REHABILITATION OUTCOMES FOLLOWING A PERIACETABULAR OSTEOTOMY (PAO): A CASE STUDY

by

Cailyn Marie Schroeder

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Exercise Physiology and Nutrition Science

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2021

ACKNOWLEDGEMENTS

To Dr. David Graham, thank you for taking me under your guidance and assisting me with this entire process. You have been an amazing mentor and I am very grateful for the time and knowledge you have shared with me.

To Dr. Jim Becker, thank you for bringing a dietitian with an interest in biomechanics into your program and immersing me into the world of research. Whether it is in dietetics or in research, I now have innumerable skills to help me be a better practitioner for my patients and hopefully the world of research.

To Dr. Laura Opstedal, you have been my rock since I met you. You have helped me grow as a person and as a professional and I appreciate you pushing and believing in me even when all seems lost. You have impacted my life in more ways that I can count, and I am forever grateful.

To Allie Hoffee, Justin Whitten, and Chris Casillas, you know I wouldn't make it through this process without you all. Thank you for helping me keep my sanity and always being there for a laugh or a vent.

To my family and the Gillis family, thank you for all of your support and help during this entire process. Whether it was happened to be laundry, cooking, or providing space for a break, in addition to your love and guidance you have always been there.

To Caleb Gillis, thank you for standing by me during this entire process. It definitely has not been easy between school and health and you have been patient, kind, and understanding throughout it all. You are always pushing me to do my best, but also are there to urge me to relax and regroup when I need a break.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Hip dysplasia is a joint deformity creating instability at the hip due to decreased acetabular coverage of the femoral head and often leads to osteoarthritis. A periacetabular osteotomy is a procedure designed to preserve the bony anatomy and delay the development of osteoarthritis. There is little known about the resulting biomechanical outcomes following periacetabular osteotomy. Two studies on a single subject having undergone periacetabular osteotomy are addressed here: 1) how does lower extremity function during a sit-to-walk change throughout recovery compared to preoperative values following a unilateral periacetabular osteotomy and 2) does gait retraining using real-time biofeedback of ground reaction forces improve return of gait function, with regard to internal hip joint moments, hip and pelvis kinematics, whole body center of mass velocity, and step length following bilateral periacetabular osteotomy in a single patient. In study one, patient reported outcomes, hip strength, and lower extremity joint moments and contributions to peak support moment during the sit-to-stand were assessed pre-operatively and at 6 weeks, 12 weeks, 6 months, and 13 months following periacetabular osteotomy. Patient reported outcome scores returned to normative ranges, however overall quality of life scores remained low. By 13 months muscle strength recovered to baseline values. Following surgery, peak support and hip extensor moments were higher on the non-surgical limb, but the contributions of hip, knee, and ankle to peak support moment did not change. On the surgical limb, while peak support moments were lower, the hip contributed less, and the knee contributed more. These asymmetric loading patterns gradually normalized over one year. In study two, hip joint kinematics, moments, vertical ground reaction forces, and symmetry between limbs during gait were assessed at 6 and 12 weeks following bilateral periacetabular osteotomy – one with gait intervention, and one without. Limb symmetry across dependent variables was not improved in the gait retraining intervention compared to the control. Future research examining biomechanical outcomes in the immediate window following periacetabular osteotomy are needed in addition to evaluation of similar interventions to better inform the rehabilitation protocols currently in place and improve patient return to baseline activity.

CHAPTER ONE

INTRODUCTION

Research Context

Hip dysplasia is characterized by reduced coverage of the femoral head by the acetabulum which creates instability and altered weight bearing, leading to increased joint stress (Michaeli, Murphy, and Hipp, 1997; Leunig, and Ganz, 2007a). This increase in joint stress is a critical factor in developing osteoarthritis of the hip (Jacobsen, and Sonne-Holm, 2005a). Osteoarthritis is the second most costly healthcare condition in the United States as of 2013, making it critical to adequately prevent or delay the onset of this disease (Torio, and Moore, 2016; The United States Bone and Joint Inititative, 2020). One method used to delay the development of hip osteoarthritis is a periacetabular osteotomy (PAO) which is a highly invasive hip preservation procedure used to correct hip dysplasia (Siebenrock, Leunig, and Ganz, 2001a). As opposed to a total hip replacement, a PAO preserves the bony anatomy of the hip joint, potentially prevents future surgeries such as total hip arthroplasty, and may save patients and insurance companies money from the costs associated with such treatment.

The Bernese PAO is a recently developed form of PAO which involves resection, reorientation, and fixation of the acetabulum in a new position in order to increase coverage of the femoral head (Ganz, Klaue, Son Vinh, and Mast, 1988a). Such an invasive technique is not without its structural and functional considerations. Due to this reorientation, the joint center of the hip is often moved medially, adjusting the load bearing at the joint as well as muscular line of action, altering the mechanics of the lower extremity during movement and activity (Sucato, et al., 2010b). All of the aforementioned factors are likely to influence biomechanical outcomes at the hip joint following PAO both clinically and functionally.

Biomechanical literature relating to PAO most commonly examines surgical planning, joint survivorship, or simulations of joint stresses at the hip following PAO (Murphy, and Deshmukh, 2002a; Trousdale, and Cabanela, 2003; Clohisy, et al., 2005; Steppacher, Tannast, Ganz, and Siebenrock, 2008; Zhao, Chosa, Totoribe, and Deng, 2010; Niknafs, et al., 2013; Zou, et al., 2013; Thomas-Aitken, Willey, and Goetz, 2018). To date, there is minimal research that either examines other activities of daily living outside of gait and/or within the immediate 24 weeks following surgery. While patients are typically cleared for full weight bearing at six to eight weeks, most studies do not examine outcomes measures until 6 months or later (Ganz, et al., 1988a; Sucato, et al., 2010b; Adler, et al., 2016). Understanding how joint biomechanics of common activities change during this initial window after surgery is critical for the development of effective rehabilitation protocols, not just in gait, but in other activities of daily living. Additionally, previous studies have demonstrated that altered gait patterns, including asymmetry between limbs, may take up to one year to resolve following PAO (Pedersen, Alkjær, Søballe, and Simonsen, 2006; Karam, Gao, and McKinley, 2011b). Therefore, it is not only important to evaluate other activities of daily living and rehabilitation in the short term following PAO, but also to evaluate possible interventions that may improve gait symmetry during the rehabilitation process.

Purpose

The purpose of this case study was twofold. The first purpose was to assess biomechanical outcomes throughout the rehabilitation process in activities of daily living, specifically a sit to walk task, in a single subject. The second purpose was to evaluate the effect of a gait retraining intervention using real-time biofeedback on limb symmetry within 12-weeks postoperatively compared to no intervention in a single subject undergoing bilateral

PAO. Two research questions were developed and are addressed in two separate studies presented in this document. The research questions and hypotheses for each purpose are as follows:

Research Question 1 (Chapter 3):

How does lower extremity function in a single subject during a sit-to-walk change throughout recovery compared to preoperative values following a unilateral PAO? Lower extremity function was defined by patient reported outcomes of hip function and pain, assessment of hip muscle strength, and support moments at the hip, knee, and ankle at various timepoint pre and post-surgery. It was hypothesized that at each subsequent timepoint after surgery, the patient reported outcomes would improve, muscle strength would increase, and support moments would normalize to baseline values by 6 months.

Research Question 2 (Chapter 4):

Does gait retraining using real-time biofeedback of ground reaction forces improve return of gait function, with regard to internal hip joint moments, hip and pelvis kinematics, whole body center of mass velocity, and step length following bilateral PAO in a single patient? It was hypothesized that gait function would improve at the 12-week time point following the PAO in which the gait retraining intervention was implemented compared to the same time point in the control PAO.

CHAPTER TWO

LITERATURE REVIEW

Hip Anatomy

The hip joint is one of the most mobile joints, second to the shoulder, but is very stable in comparison because of its superior congruence (Moore, Dalley, and Agur, 2014). The ball and socket design of the hip joint supports loads being transferred to, or from, the lumbar spine and pelvic girdle (Moore, et al., 2014). Importantly, it bears large loads throughout a large range of motion in three planes and about three axis of motion.

The hip joint is a ball and socket type joint with the 'socket' portion of the hip joint being the acetabulum. The acetabulum is a shallow, bony, concave portion of the pelvis located laterally to the pubic arch, and inferiorly to the anterior superior iliac spine (ASIS) (Figure 1). Inferiorly, there is a portion of the acetabular rim that appears incomplete, called the acetabular notch. The primary function of the notch is to provide an attachment point for the transverse acetabular ligament of the hip and the ligament teres femoris (Figure 2) (Grant, Sala, and Davidovitch, 2012). Extending superiorly from the acetabular notch is the acetabular fossa. Together the acetabular notch and fossa create a deficit in the smooth

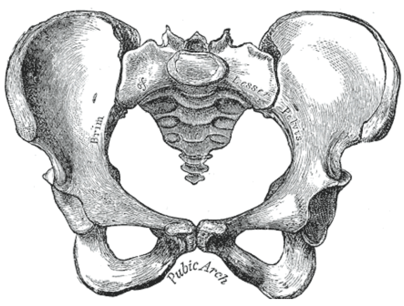

Figure 1: Pelvis Anatomy (Gray's Anatomy)

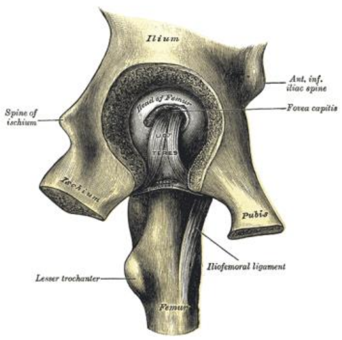

Figure 2: Ligament Teres (Gray's Anatomy)

surface of the acetabulum where the femoral head articulates. Lining the remaining portion of the acetabular surface is articular cartilage. Articular cartilage is very smooth in nature which allows for the transmission of loads with a lower frictional coefficient (Sophia Fox, Bedi, and Rodeo, 2009). Attached at the edge of the articular cartilage, running along the bony rim of the acetabulum, is the acetabular labrum. The labrum, a cartilaginous structure, extends the cup-like shape of the acetabulum and increases its articular area by almost 10% (Moore, et al., 2014). This labral component enhances hip stability and protects the articular surface (Grant, et al., 2012). The previously described transverse acetabular ligament, is a continuation of the labrum and bridges the acetabular notch. Due to the labrum's extended coverage of the acetabulum, over half of the femoral head is able to fit within the acetabulum.

The 'ball' of the hip joint is the superior portion of the femur that interacts with the hip joint called the femoral head. The femoral head is associated with the femoral neck (which connects the femoral head to the shaft of the femur), and the greater and lesser trochanters. The shape of the femoral head is roughly 2/3 of a sphere and, like the acetabulum, is lined with articular cartilage (Figure 3) (Moore, et al., 2014). The trapezoidal portion below the head of the femur is the femoral neck (Figure 3). This segment is narrow

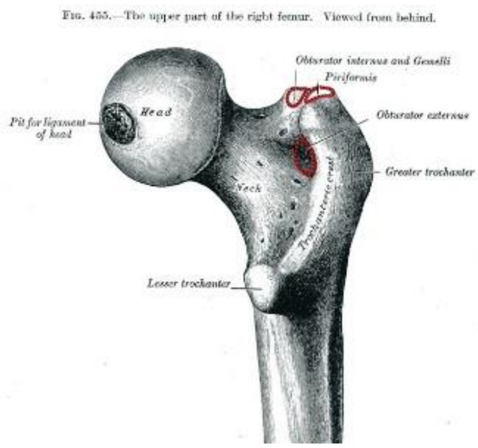

Figure 3: Superior end of femur (Gray's Anatomy)

where it supports head and widens out, ultimately becoming continuous with the shaft of the femur (Moore, et al., 2014). The angle of the femoral neck relative to the shaft of the femur, also known as inclination angle, is approximately 126° in adults. Inclination angle is larger at birth and gradually decreases throughout the lifespan (Moore, et al., 2014). Inclination angle also tends to be lower in females due to the increased width of the acetabulum and greater obliquity of the femoral shaft (Moore, et al., 2014). The inclination angle can increase the mobility of the joint by placing the head and neck more perpendicular in relation to the acetabulum. This orientation places the abductors and rotators, which attach at the greater trochanter, in position to pull more laterally than vertically. This provides them with more leverage capability and allows the mass to be located in the gluteal region, which frees up the lateral shaft of the femur for attachment of knee extensor muscles. This geometry is ideal for bipedal walking, however it places large amounts of strain on the femoral neck (Moore, et al., 2014).

