Accessed: 10-Nov-2016].

[67] G. Sole, J. Hamrén, S. Milosavljevic, H. Nicholson, and S. J. Sullivan, “Test-Retest Reliability of Isokinetic Knee Extension and Flexion,” *Arch. Phys. Med. Rehabil.*, vol. 88, no. 5, pp. 626–631, May 2007.

[68] P. Macadam, J. Cronin, and B. Contreras, “An Examination of the Gluteal Muscle Activity Associated with Dynamic Hip Abduction and Hip External Rotation Exercise: A Systematic Review,” *Int. J. Sports Phys. Ther.*, vol. 10, no. 5, pp. 573–591, Oct. 2015.

[69] T. P. Andriacchi, E. J. Alexander, M. K. Toney, and C. Dyrby, “A point cluster method for in vivo motion analysis: applied to a study of knee kinematics,” *J. Biomech. Eng.*, vol. 120, no. 6, p. 743, Dec. 1998.

[70] S. T. Jamison, M. P. McNally, L. C. Schmitt, and A. M. Chaudhari, “The effects of core muscle activation on dynamic trunk position and knee abduction moments: Implications for ACL injury,” *J. Biomech. Kidlington*, vol. 46, no. 13, p. 2236, 2013.

[71] S. B. Abujaber, A. R. Marmon, F. Pozzi, J. J. Rubano, and J. A. Zeni Jr., “Sit-To-Stand Biomechanics Before and After Total Hip Arthroplasty,” *J. Arthroplasty*, vol. 30, no. 11, pp. 2027–2033, Nov. 2015.

[72] B. Bowser, S. O’Rourke, C. N. Brown, L. White, and K. J. Simpson, “Sit-to-stand biomechanics of individuals with multiple sclerosis,” *Clin. Biomech.*, vol. 30, no. 8, pp. 788–794, Oct. 2015.

[73] G. Frykberg E and C. K. Häger, “Movement analysis of sit-to-stand: research informing clinical practice,” *Phys. Ther. Rev.*, vol. 20, no. 3, p. 156, 2015.

[74] C. A. Stevermer and J. C. Gillette, “Kinematic and Kinetic Indicators of Sit-to-Stand,” *J. Appl. Biomech.*, vol. 32, no. 1, pp. 7–15, Feb. 2016.

[75] S. Usuda and T. Yamaji, “Kinematic Motion Analysis of the Sit-to-Stand Motion. The Influence of Chair Height,” *J. Exerc. Physiol.*, vol. 9, no. 4, pp. 187–192, 1994.

[76] S. Yoshioka, A. Nagano, D. C. Hay, and S. Fukashiro, “Peak hip and knee joint moments during a sit-to-stand movement are invariant to the change of seat height within the range of low to normal seat height,” *Biomed. Eng. OnLine*, vol. 13, p. 27, 2014.

[77] T. P. Andriacchi, E. J. Alexander, M. K. Toney, C. Dyrby, and J. Sum, “A point cluster method for in vivo motion analysis: applied to a study of knee kinematics,” *J. Biomech. Eng.*, vol. 120, no. 6, p. 743, 1998.

[78] M. P. Kadaba, H. K. Ramakrishnan, and M. E. Wootten, “Measurement of lower extremity kinematics during level walking,” *J. Orthop. Res. Off. Publ. Orthop. Res. Soc.*, vol. 8, no. 3, p. 383, 1990.

[79] P. S. Sung, “A compensation of angular displacements of the hip joints and lumbosacral spine between subjects with and without idiopathic low back pain during squatting,” *J. Electromyogr. Kinesiol.*, vol. 23, no. 3, pp. 741–745, Jun. 2013.

[80] S. Parkinson, A. Campbell, W. Dankaerts, A. Burnett, and P. O'Sullivan, "Upper and lower lumbar segments move differently during sit-to-stand," *Man. Ther.*, vol. 18, no. 5, pp. 390–394, Oct. 2013.

[81] X. Qu, "Effects of lower-limb muscular fatigue on stair gait," *J. Biomech. Kidlington*, vol. 48, no. 15, pp. 4059–4064, 2015.

[82] S. A. Sayeed, A. J. Johnson, D. E. Jaffe, and M. A. Mont, "Incidence of Contralateral THA After Index THA for Osteoarthritis," *Clin. Orthop.*, vol. 470, no. 2, pp. 535–540, Feb. 2012.

[83] M. Perron, F. Malouin, H. Moffet, and B. J. McFadyen, "Three-dimensional gait analysis in women with a total hip arthroplasty," *Clin. Biomech.*, vol. 15, no. 7, pp. 504–515, Aug. 2000.

[84] O. Chechik, M. Khashan, R. Lador, M. Salai, and E. Amar, "Surgical approach and prosthesis fixation in hip arthroplasty world wide," *Arch. Orthop. Trauma Surg.*, vol. 133, no. 11, pp. 1595–1600, Nov. 2013.

[85] S. Petis, J. L. Howard, B. L. Lanting, and E. M. Vasarhelyi, "Surgical approach in primary total hip arthroplasty: anatomy, technique and clinical outcomes," *Can. J. Surg.*, vol. 58, no. 2, pp. 128–139, Apr. 2015.

[86] G. E. Bertocci, M. C. Munin, K. L. Frost, R. Burdett, C. A. Wassinger, and S. G. Fitzgerald, "Isokinetic Performance after Total Hip Replacement," *Am. J. Phys. Med. Rehabil.*, vol. 83, no. 1, pp. 1–9, 2004.

[87] M. L. Beaulieu, M. Lamontagne, and P. E. Beaulé, "Lower limb biomechanics during gait do not return to normal following total hip arthroplasty," *Gait Posture*, vol. 32, no. 2, pp. 269–273, Jun. 2010.

[88] U. Della Croce, A. Cappozzo, and D. C. Kerrigan, "Pelvis and lower limb anatomical landmark calibration precision and its propagation to bone geometry and joint angles," *Med. Biol. Eng. Comput. Heidelb.*, vol. 37, no. 2, pp. 155–61, Mar. 1999.