In individuals with healthy hip anatomy, the femoral head fits snuggly into the acetabulum and is encapsulated by the hip joint capsule including a synovial membrane and multiple ligaments (Figure 4). The synovial membrane lines the interior surface of the capsular ligaments and the bony surfaces not lined by articular cartilage. It secretes synovial fluid, to lubricate the joint. In the case of the hip, the synovial membrane essentially lines the femoral neck. The ligaments that make up the hip joint capsule include: the iliofemoral

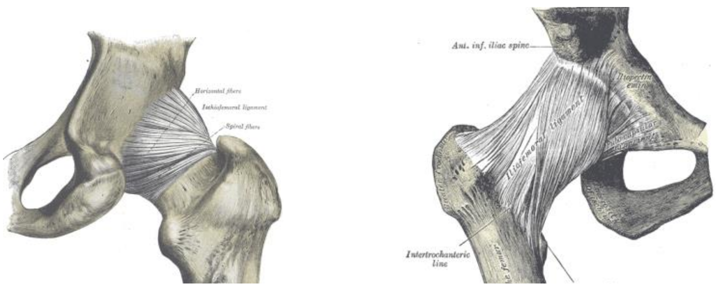

Figure 4: Joint Capsule & Structure (Gray’s Anatomy)

ligament, pubofemoral ligament, and the ischiofemoral ligament (Figure 4) (Moore, et al., 2014). The iliofemoral ligament is considered the strongest of the three ligaments. It prevents hyperextension of the joint when in a standing position by ‘screwing’ the femoral head into the acetabulum due to its Y-like shape that inserts at the anterior inferior iliac spine, proximal acetabular rim, and intertrochanteric line (Moore, et al., 2014). The joint capsule not only serves to help maintain lubrication of the joint space but also helps to strengthen the joint and maintain its function. Those with alterations in the anatomy of the hip are more susceptible to injury and complications down the road.

Hip Dysplasia and Osteoarthritis

Hip instability is a multifactorial condition, one factor being developmental dysplasia of the hip (Kraeutler, Garabekyan, Pascual-Garrido, and Mei-Dan, 2016). Hip dysplasia is a condition in which the shallowing of the acetabulum results in decreased coverage of the femoral head. Using universal screenings at birth, the prevalence of developmental hip dysplasia is only 0.24% (Kraeutler, et al., 2016). However, many cases are not diagnosed until adulthood where it is estimated that 0.1% of the US adult population has this condition (Gala, Clohisy, and Beaulé, 2016). Risk factors for developing hip dysplasia include gender, with females being more at risk, primiparity, breech position, and family history (Chan, et al., 1997; Cady, 2006).

Hip dysplasia is generally assessed using a radiograph of the pelvis by measuring the lateral center edge angle. A vertical line is drawn through the center of the femoral head and another is drawn tangential to lateral margin of acetabulum with the angle measured between the two (Beltran, et al., 2013). Developmental dysplasia is diagnosed in those with lateral center edge angles of less than 20 degrees compared to 25-35 degrees in those with normal hips (Wiberg, 1939). This shallow acetabulum creates poor coverage of the femoral head, moves the hip joint center laterally, and decreases contact area of the acetabulum with the femoral head thus increasing the mechanical joint stress placed on the cartilage (Gala, et al., 2016). This altered loading pattern across the hip joint may lead to cartilage and labral damage (Michaeli, et al., 1997; Armand, et al., 2005), for example, Henak et al. (2014) revealed that the acetabular labrum plays a greater role in load bearing and supports more load overall in those diagnosed with hip dysplasia compared to those with normal hips, thus indicating the substantial altered loading patterns in those with dysplastic hips.

Not only does hip dysplasia have short term injury implications but there are more long-term health risks associated with the condition, including osteoarthritis (Wiberg, 1939; Wedge, and Wasylenko, 1979; Weinstein, 1987; Murphy, Ganz, and Muller, 1995; Clohisy, et al., 2011; Yasunaga, Yamasaki, and Ochi, 2012). It is thought that the decreased load bearing surface area of a dysplastic hip may lead to premature degeneration of the hip anatomy (Wiberg, 1939; Stulberg, and Harris, 1974; Stulberg, 1975). In a study examining hip dysplasia and femoroacetabular impingement (FAI) in osteoarthritis development, dysplastic hips demonstrated the earliest degenerative changes via radiography compared to FAI, and those with combined dysplasia and FAI on the same hip had more rapid development of osteoarthritis (Wyles, et al., 2017). It has also been shown that in single limb total hip arthroplasty, it is almost inevitable that the contralateral limb will develop osteoarthritis (Murphy, et al., 1995). Whether it is structural deformities or surgical intervention of such deformities, the altered loading patterns experienced at the hip joint have detrimental effects in terms of joint degradation leading to the development of osteoarthritis.

Osteoarthritis is a disease involving inflammation and structural changes at the affected joint. Symptoms include pain and stiffness before, during, and after performing activities of daily living and physical exercise. The prevalence of hip osteoarthritis globally in 2010 was 0.85% and was highest in North America compared to other global regions (Cross, et al., 2014). In the United States alone, osteoarthritis affects approximately 32.5 million individuals. It was also the second most costly health condition as of 2013 with 16.5 billion dollars spent on hospital associated costs of the condition (Torio, and Moore, 2016; The United States Bone and Joint Inititative, 2020). Even in those privately insured it accounted for 6.2 billion in hospital costs (Torio, and Moore, 2016). With such significant costs associated with osteoarthritis, it is critical to develop effective treatment options for those predisposed its development. Treating hip dysplasia would theoretically allow delayed development of osteoarthritis and ultimately reduce costs associated with the disease state. In doing so it may help to provide a better quality of life for dysplastic patients by limiting the amount of time spent in a symptomatic state, potentially reducing the amount of orthopedic procedures needed to correct it, including hip arthroplasty.

Treatment Options

Hip dysplasia is commonly treated via surgical intervention. Surgical interventions range from minimally invasive surgeries, including arthroscopic procedures, to highly invasive options, including total hip arthroplasty (THA) and pelvic osteotomies. Arthroscopic intervention is commonly performed in individuals presenting with femoroacetabular impingement (FAI) where there is excess bone development either on the acetabular rim (pincer) or femoral neck (cam), or a combination of the two. In this surgery, the bony growth is removed and labral tears, commonly occurring from the condition, are repaired. Patients presenting with borderline hip dysplasia and concomitant FAI have demonstrated positive outcomes following a careful approach to labral repair and closure of the hip joint capsule

(Nawabi, et al., 2016). However, standard dysplasia is associated with variable outcomes and higher rates of re-operation and transition to THA (Yeung, Kowalczuk, Simunovic, and Ayeni, 2016).

THA involves the resection of the acetabular cartilage and subchondral bone as well as resection of the femoral head and proximal neck. They are then replaced with corresponding prostheses for both the acetabulum and femoral head and neck. The acetabular prosthetic is a concave piece similar to the shape of a normal acetabulum. The femoral prosthetic consists of a stem with a similarly shaped head to take place of the resected femur. These artificial joint components generally have a porous nature on the boney side, allowing the living bone tissue to grow into the prosthetic and ultimately fix the artificial piece in place (Choi, 2015). In dysplastic patients who already present with a shallowing of the acetabulum, this can pose a challenge to ensure adequate bony coverage of the new prosthetic cup. With cases of severe hip dysplasia, the shallow acetabulum does not provide an adequate bed in which to place the prosthetic cup. To enlarge the acetabular bed, bone is surgically reamed out, being careful not to perforate the inner table of the ilium (Crowe, Mani, and Ranawat, 1979). In the event that acetabular coverage is too small for this intervention, bone grafts can be used to increase depth of the bed. A portion of the resected femoral head is used as the graft and attached via screws or pins to the anterosuperior margin of the original acetabulum (Crowe, et al., 1979). Disadvantages to a THA, especially at a young age, include increased risk of subsequent revisions or prosthetic replacement, and prosthetic loosening and wear issues, especially in those that are highly active (Kim, and Kim, 2020).

To address these disadvantages, a periacetabular osteotomy (PAO) may be a more effective option. A PAO involves resecting the acetabular component of the hip joint and reorienting it into a new position to improve acetabular coverage where it is then fixed in place with screws. A PAO is most commonly performed on younger (usually <40 years old) active patients with a viable joint in terms of articular cartilage health (Coobs, Xiong, and Clohisy, 2015) because of the invasive nature of the procedure and the extended recovery time and rehabilitation. There are a few factors that can predict poor outcomes of PAO including: patient age, anterior impingement, limp preoperatively, increased osteoarthritis grade preoperatively, as well as lower preoperative functional scores (Steppacher, et al., 2008). As such, there is also greater risk associated with a PAO, failures in PAO are typically classified as transfer to THA. In a study of 75 PAO performed at an experienced PAO institution, survival rate, or lack of transfer to THA, across 20 years was 60.5% (Steppacher, et al., 2008). Patients who demonstrate symptomatic hip dysplasia who experience subluxation, had all undergone THA by the time they reached 45 years of age, however in symptomatic patients with subluxation receiving PAO, 54% did not have additional surgery or THA by age 41 (Hartofilakidis, Karachalios, and Stamos, 2000; Steppacher, et al., 2008). PAO patients typically report high satisfaction scores and a willingness to repeat surgery with significant improvements in overall quality of life and ability to participate in sports and social activities (Klit, et al., 2014). A systematic review demonstrated reliable deformity correction and significant improvements in hip function across 626 hips with 79% of patients experiencing good or excellent clinical outcomes with only a 7.3% conversion to THA (Gala, et al., 2016)(Clohisy, et al., 2009). These outcomes demonstrate that hip preservation options such as PAO may be more beneficial than THA in younger, more active patients who would normally outlive their prosthetic if receiving THA.

PAO Surgery

There are multiple forms of PAO which include the Salter innominate osteotomy, double innominate osteotomy by Sutherland, triple innominate osteotomy by Steel and Tonnis, spherical by Wagner, pericapsular by Pemberton, Bernese PAO, and shelf procedures including the Chiari osteotomy (Gala, et al., 2016). The Salter osteotomy shifts the roof of the acetabulum inferiorly and laterally, which leads to acetabular retroversion and is thus not recommended in skeletally mature individuals. A triple innate osteotomy described by Steel corrects acetabular hip dysplasia but because the posterior column gets osteomized, the patient is not allowed to be mobilized in the first four to six weeks post operatively (Steel, 1973). Tonnis also describes a triple osteotomy where the ischial osteotomy is made closer to the acetabulum which allows for greater coverage of the femoral head and translational movement in three planes (Tonnis, 1990). Ganz (Ganz, et al., 1988a; Siebenrock, et al., 2001a) developed a triplanar PAO in 1982, also known as a Bernese PAO, that involves orthogonal cuts and leaves the posterior column intact, thus not altering the shape of the true pelvis. Due to the triplanar nature, careful 3D planning is required and the procedure itself is more technically demanding. Ganz's version showed good to excellent outcomes in 73% and 60% in hips respectively and improved to 88% and 75% respectively when those with preoperative osteoarthritis were excluded (Steppacher, et al., 2008; Matheney, et al., 2009). With the majority of PAO now being conducted using a Bernese approach, it is important to describe the procedure in more detail. A modified Smith-Peterson approach is commonly used to initiate the procedure and progress through the musculature to reach the pelvis (Matta, Stover, and Siebenrock, 1999). With the patient lying in a supine position, an incision is made from the anterior half of the iliac crest to anterior superior iliac spine and then inferiorly in the direction of the lateral patella for a length of 8-10 cm. After identifying the gap between the sartorius and tensor fasciae latae (TFL) and dissecting through the subcutaneous fat, an incision is made to detach the origin of the TFL of the iliac. In the case of our single subject analysis, a rectus and sartorius sparing approach was utilized (Peters, Erickson, Anderson, and Anderson, 2015). Instead of detaching the rectus femoris at its origins, an osteotomy of the anterosuperior iliac spine is performed with the sartorius and abdominal muscles intact. It is retracted medially, then the interval between the rectus and iliacus is developed by retracting the iliopsoas tendon medially. This approach demonstrated less overall inpatient pain and improved inpatient physical therapy performance (Peters, et al., 2015).

Following the resection/retraction of muscle, the body of the ischium is scored and a blade is hammered 5-10 mm into the bone without attempting to break it. Next is the division of the pubic ramus from the acetabulum. With the hip slightly flexed and adducted the iliopsoas and femoral nerves are protected with a retractor while a transverse osteotomy of the pubis immediately adjacent to the acetabulum is conducted. The third step is performed in two steps and is started by scoring the ilium, both the inside and the outside. The surgical limb is extended and slightly abducted for the cut on the outside of the ilium, while it is then slightly flexed for the inside cut. The actual osteotomy is started proximal to the anteroinferior iliac spine to allow the fixation of a screw into the acetabular fragment and is done with an oscillating saw. The first 15 mm of the posterior leg of the osteotomy is marked with an osteoma on the inner and outer table of the pelvis, aiming at the ischial spine and therefore forming an angle of 110°-120° with the anterior leg of the osteotomy. Only the first 15 mm of the posterior leg needs to be osteomized as the remaining pelvis will break spontaneously toward the ischial spine without breaking into the joint or the sciatic notch. At this point the acetabulum is only attached to the ischium. Now, a screw is inserted into the supraacetabular bone without entering the hip joint and used to lever the acetabulum to make the quadrilateral surface to the obturator foramen visible. An osteoma is placed 4 cm below the pelvic brim and oriented 50° to the quadrilateral surface. The length of this osteotomy is 2-3 chisel widths until the acetabular fragment breaks loose and can be reoriented. The surgeon reorients the acetabular fragment to provide increased coverage of the femoral head and then fixes it in place with three screws. Two screws running from the superior iliac spine down to the superior portion of the acetabular fragment, and one screw running from the anterior portion of the fragment, posteriorly into the pelvis as shown in Figure 6, taken from Steppacher et al. (2008). Medical images are taken throughout the entire process to ensure correct placement of the osteotomes, osteotomies, and fragment orientation with imaging done post operatively to provide observation of the femoral head, position of the acetabular roof, and position of the fossa acetabuli relative to the weight bearing area (Ganz, et al., 1988a).

Post operatively, the hip is placed in a neutral position with appropriate dressings. The patient is generally recommended to be out of bed on the second or third postoperative day when crutch walking with partial weight bearing is initiated. At 6 weeks, bony healing is verified via radiograph and the patient is cleared to advance in the rehabilitation protocol as medically appropriate (Ganz, et al., 1988a). The standard rehabilitation protocols will be described in the next section.

Current Rehabilitation Process

While there are no standard protocols for rehabilitation following PAO, there are common approaches, specifically with respect to returning to weight bearing. Complete restriction of weight bearing is not recommended because it may decrease bone mineral density, decrease compressive load tolerance, lead to a delay in bony union at ostomy sites, and increase the demand placed on abductor muscles and the iliotibial band to stabilize the suspended femur (Inman, 1947; Givens-Heiss, et al., 1992; Vanwanseele, Lucchinetti, and Stüssi, 2002; Behrens, Bitter, Kurz, and Russlies, 2006). This altered musculature utilization may lead to increases iliopsoas and proximal tendonitis (Schwachmeyer, et al., 2013). Non weight bearing precautions lasting two to four weeks also demonstrated functional deficits for up to one year compared to those permitted to bear weight as tolerated (Kaku, et al., 2004). In general, following hip operations, patients are returned to bipedal mobility using crutches which are recommended over a walker as they decrease the opportunity to abduct and externally rotate the femur while in motion (Youdas, Kotajarvi, Padgett, and Kaufman, 2005). It is suggesting that crutches also allow the patient to better mimic the mechanics of gait through the upright posture and proper length tension properties of the hip flexor musculature (Youdas, et al., 2005).

Adler and colleagues describe a phased approach to rehabilitaiton (Adler, et al., 2016). Phase 1 is considered immediately postoperatively up until four to six weeks. In this phase, passive range of motion (ROM) and manual therapy help to prevent stiffness and adhesions. Prone lying is encouraged to provide a gentle stretch of hip flexors and place the pelvis in a neutral position. Once able to sit comfortably in an upright position, the patient is able to ride a stationary bike with no resistance to promote active assisted ROM. Before initiating phase two, the patient should have radiographic imaging demonstrating appropriate healing at osteotomy sites.

The goals of phase two are to restore ROM and reeducate normal muscular firing patterns to create sufficient dynamic stabilization. At this point aquatic therapy may be utilized as long as appropriate wound closure is observed. ROM should be progressed according to patient tolerance. Some tightness of the posterior capsule may be improved with quadruped rocking, also increasing passive hip flexion. Strength and endurance of the gluteal complex, quadriceps, and hamstrings should be progressively incorporated to meet muscular demands of ambulation. Core exercises should also be included to increase dynamic stability. In this phase, weight bearing may be advanced to 50% of patient body weight for the first two weeks, then progressed to 75% in the third week with the absence of increased pain abnormalities. This gradual return to full weight bearing decreases the rate of postoperative fractures and may increase cartilage regeneration (Nishino, et al., 2010; Ito, et al., 2014).

Phase three of the rehab process focuses on normalizing gait and returning strength to levels that allow the patient to perform activities of daily living. Knee extensor and hip abductor strength should be addressed in terms of preparing the patient to walk without assistance (Bohannon, 1997). Navigation of stairs requires physiologic ROM and appropriate muscle strength (Andriacchi, et al., 1980; Bergmann, et al., 2001; Nadeau, McFadyen, and Malouin, 2003). Hip flexor exercises should be incorporated to help facilitate the necessary motion. At this point, as deemed appropriate by healthcare staff, the patient is granted the ability to perform activities of daily living as appropriate.

Once the patient reaches phase four, they are able to start expanding their focus into more dynamic and sport-like rehabilitation. This includes muscular endurance, cardiovascular fitness, and low impact activities such as spinning, elliptical, slide board, and aqua jogging. Machines and dumbbell exercises can also be used. Fatigue should be monitored closely as this may impact ability to maintain proper technique and may open up the risk for injury or undesired patterns.

Return to sport is generally the final phase of any rehabilitation protocol. In those who have undergone hip preservation surgeries including PAO, it is generally not recommended to return to ballistic or high impact sports, though not impossible. There is no clinical tool to predict successful return to sport and multiple criteria must be met and agreed upon by the patient, surgeon, rehabilitation specialist. In terms of objective measurements, it is recommended that a minimum of 85% strength of the contralateral limb is achieved before fully returning to sport (Wilk, Reinold, and Hooks, 2003; Jacobs, et al., 2005), however, equal strength is preferred. It is recommended that testing should be sport specific in both load and movement dynamics and all movements should be able to be completed pain free prior to clearance (Domb, Stake, Finch, and Cramer, 2014).

For example, a case study by Tippett and colleagues examined the return to sport of a 15 year old female tennis player (Tippett, 2006b). Immediately postoperatively the patient was cleared to perform hip ROM and gentle isometric hamstring and quadricep sets in addition to partial weight bearing on crutches. At week four postoperatively the patient was advanced to 40 pounds weight bearing on the involved limb. At this point hip flexor strengthening, open and closed kinetic chain quadriceps as well as gluteus medius strengthening were initiated. At eight weeks postoperatively the patient had active standing hip flexion of 90° and hip extensor strength had improved to the point that the patient could perform single leg bridge exercises. Rehabilitation at this point focused on strengthening hip musculature and abdominals. The patient was instructed to progress to full weight bearing at week nine postoperatively. At postoperative week 18 the patient’s rehab continued to focus on lower extremity and core strengthening as well as functional progression activities specific to tennis. These exercises started with bilateral side to side and front to back jumping and technique specific drills, advanced to unilateral exercises, then full court jogs and light tennis volleys. After this it progressed further to sprinting, regular volleys, running racquet swings, and acceleration/deceleration before progressing to full tennis doubles and singles.

While every surgeon performing a PAO may have their own variant of postoperative protocols, all follow a similar trend outlined above. The specific rehabilitation process for this study is outlined in Chapter 3. The rehabilitation process has a direct impact on the biomechanical outcomes and function in the tasks of both sport and daily living.

Outcomes Following Rehabilitation

Biomechanical studies in PAO commonly examine the planning process or simulations to predict the joint stress following surgery based on patient imaging (Zhao, et al., 2010; Niknafs, et al., 2013; Zou, et al., 2013; Lee, et al., 2015; Murphy, et al., 2015; Thomas-Aitken, et al., 2018). However, relatively little is known with respect to the impact of PAO on hip joint biomechanics and its function within activities of daily living, and in particular, gait. An early study examined gait in patients who had undergone PAO and found that a more upright walking pattern was demonstrated at 18 months postoperatively, and that peak knee extension at heel strike, peak knee flexion in stance phase, and peak knee extension were all greater post PAO compared to preoperatively. The authors also found that the peak hip extensor moment decreased following surgery (Pedersen, et al., 2006). In a similar study examining gait patterns, both pre and 11.5 months post PAO, patients demonstrated a trend of increased walking velocity and a significant increase in stride length and reduction in pain relief at 11.5 months post PAO (Karam, et al., 2011b). Because the Bernese PAO allows the hip joint center to be moved medially and limits the amount of abductor muscle dissection during the operation, it improves abductor function postoperatively. It has been demonstrated that at 6 months post operatively there is a decrease in hip abductor strength of approximately 6.4%, however by one year it was returned to, and exceeded, baseline values (Sucato, et al., 2010b). The patients in this study also demonstrated increased walking velocity at six months and one year as well as increased hip abductor impulse by one year with gait velocity at one year continuing to be slower than healthy controls. Another study examining 35 post-operative PAO patients compared to 35 healthy controls, found that pelvic tilt ROM, peak hip extension, hip flexion-extension ROM, knee flexion-extension ROM, maximum ankle dorsiflexion, and ankle dorsi-plantar flexion ROM were different in the sagittal plane between the groups. However, there were no differences in sagittal plane kinetic moments outside of a decrease in the mean peak hip external flexion moment in those patients with a perfect postoperative Harris Hip Score, which the authors attributed to a possible reduction in gluteus maximus and hamstring activation (Gahramanov, et al., 2017). Collectively these studies demonstrate that gait alterations occur following PAO, and that in many cases, return to baseline levels up to one year later. Thus, it is of interest to examine further rehabilitation protocols or interventions that may improve patient outcomes to return said gait alterations to baseline levels within a shorter postoperative window of time.

Most literature describing rehabilitation following PAO focuses on gait, however, it is important to examine other common activities of daily living and the recovery outcomes of patients in these areas. While a number of studies discuss other activities of daily living, most of the information is reported from the use of questionnaires completed by the patient and not human movement data collected in a laboratory setting. For example, a study conducted by Boje et al. (2019) including 321 participants, patients expressed an increase in satisfaction in performing activities of daily living and sport/recreation at two years post PAO compared to baseline using the Hip disability and Osteoarthritis Outcome Score (HOOS) questionnaire. Another study followed patients preoperatively and six months, two years, five years, and 10 years post operatively the HOOS questionnaire (Larsen, et al., 2020). The authors demonstrated that patients had increased scores of activities of daily living, compared to pre-operation, at all time points post operatively, with the greatest increase being seen at two and five years post PAO. These questionnaires reveal the perceived improvement with activities of daily living but importantly do not demonstrate the mechanical function at the joint and lower limb behind these perceived improvements.

This indicates that there is a clear need for studies examining activities such as sit to stand, sit to walk, stair climbing, and lifting from the ground to be conducted in order to better understand functional outcomes following PAO across a wide range of common activities of daily living.

CHAPTER THREE

RECOVERY OF LOWER EXTREMITY FUNCTION IN THE INITIAL YEAR FOLLOWING PERIACETABULAR OSTEOTOMY: A SINGLE SUBJECT ANALYSIS

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

Author: Cailyn Schroeder

Contributions: Primary investigator and developer of study methodology. Primary processor and analyzer of study data. Author of manuscript.

Co-Author: Linnea Zavala, MS

Contributions: Assisted with data collection and analysis.

Co-Author: Laura Opstedal, PT, DPT

Contributions: Provided clinical input for study methodology. Reviewed study design, results, analysis, and final manuscript.

Co-Author: James Becker, PhD

Contributions: Assisted with development of study methodology, data analysis, and development of conclusions and final manuscript. Provided recommended changes to all aspects of study from design to final manuscript.

Manuscript Information

Cailyn Schroeder, BS, Linnea Zavala, MS, Laura Opstedal, DPT, James Becker, PhD

Physiotherapy Theory and Practice

Status of Manuscript:
____ Prepared for submission to a peer-reviewed journal
____ Officially submitted to a peer-reviewed journal
____ Accepted by a peer-reviewed journal
__X_ Published in a peer-reviewed journal

Taylor and Francis Group, LLC

10.1080/09593985.2020.1833388

Recovery of Lower Extremity Function in the Initial Year Following Periacetabular Osteotomy: A Single Subject Analysis

Cailyn Schroeder, BS[1], Linnea Zavala, MS[1], Laura Opstedal, DPT[2], James Becker, PhD[1]

[1]Department of Health and Human Development, Montana State University, Bozeman, MT, USA

[2]Build Physio & Performance, Bozeman, MT, USA

Corresponding Author
Dr. James Becker
Department of Health and Human Development
219 Herrick Hall
Montana State University,
Bozeman, MT 59717
Email: james.becker4@montana.edu

Ethical Statement: All protocols in this study were approved by the Institutional Review Board at Montana State University. Written informed consent was obtained from the participant prior to participating in the study.

Funding: This study was supported by the Ellen Kreighbaum Movement Science Laboratory Endowment at Montana State University.

ABSTRACT

Background: Little is known regarding how lower extremity joint function recovers in the six months following periacetabular osteotomy (PAO) for activities other than walking. **Purpose:** Assess patient reported outcomes, hip strength, lower extremity joint moments, and moment distributions during sit-to-stand in a female athlete during the one-year period following PAO. **Methods:** Patient reported outcomes (hip and groin outcome score; HAGOS), hip strength, and lower extremity joint moments and contributions to peak support moment during the sit-to-stand were assessed pre-operatively and at 6 weeks, 12 weeks, 6 months, and 13 months following PAO. **Results:** HAGOS scores returned to normative ranges, however overall quality of life scores remained low. By 13 months muscle strength recovered to baseline values. Following surgery, peak support and hip extensor moments were higher on the non-surgical limb, but the contributions of hip, knee, and ankle to peak support moment did not change. On the surgical limb, while peak support moments were lower, the hip contributed less, and the knee contributed more. These asymmetric loading patterns gradually normalized over one year. **Conclusions:** Asymmetric loading following PAO should be considered when developing rehabilitation plans following this surgery.

Key Words: Support moment distribution; hip preservation surgery; rehabilitation; activities of daily living

Word Count: 4,754

INTRODUCTION

Periacetabular osteotomy (PAO) is a hip preservation procedure used to correct hip dysplasia (Leunig, Siebenrock, and Ganz, 2001). In dysplastic hips, acetabular coverage of the femoral head is reduced, creating instability and altered weight bearing (Leunig and Ganz, 2007). This results in increased joint stress (Michaeli, et al., 1997) and is a contributing factor to the development of hip osteoarthritis (Jacobsen and Sonne-Holm, 2005; Reijman, et al., 2005). In pre-osteoarthritic or young (< 30 years) patients, PAO can be used to improve femoral head coverage and prolong the development of osteoarthritis (Ganz, Klaue, Son Vinh, and Mast, 1988; Leunig, and Ganz, 2007; Millis, Murphy, and Poss, 1995; Steppacher, Tannast, Ganz, and Siebenrock, 2008). The most common PAO technique is the Bernese PAO during which the surgeon transects the pubic ramus freeing the acetabulum from the rest of the ilium, reorients the acetabular fragment to improve femoral head coverage and then screws the fragment in place (Ganz, et al., 1988a). Bernese PAO has several advantages over other pelvic osteotomy techniques in that it maintains vascularization of the acetabular fragment, facilitates extensive acetabular reorientation, maintains the shape of the pelvic rim, and allows the posterior column of the pelvis to remain intact (Ganz, et al., 1988; Leunig, and Ganz, 2007; Siebenrock, Leunig, and Ganz, 2001). This last factor means external fixation is not required and patients can begin weight bearing relatively soon after surgery.

Much of the literature on PAO focuses on clinical outcomes and joint survivorship (Clohisy, et al., 2005; Jacobsen, et al., 2019; Murphy, and Deshmukh, 2002; Kralj, et al., 2005; Trousdale, and Cabanela, 2003; Steppacher, et al., 2008), using computer guidance for planning and improving surgery (Zou et al., 2013; Murphy et al., 2015; Niknafs et al., 2013), or computer simulations of joint stress following surgery (Lee, et al., 2015; Thomas-Aitken, Willey, and Goetz, 2018; Zhao, Chosa, Totoribe, and Deng, 2010; Zou, et al., 2013).

Relatively little is known regarding how PAO impacts hip biomechanics and function during daily activities. Several studies have reported that patients who undergo PAO display reduced walking velocities compared to controls, both at baseline and up to one year following surgery (Karam, Gao, and McKinley, 2011; Nishimura, et al., 2015; Sucato, et al., 2010). These patients also have less hip extension range of motion, smaller hip extensor moments during walking and running, and generate reduced hip abductor moments preoperatively, although these values slowly return to levels of healthy controls following surgery (Gahramanov et al., 2017; Jacobsen et al., 2014; Pedersen, Alkjær, Søballe, and Simonsen, 2006; Sucato et al., 2010).

Combined these studies suggest that hip biomechanics slowly return to those of normal healthy control levels following PAO. However, these studies have only evaluated walking and running gait. It is unclear whether similar improvement timelines are present for other common activities of daily living. Second, the earliest postoperative assessment in these studies occurs six months following PAO. However, patients are typically cleared for full weight bearing between six and eight weeks following surgery (Ganz, et al., 1988a; Siebenrock, et al., 2001b; Trousdale, and Cabanela, 2003). Understanding how mechanics change in this initial window following surgery is important for developing effective rehabilitation protocols. Finally, to date, studies on gait following PAO have only looked at single joints in isolation. Other analyses such as support moment distributions provide additional insight into how the joints of the lower extremity work synergistically to accomplish the overall goal of body weight support (Winter, 1980). While such an approach has been used to evaluate recovery of limb function following total knee replacement (Mandeville, Osternig, and Chou, 2007) and arthroscopic surgery for femoroacetabular impingement (Samaan, et al., 2017), to date they have not been applied in PAO patients.

Given these gaps, the purpose of this case study was to describe recovery of lower function during a sit-to-walk (STW) task in a patient undergoing unilateral PAO. Patient reported outcomes (PRO) of hip function and pain, dynamometer assessments of hip muscle strength, and kinematic and kinetic motion capture analyses of the STW were assessed preoperatively, and six weeks (6WK), twelve weeks (12WK), six months (6MO), and 13 months (13MO) following PAO.

MATREIALS AND METHODS

Participant Description

All procedures in this study were approved by the university Institutional Review Board and the participant provided written informed consent prior to participating (Appendix A). The participant was a 23-year-old female (height: 1.80 m.; mass: 81 kg) who underwent a unilateral PAO on her left hip. The participant had a history of three previous arthroscopic hip surgeries prior to PAO including one for repair of femoroacetabular impingement and associated labral tear, one capsular plication, and one to repair a subsequent labral tear. The participant experienced a subluxation approximately ten days following the last labral repair and was subsequently diagnosed with a dysplastic hip due to a shallowing of the acetabulum from previous surgeries. It was determined that boney stability needed to be regained and the participant underwent PAO approximately five months following the last labral tear.

A Bernese PAO using a modified Smith-Peterson approach was performed. The anterior superior iliac spine was osteomized to keep the sartorius and conjoint tendons intact. Cuts were made through the inner and outer ischium tables, transversely across ilium, then down toward the posterior inferior pubis. The acetabular fragment was anterior-laterally rotated to increase coverage of the femoral head and secured in place using three screws. A fourth screw was used reattach the anterior superior iliac spine. Radiographic images showing the original and repaired hip joints are shown in Figure 1. Center-edge angles were 30° at baseline and increased to 42° following surgery.

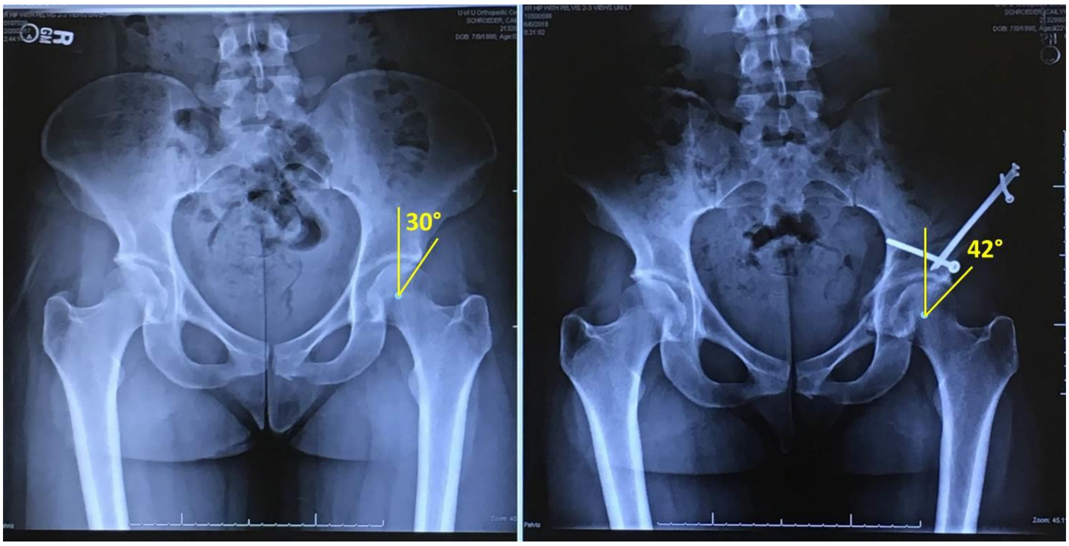

Figure 1: *Radiographic images of the hip joint before (left) and after (right) surgery*

Physical therapy was initiated immediately upon completion of surgery. There is no standardized therapy protocol following PAO. Thus, the general principles of this protocol included: progressing from 25% weight bearing to 100% weight bearing by 6WK at which point the participant was cleared to walk without crutches, limiting exercise in the first two weeks to small range of motion or isometrics, and restrictions on hip extension. Exercises progressed through 12WK to closed chain single limb support. Full details of the rehabilitation protocol are shown in Table 1.

Table 1. The rehabilitation program initiated immediately after PAO surgery. Pertinent abbreviations: range of motion (ROM), transverse abdominis (TrA), internal (int.), external (ext.), body weight (BW), and lower extremity (LE).

Time Postop	Weight Bearing	Goals	Exercises	Other
Weeks 0-2	25-50% BW with crutches	Hip flexion passive & active ROM = 0-90° < 3/10 pain scale Normal ankle and knee ROM Pain free exercises	Ankle pumps Gluteal sets/Quad Sets Seated knee extension Prone ham curls Isometric TrA	No int./ext. rotation of hip No hip extension
Weeks 2-4	50% BW with crutches	Hip flexion passive & active ROM = 0-90° < 2/10 pain scale All exercises pain free including hip flexion	Continue above Heel slides/active assist hip flexion Side-lying hip abduction Side-lying hip adduction Standing 4-way hip – surgical side only Bridging	May start stationary bike with no resistance Hip flexion < 90°
Weeks 4-6	Progress to 75% BW while maintaining good gait pattern	Normalize gait with crutches 0/10 pain scale	Everything previously plus: Supine and prone hip passive ROM all directions Progress core stabilization Scar mobilization	Stationary bike ok If incision healed- start pool walking and leg exercises ROM of hip below 90°
Weeks 6-12	Weight bearing as tolerated	Work toward full hip ROM pain free	Everything previously plus: Progression LE isotonic exercises @ 8 weeks Single leg balance progression Squat Progression	Biking ok May start golf progression at 12 weeks
Weeks 12 +	Weight bearing as tolerated	Full ROM	Continue above exercises Advance closed chain exercises as tolerated	Start return to run program if no increase in pain or limp

Patient Reported Outcomes and Muscle Strength Measurements

The hip and groin outcome score (HAGOS) was used to evaluate PROs for hip function and pain (Thorborg, et al., 2011)(Appendix B). This questionnaire was specifically developed for use in young, physically active individuals. The questionnaire contains 37 questions, answered by the participant, inquiring about hip and groin function in six different domains: pain, symptoms, activities of daily living, activities related to sport or recreation, physical activity, and impacts on overall quality of life. Questions from each domain are scored on a 5-point Likert scale, with 0 indicating no problems and 4 indicating severe limitations. Raw scores are then transformed to a 0-100 scale where 100 represents no hip or groin problems. The HAGOS has both high reliability and criterion validity (Kemp, Collins, Roos, and Crossley, 2013; Thomeé, et al., 2015; Thorborg, et al., 2011; Ramisetty, Kwon, and Mohtadi, 2015).

Muscle strength for the hip flexors, extensors, abductors, adductors, internal, and external rotators were measured using hand-held dynamometry (Microfet 2, Hoggan Scientific, Salt Lake City, UT). All dynamometer tests were performed by one of the authors (LZ) who has extensive experience performing these evaluations. For each muscle group the participant was positioned as shown in Figure 2. Straps securing both the participant and dynamometer were used to improve the reliability of the measurements, as previous studies have reported that using straps for handheld dynamometry results in intraclass correlation coefficients ranging from 0.80 to 0.99 (Katoh, and Yamasaki, 2009; Kim, Kim, Seo, and Kang, 2014; Martins, da Silva, and Bevilaqua-Grossi, 2017). Martins et al. (Martins, et al., 2017) also reported that handheld dynamometry measures recorded using this method strongly correlate (r ranging from 0.69 to 0.91) with gold standard measurements from an isokinetic dynamometer. For all tests, participants were instructed to slowly build pressure against the dynamometer over a three to five second window and then apply maximal effort for three seconds. Three repetitions for each muscle group were performed, with one-minute rest between repetitions. Peak force on each repetition was recorded, normalized to body weight, and the average of the two most valid trials was used for subsequent analysis (Diamond, et al., 2016).

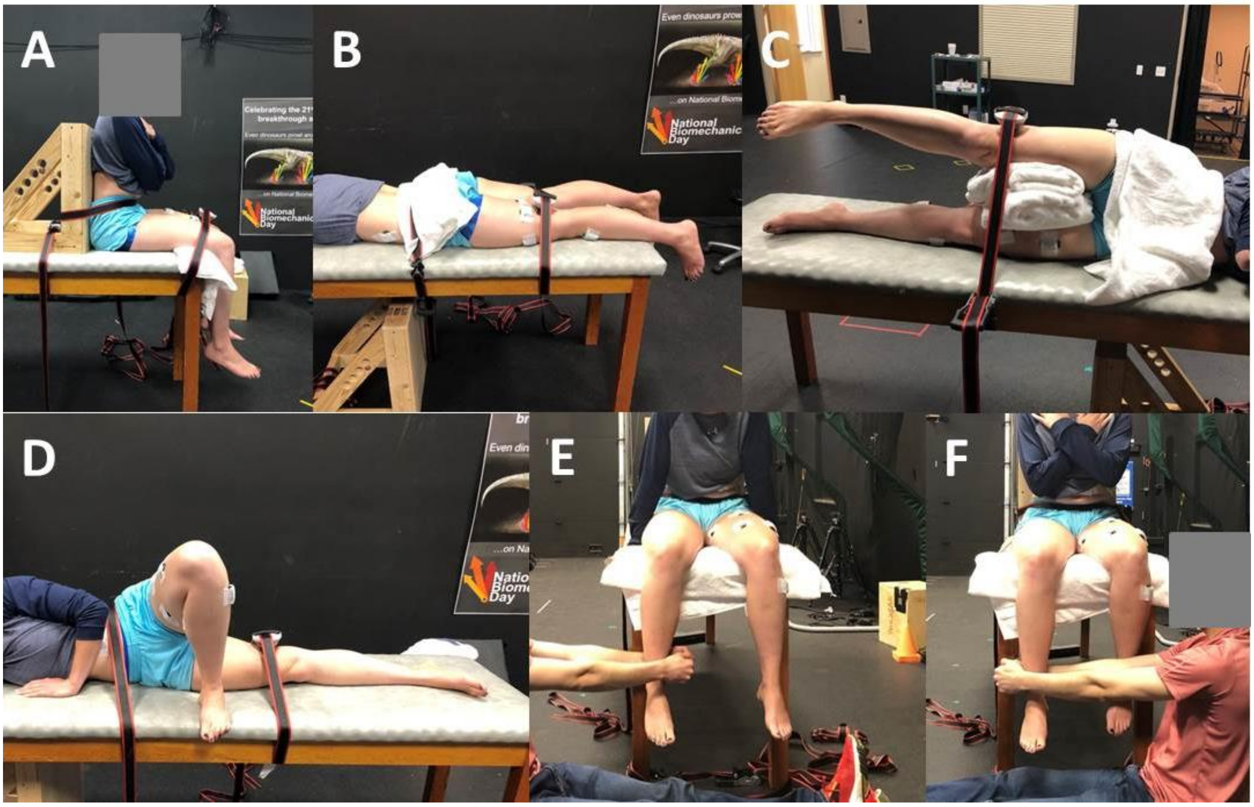

Figure 2: *Patient positioning for the isometric muscle strength tests for hip flexors (A), extensors (B), abductors (C), adductors (D), external rotators (E), and internal rotators (F).*

Motion Analysis

Retroreflective markers were placed bilaterally on specific bony landmarks using a previously described modified Helen Hayes marker set (Chou, Kaufman, Hahn, and Brey, 2003). A static calibration trial was collected with the participant in a standing T-pose position, after which the medial femoral epicondyle and malleoli markers were removed. A stool was adjusted in height so the participant sat with hips and knees both flexed 90° and feet flat on the ground, with knee angle being measured with a goniometer. The participant was instructed to stand up from the stool and walk forward three meters at self-selected pace. Ten STW trials were performed, with one minute of rest between trials. Whole body kinematics were recorded using a 10-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) sampling at 200 Hz. Ground reaction forces were recorded with two force plates (AMTI, Watertown, MA) sampling at 1000 Hz. The stool was positioned just behind the force plates so that it was not on the plates, but the participant could sit with their knees flexed 90° and one foot in the center of each plate.

Marker trajectories and ground reaction forces were exported to Visual 3D (C-Motion, Inc., Rockville, MD) where they were filtered using dual-pass, low pass Butterworth filters with cutoff frequencies of 6 and 15 Hz, respectively. Internal sagittal plane joint moments at the hip, knee, and ankle were calculated using standard Newtonian-Euler inverse dynamics, and with the extensor moments being expressed as positive, were summed to yield the total support moment (Winter, 1980). The following dependent variables were then calculated during the sit-to-stand portion of the STW: peak support moment (pMs), peak hip (pHEM), knee (pKEM), and ankle (pAEM) extensor moments, and the percent contribution from the hip, knee, and ankle to the pMs. This approach was specifically chosen as it allows assessment of the total mechanical demand the lower extremity must overcome in order to prevent limb collapse, and the synergistic nature in which the hip, knee, and ankle joints achieve that goal (Winter, 1980). Initiation and seat-off during the STW were determined using the methods described by Kerr and colleagues (Kerr, Durward, and Kerr, 2004). Full upright standing was identified as the highest point of the center of mass following seat-off.

Data and Statistical Analysis

Differences in muscle strength, peak moments and moment distributions across time points were evaluated using Model Statistics, a statistical approach specifically designed for single subject analyses (Dufek, Bates, Stergiou, and James, 1995a; Bates, 1996). The technique uses a weighting factor which varies depending on the number of trials and desired alpha level. A pooled standard deviation is multiplied by the weighting factor to yield a critical difference. If the difference in means is greater than the critical difference one can be confident that the two measurements or groups are statistically different at the desired alpha level. To minimize the chance of a Type I error an alpha level of $p < .01$ was used. Additionally, effect sizes (***d*,** mean difference divided by average standard deviation) were calculated to aid in interpretation of the results. Effect sizes were interpreted according to Hopkins (2006) with small, medium, and large effects being defined as 0.2 or under, 0.63, and 1.15 or greater, respectively.

RESULTS

Patient Reported Outcomes

HAOGS scores for each domain are shown in Figure 3. At baseline all scores were low, indicative of severe problems in the hip. Marginal improvement occurred by 12WK and by 6MO all domains except sports and recreation and overall quality of life had returned within normal ranges. By 13MO following surgery all scores had reached normative levels, except for physical activity and overall quality of life.

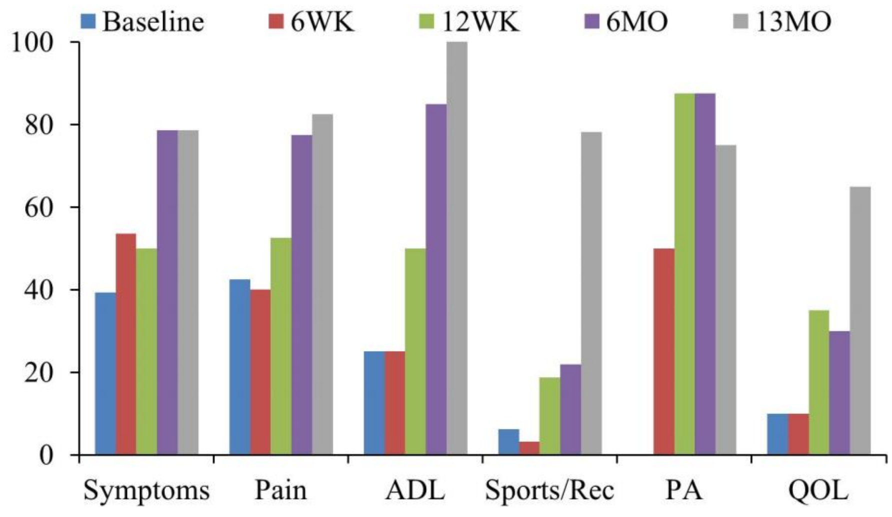

Figure 3: *Normalized HAGOS scores for each of the six domains: symptoms, pain, activities of daily living (ADL), sports and recreations (Sports/Rec), physical activity (PA), and overall quality of life (QOL). Maximum score in each category is 100 points.*

Strength

Mean hip muscle strengths are shown in Figure 4. At baseline the hip adductors in the surgical limb were weaker than the non-surgical limb (***d*** = 5.43). Given limitations placed on the participant following surgery, only the hip flexors and extensors could be collected at the 6WK time point. Both muscle groups were significantly weaker on the surgical leg than the non-surgical leg (***d*** = 1.62 and 21.45, respectively), and were significantly weaker than at baseline (***d*** = 10.43 and 3.42, respectively). At 12WK, hip flexors (***d*** = 7.10), extensors (***d*** = 2.73), abductors, (***d*** = 3.38), adductors (***d*** = 19.96), and external rotators (***d*** = 3.07) were all significantly weaker in the surgical limb than non-surgical limb. By 6MO, only the hip adductors were still weaker on the surgical leg (***d*** = 7.05) and weaker than baseline (***d*** = 3.38). By 13MO there were no differences between limbs or compared to baseline.

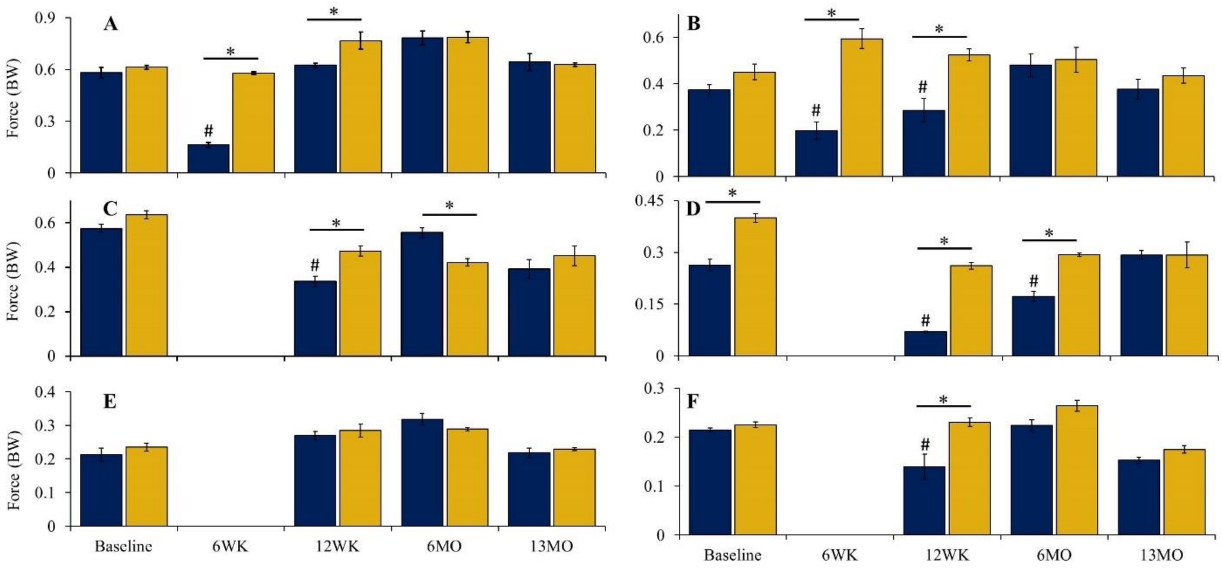

Figure 4: *Mean muscle strength values for the surgical (blue) and non-surgical (gold) limbs for the hip extensors (A), flexors (B), abductors (C), adductors (D), internal rotators (E), and external rotators (F). Due to limitations placed on the participant only flexors and extensors could be collected at the 6WK time point. * indicates a significant difference between limbs at a given time point. # indicates the surgical limb is statistically different than baseline at a given time point. All statistical differences are at the* p < *.01 level.*

Joint Moments and Moment Distributions

Peak joint moments during the sit-to-stand phase of the STW are shown in Figure 5. At baseline, pMs and pHEM were higher on the non-surgical limb than the surgical limb (*d* = 2.76 and 2.66, respectively). By 6WK there were 35.5% and 40.4% increases in pMs (*d* = 8.59) and pHEM (*d* = 5.75) on the non-surgical limb. These were accompanied by 49.9% and 67.2% decreases in pMs (*d* = 3.53) and pHEM (*d* = 7.44) on the surgical limb. Similar effects were observed at the knee, with a 12.6% increase in pKEM (*d* = 2.56) on the non-surgical leg and a 21.3% decrease in pKEM (*d* = 1.87) on the surgical leg.

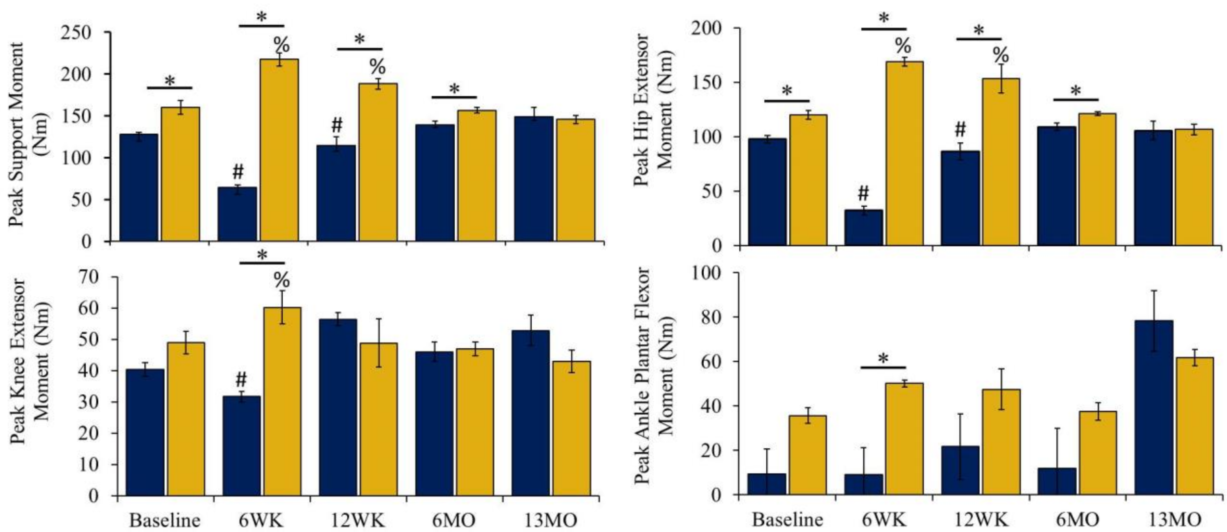

Figure 5: *Peak support moment and hip, knee, and ankle extensor moments for the surgical leg (blue bars) and non-surgical leg (gold bars). * indicates a statistical difference between limbs at a given time point. # and % indicate a statistically significant difference between the time point and baseline for the surgical and non-surgical limbs, respectively. All statistical differences are at the p < .01 level.*

At 12WK, pMs (*d* = 3.89) and pHEM (*d* = 2.85) were still higher on the non-surgical limb than surgical limb, and when compared to baseline values, were still lower on the surgical limb (*d* = 3.11 and 2.82, respectively) and higher on the non-surgical limb (*d* = 1.97 and 2.61, respectively). By 6MO following surgery, pMs and pHEM had returned to baseline values, however they were still higher on the non-surgical limb than the surgical limb (*d* = 2.07 and 2.04, respectively). By 13 MO there were no differences between limbs.

The contribution of each joint to pMs is shown in Figure 6. Despite the higher absolute load on the non-surgical limb, at baseline there were no differences between limbs for the amount the hip, knee, or ankle contributed to pMs. At 6WK there was a large redistribution of load within the surgical limb, with a 34.7% decrease in the percent contribution from the hip (d = 3.22) and a 74.7% increase in the percent contribution from the knee (d = 2.75). However, there were no changes in load distribution within the non-surgical limb. By 12WK these differences began to normalize, however, compared to baseline, on the surgical limb the hip still contributed 17.7% less to pMs (d =2.04) while the knee contributed 58.9% more (d = 2.91). By 6MO there were no differences between limbs for amount the hip, knee, or ankle contributed to pMs, and this remained the case at 13MO.

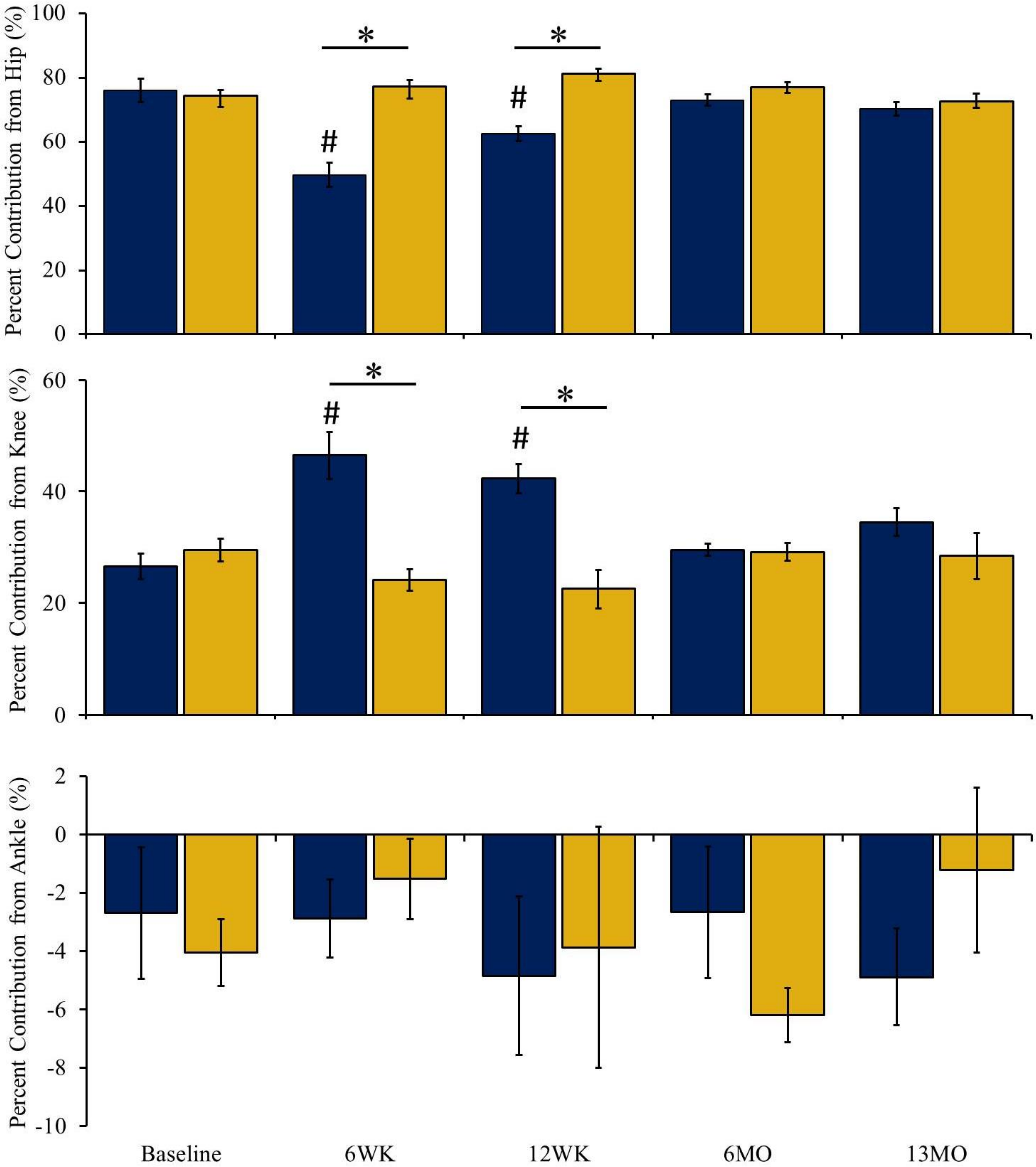

Figure 6: *Percent contributions to peak support moment from the hip, knee, and ankle joints for the surgical (blue bars) and non-surgical (gold bars) limbs. * indicates a significant difference between limbs at a given time point. # indicates the surgical limb is significantly different than baseline at that time point. All statistical differences are at the* p *< .01 level.*

DISCUSSION

This case study describes changes in patient reported outcomes, muscle strength, and joint kinetics during a STW task during the immediate recovery following PAO. To the authors' knowledge, this is both the first study to describe the immediate (within six months) recovery from PAO and the first to assess activities other than walking or running. Our main findings were that in the initial 12WKs following surgery there were large changes in loading between limbs and load distribution within limbs. More specifically, while the non-surgical limb carried more absolute load as evidenced by the higher pMs, the distribution of the load across the hip, knee, and ankle did not change. In contrast, while the surgical limb was off-loaded with lower pMs, the distribution of load within the limb still changed, with smaller contributions from the hip and greater contributions from the knee.

The baseline HAGOS scores for our participant ranged from 0 to 42 which is slightly lower than median values reported in other studies (Jacobsen et al., 2014; Jacobsen et al., 2019) and well below ranges reported for healthy populations (Harris, et al., 207; Thorborg, et al., 2014). However, in both the current study, and in previous studies (Jacobsen et al., 2014; Jacobsen et al., 2019), the preoperative quality of life domain had the lowest score. By 13MO all domains had improved substantially, with the recovery timeline and final values of our participant being consistent with previously reported improvements in HAGOS scores following PAO (Jacobsen et al., 2014; Jacobsen et al., 2019). However, similar to other reports (Jacobsen et al., 2014; Jacobsen et al., 2019), even at the one year mark the lowest two scores were for the physical activity and quality of life domains.

There are several possible explanations for why these domains had the lowest scores. Jacobsen et al.(Jacobsen, et al., 2019) observed there were strong associations between changes in muscle-tendon pain and changes in HAGOS scores. Our participant consistently reported pain and discomfort in the hip musculature which may have resulted in lower quality of life scores. Alternatively, the physical activity and quality of life scores assess patients' perceived ability to participate in preferred physical activities and perceived overall impacts on their quality of life. Prior to undergoing PAO our participant was a competitive collegiate athlete and spent approximately twenty hours per week training, often including heavy weightlifting and deep squatting exercises. After undergoing PAO our participant was medically retired as an athlete and many of their previous training activities were contra-indicated. Thus, while the improved sports and recreation domain score indicate overall improved physical capability, the low physical activity and quality of life domain scores may represent the participants' view on their current physical capabilities compared to what they were capable of previously. Interestingly, a recent article by Jacobsen et al.(2018) reported a mismatch between patient perceptions of physical activity as measured by HAGOS scores and objective accelerometer based measures of physical activity. While patients' perceived physical activity increased, the accelerometer measurements revealed no changes in physical activity before and after PAO. The relationship between patient perceptions of capability, actual amount of activity, and how these interact to influence function and outcomes following PAO, requires further investigation.

One of the suggested benefits of a Bernese PAO is the limited need for removal of the abductor muscles from the ilium, which should result in faster recovery and avoidance of Trendelenburg gait following surgery (Sucato, et al., 2010a). Despite this assertion, there is limited data in the literature documenting how PAO affects muscle strength. Ezoe et al. (2006) reported that prior to surgery patients undergoing a curved PAO displayed weaker hip abductor, adductor, flexor, and extensor muscles than healthy controls. In contrast, the mean strength values for our participant at baseline were within ranges reported for healthy individuals (Katoh, and Yamasaki, 2009; Martins, et al., 2017) and the only difference in strength preoperatively occurred in the adductors, which were weaker in the surgical limb than the non-surgical limb. We also observed that the initial decreases in flexor, extensor, abductor, and external rotator strength all recovered back to baseline values or above by

6MO, with adductor strength taking 13MO to return to baseline levels. In contrast, Sucato et al.(Sucato, et al., 2010a) reported no changes in abductor strength following surgery and that hip flexor strength was still decreased 6MO following surgery, only recovering at the one year mark. Finally, Ezoe et al. (Ezoe, et al., 2006) observed that strength of all muscle groups were lower 6MO following surgery, but recovered to greater than preoperative levels by one year. These differences could be due to the techniques used to assess muscle strength, as the current study used hand held dynamometry while Sucato et al. (Sucato, et al., 2010a) and Ezoe et al. (Ezoe, et al., 2006) used isokinetic dynamometers. The differences might also be due to type of PAO performed, as both the current study and Sucato et al.(Sucato, et al., 2010a) assessed participants who underwent Bernese PAO while Ezoe et al.(Ezoe, et al., 2006) assessed patients who underwent curved PAO. Regardless, the disparate results, combined with the lack of data in the literature, suggest that further studies are needed both regarding strength deficits in patients undergoing PAO, and in the recovery of strength following PAO. Such information would provide important clinical insights into coping prior to surgery and rehabilitation following surgery.

Preoperatively, the participant favored the non-surgical limb during the STW, generating higher pMs on this limb. The higher pMs were largely due to greater pHEM on the non-surgical limb, with trends towards also having higher pKEM and pAEM. Such asymmetry has not been reported with less severe orthopedic conditions such as mild hip osteoarthritis (Eitzen, et al., 2014) or femoroacetabular impingement (Samaan, et al., 2017). However, these conditions can often be managed with non-surgical, conservative approaches (Pisters, et al., 2007; Wall, Fernandez, Griffin, and Foster, 2013). Patients with more severe conditions requiring surgical intervention, such as total hip replacement for advanced osteoarthritis, do demonstrate asymmetric joint moments during sit-to-stand before surgery

(Abujaber, et al., 2015). Thus, the presence or absence of between limb asymmetry during sit-to-stand might be a useful clinical indicator for the progression of hip dysfunction. However, patients who have undergone total hip replacement still demonstrate asymmetric joint loading one year following surgery (Abujaber, et al., 2015; Miura, Tagomori, Ikutomo, and Nakagawa, 2018a). While the participant in the current study demonstrated substantial asymmetries immediately following surgery, they were no longer present by 13MO. This may indicate that by the time a patient is a candidate for PAO, the deficits in hip function are worse than those observed in hip conditions which can be treated non-surgically. However, following PAO patients can regain normal function within a year, something which they cannot do if the whole joint is replaced.

Pre-operatively, despite the higher absolute load on the non-surgical leg, there were no differences between legs in how the hip, knee, and ankle contributed to pMs. Additionally, both the peak joint moments, their profiles across the sit-to-stand, and the distribution of total support moment across the joints were similar to those reported for healthy individuals (Samaan, et al., 2017). Following surgery, despite overall reduced loading in the surgical limb, there was a redistribution of load among the joints, with the hip contributing less to pMs and the knee contributing more. Likely, the increased contribution from the knee was compensation for the surgically repaired hip not being able to contribute to the support moment. Such compensation was theorized by Winter (Winter, 1980) who suggested that disruption to one joint would require additional contributions from other joints in order to prevent limb collapse. Similar compensation has been observed in patients who have undergone total knee replacement, with the hip and ankle contributing more to pMs and the knee contributing less (Mandeville, et al., 2007). Interestingly, in the non-surgical limb, the percent contributions from the hip, knee, and ankle, to pMs did not change despite substantially higher loads on this leg. This suggests our patient adapted to the higher load by distributing the increased demand evenly across the joints, something which was not possible in the surgical limb. Whether this inability to evenly distribute load across the joint is due to the mechanical disruption of the joint in the surgical process or altered neuromuscular control following surgery requires further investigation.

The findings of higher absolute loads on the non-surgical limb and altered load distribution within the surgical limb following PAO have implications for rehabilitation following PAO. Several rehabilitation protocols have been reported in detail (Adler, et al., 2015; Ito, et al., 2014; Tippett, 2006) and, while there is no one standard approach, one common element is progression to partial weight bearing approximately six to eight weeks following surgery. However, none of these rehabilitation plans mention unloading the non-surgical limb or the knee on the surgical limb. Based on our results, it is likely that patients will have substantial asymmetries in loading both between and within limbs up to 12WK following PAO, with larger absolute loading of the non-surgical limb and larger relative loading of the knee in the surgical limb. This may mean the non-surgical limb and surgical limb knee experience increased joint contact forces. If not addressed, such higher forces could have potentially damaging consequences to the articular cartilage within the joint. Such unintended negative outcomes have previously been reported for total hip replacement patients where, due to overloading the non-surgical limb during recovery, there is a higher than normal rate of osteoarthritis in the knee on the non-surgical limb (Umeda, et al., 2009). Given that PAO is typically performed to prolong the onset of osteoarthritis, it would be particularly ironic if the rehabilitation protocol contributes to progression of osteoarthritis in the contralateral joints or ipsilateral knee. This hypothesis requires further investigation in a larger patient population, especially since in the current patient the asymmetric loading normalized by one year. Whether such a short duration of altered loading could increase the progression of osteoarthritis is unknown. However, the participant did report pain in both the contralateral hip and ipsilateral knee during the rehabilitation process and were subsequently scheduled to undergo PAO on the contralateral hip.

We recommend clinicians carefully consider, and potentially take steps to address this altered loading when planning rehabilitation following PAO. This could be achieved by using technologies such as force plates or pressure mats to provide real-time biofeedback when performing bilateral exercises. Such tools are rapidly becoming more available in clinical settings and could ensure exercises are performed with symmetric limb loading. Similarly, exercises could be done with reduced overall bodyweight using various types of assistance devices such as harnesses or positive pressure treadmills. While this may not reduce the asymmetry between limbs, it could reduce the overloading of the non-surgical limb. Finally, once the patient has progressed sufficiently, rehabilitation could focus on single limb exercises which would require similar levels of weight borne on each leg. These are only two examples, and clinicians could likely develop additional strategies to monitor loading asymmetry. However, whether doing so improves biomechanics and functional outcomes following PAO requires further investigation.

There are a few limitations which should be considered when interpreting the results of this case study. First, and foremost is that this is a single subject research study, and thus the differences we observed might not be generalizable to other PAO patients. Additionally, we cannot determine the influence, if any, of our participants' history of three previous hip surgeries on the same hip. While it has been shown that clinical outcomes do not differ between patients undergoing PAO with and without previous hip surgery (Kain, et al., 2011; De La Rocha, Sucato, Tulchin, and Podeszwa, 2012), it is unknown whether a history of previous surgery influences biomechanical function. Second, prior to PAO, the participant was a high-level athlete with access to intensive physical therapy. Whether similar improvements would occur, or occur over the same timelines, in individuals without a high training background or similar access to care is not known. From a methodological stand point, we did not consider the effect of different torso positions or speed of movement during sit-to-stand on the resulting joint moments. Both factors could influence lower extremity joint moments, and thus could be used as covariates in statistical analyses. However, the model statistics method used in the current study does not allow for such covariates. Visibly there did not appear to be differences in torso positioning or speed of performance across time points, however we cannot completely rule this out.

In summary, this case documented the immediate recovery of HAGOS domains, muscle strength, and lower extremity function during sit-to-walk movement in a patient who underwent PAO. HAGOS scores return to normative ranges within a year following PAO, however, there were lingering effects on overall quality of life. Most strength measures returned to preoperative levels within 6MO following surgery. Finally, there was a large shift in load to the non-surgical limb and a redistribution of load within the surgical limb, both of which normalized by one year following surgery. This is just a single case and further investigation is required to determine whether similar changes are observed in larger patient populations. If so, then rehabilitation plans following PAO should consider these altered loading environments. Further investigations are also necessary to document biomechanics following PAO in other activities of daily living, as well as assess whether accounting for altered loading during rehabilitation improves long term outcomes.

Acknowledgements
The authors would like to acknowledge William Goodman, Christopher Casillas, and Allison Hoffee for their assistance in data collection, and to acknowledge the University of Utah Medical Center where the surgery was performed for sharing medical reports and radiographic images.

Conflicts of Interest
The authors have no financial disclosures or conflicts of interest to report.

References

Abujaber SB, Marmon AR, Pozzi F, Rubano JJ, Zeni JA 2015 Sit-To-Stand Biomechanics Before and After Total Hip Arthroplasty. Journal of Arthroplasty 30: 2027–2033.

Adler KL, Cook PC, Frcs C, Geisler PR, Yen Y, Giordano BD 2015 Current Concepts in Hip Preservation Surgery : Part II — Rehabilitation. Sports Health: A Multidisciplinary Approach 8: 57–64.

Adler KL, Cook PC, Geisler PR, Yen YM, Giordano BD 2016 Current Concepts in Hip Preservation Surgery: Part II—Rehabilitation. Sports Health 8: 57–64.

Andriacchi T, Andersson G, Fermier R, Stern D, Galante J 1980 A study of lower-limb mechanics during stair-climbing. The Journal of Bone and Joint Surgery 62: 749–757.

Armand M, Lepistö J, Tallroth K, Elias J, Chao E 2005 Outcome of periacetabular osteotomy: Joint contact pressure calculation using standing AP radiographs, 12 patients followed for average 2 years. Acta Orthopaedica 76: 303–313.

Bates BT 1996 Single-subject methodology: an alternative approach. Medicine and Science in Sports and Exercise 28: 631–638.

Behrens P, Bitter T, Kurz B, Russlies M 2006 Matrix-associated autologous chondrocyte transplantation/implantation (MACT/MACI)-5-year follow-up. Knee 13: 194–202.

Beltran LS, Rosenberg ZS, Mayo JD, De Tuesta MD, Martin O, Neto LP, Bencardino JT 2013 Imaging evaluation of developmental hip dysplasia in the young adult. American Journal of Roentgenology 200: 1077–1088.

Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, Duda GN 2001 Hip contact forces and gait patterns from routine activities. Journal of Biomechanics 34: 859–871.

Bohannon RW 1997 Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. Age and Ageing 26: 15–19.

Boje J, Caspersen CK, Jakobsen SS, Søballe K, Mechlenburg I 2019 Are changes in pain associated with changes in quality of life and hip function 2 years after periacetabular osteotomy? A follow-up study of 321 patients. Journal of Hip Preservation Surgery 6: 69–76.

Cady RB 2006 Developmental dysplasia of the hip: Definition, recognition, and prevention of late sequelae. Pediatric Annals 35: 92–101.

Carpes FP, Mota CB, Faria IE 2010 On the bilateral asymmetry during running and cycling - A review considering leg preference. Physical Therapy in Sport 11: 136–142.

Chan A, McCaul KA, Cundy PJ, Haan EA, Byron-Scott R 1997 Perinatal risk factors for developmental dysplasia of the hip. Archives of Disease in Childhood: Fetal and Neonatal Edition 76: 94–100.

Choi S 2015 Total hip arthroplasty. Decision-Making in Orthopedic and Regional Anesthesiology: A Case-Based Approach 95–100.

Chou LS, Kaufman KR, Hahn ME, Brey RH 2003 Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. Gait and Posture 18: 125–133.

Clohisy JC, Barrett SE, Gordon JE, Delgado ED, Schoenecker PL 2005 Periacetabular osteotomy for the treatment of severe acetabular dysplasia. Journal of Bone and Joint Surgery - Series A 87: 254–259.

Clohisy JC, Dobson MA, Robison JF, Warth LC, Zheng J, Liu SS, Yehyawi TM, Callaghan JJ 2011 Radiographic structural abnormalities associated with premature, natural hip-joint

failure. Journal of Bone and Joint Surgery - Series A 93: 3–9.
Clohisy JC, Schutz AL, St L, Bs J, Schoenecker PL, Wright RW 2009 A Systematic Literature Review. 2041–2052.
Coobs BR, Xiong A, Clohisy JC 2015 Contemporary Concepts in the Young Adult Hip Patient: Periacetabular Osteotomy for Hip Dysplasia. Journal of Arthroplasty 30: 1105–1108.
Cross M, Smith E, Hoy D, Nolte S, Ackerman I, Fransen M, Bridgett L, Williams S, Guillemin F, Hill CL, Laslett LL, Jones G, Cicuttini F, Osborne R, Vos T, Buchbinder R, Woolf A, March L 2014 The global burden of hip and knee osteoarthritis: Estimates from the Global Burden of Disease 2010 study. Annals of the Rheumatic Diseases 73: 1323–1330.
Crowe J, Mani V, Ranawat C 1979 Total hip replacement in congenital dislocation and dysplasia of the hip. The Journal of Bone and Joint Surgery 61: 15–23.
Daggfeldt K, Thorstensson A 2003 The mechanics of back-extensor torque production about the lumbar spine. Journal of Biomechanics 36: 815–825.
Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, Guendelman E, Thelen DG 2007 OpenSim: Open-source software to create and analyze dynamic simulations of movement. IEEE Transactions on Biomedical Engineering 54: 1940–1950.
Diamond LE, Wrigley T V., Hinman RS, Hodges PW, O'Donnell J, Takla A, Bennell KL 2016 Isometric and isokinetic hip strength and agonist/antagonist ratios in symptomatic femoroacetabular impingement. Journal of Science and Medicine in Sport 19: 696–701.
Domb BG, Stake CE, Finch NA, Cramer TL 2014 Return to sport after hip arthroscopy: Aggregate recommendations from high-volume hip arthroscopy centers. Orthopedics 37: e902–e905.
Dufek J, Bates B, Stergiou N, James CR 1995a Interactive effects between group and single subject response patterns. Human Movement Science 14: 301–323.
Dufek JS, Bates BT, Stergiou N, James CR 1995b Interactive effects between group and single-subject response patterns. Human Movement Science 14: 301–323.
Eitzen I, Fernandes L, Nordsletten L, Snyder-mackler L, Arna M 2014 Gait & Posture Weight-bearing asymmetries during Sit-To-Stand in patients with mild-to-moderate hip osteoarthritis. Gait & Posture 39: 683–688.
Ezoe M, Naito M, Asayama I 2006 Muscle Strength Improves after Abductor-sparing. Clinical Orthopaedics and Related Research 444: 161–168.
Gahramanov A, İnanıcı F, Çağlar Ö, Aksoy C, Tokgözoğlu AM, Güner S, Baki A, Atilla B 2017 Functional results in periacetabular osteotomy: Is it possible to obtain a normal gait after the surgery? HIP International 27: 449–454.
Gala L, Clohisy JC, BeauĺE PE 2016 Hip dysplasia in the young adult. Journal of Bone and Joint Surgery - American Volume 98: 63–73.
Ganz R, Klaue K, Son Vinh T, Mast J 1988a A New Periacetabular Osteotomy for the Treatment of Hip Dysplasias: Technique and Preliminary Results. Clinical Orthopaedics and Related Research 232: 26–36.
Ganz R, Klaue K, Vinh TS, Mast JW 1988b A New Periacetabular Osteotomy for the Treatment of Hip Dysplasias. Clinical Orthopaedics and Related Research 232: 26–36.
Givens-Heiss DL, Krebs DE, Riley PO, Strickland EM, Fares M, Hodge WA, Mann RW, Oatis CA 1992 In vivo acetabular contact pressures during rehabilitation, Part II: Postacute phase. Physical Therapy 72: 700–710.
Graham DF, Carty CP, Lloyd DG, Lichtwark GA, Barrett RS 2014 Muscle contributions to recovery from forward loss of balance by stepping. Journal of Biomechanics 47: 667–

674.
Grant AD, Sala DA, Davidovitch RI 2012 The labrum: Structure, function, and injury with femoro-acetabular impingement. Journal of Children's Orthopaedics 6: 357–372.
Hamner SR, Seth A, Delp SL 2010 Muscle contributions to propulsion and support during running. Journal of Biomechanics 43: 2709–2716.
Hansen W, Shim VB, Obst S, Lloyd DG, Newsham-West R, Barrett RS 2017 Achilles tendon stress is more sensitive to subject-specific geometry than subject-specific material properties: A finite element analysis. Journal of Biomechanics 56: 26–31.
Harrington ME, Zavatsky AB, Lawson SEM, Yuan Z, Theologis TN 2007 Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging. Journal of Biomechanics 40: 595–602.
Harris JD, Mitchell RJ, Qadeer A, Gerrie BJ, Mcculloch PC 2017 Patient Reported Outcomes and Symptomatic Impingement in US Women's Professional Soccer. The Orthopaedic Journal of Sports Medicine 5: 1.
Hartofilakidis G, Karachalios T, Stamos KG 2000 Epidemiology, Demographics, and Natural History of Congenital Hip Disease in Adults. Orthopedics 23: 823–827.
Henak CR, Abraham CL, Anderson AE, Maas SA, Ellis BJ, Peters CL, Weiss JA 2014 Patient-specific analysis of cartilage and labrum mechanics in human hips with acetabular dysplasia. Osteoarthritis and Cartilage 22: 210–217.
Hopkins W 2006
Inman VT 1947 Functional Aspects of the Abductor Muscles of the Hip. The Journal of Bone and Joint Surgery 29: 607–619.
Ito H, Tanino H, Sato T, Nishida Y, Matsuno T 2014 Early weight-bearing after periacetabular osteotomy leads to a high incidence of postoperative pelvic fractures. BMC Musculoskeletal Disorders 15: 1–7.
Jacobs C, Uhl TL, Seeley M, Sterling W, Goodrich L 2005 Strength and fatigability of the dominant and nondominant hip abductors. Journal of Athletic Training 40: 203–206.
Jacobsen JS, Nielsen DB, Sørensen H, Søballe K, Mechlenburg I 2014 Joint kinematics and kinetics during walking and running in 32 patients with hip dysplasia 1 year after periacetabular osteotomy. Acta Orthopaedica 85: 592–599.
Jacobsen JS, Søballe K, Thorborg K, Bolvig L, Jakobsen S, Hölmich P, Mechlenburg I, Jacobsen JS, Søballe K, Thorborg K, Bolvig L 2019 Patient-reported outcome and muscle – tendon pain after periacetabular osteotomy are related : 1- year follow-up in 82 patients with hip dysplasia Patient-reported outcome and muscle – tendon pain after periacetabular osteotomy are related : 1-year follow. Acta Orthopaedica 90: 40–45.
Jacobsen JS, Thorborg K, Hölmich P, Bolvig L, Storgaard Jakobsen S, Søballe K, Mechlenburg I 2018 Does the physical activity profile change in patients with hip dysplasia from before to 1 year after periacetabular osteotomy? Acta Orthopaedica 89: 622–627.
Jacobsen S, Sonne-Holm S 2005a Hip dysplasia: A significant risk factor for the development of hip osteoarthritis. A cross-sectional survey. Rheumatology 44: 211–218.
Jacobsen S, Sonne-Holm S 2005b Hip dysplasia: A significant risk factor for the development of hip osteoarthritis. A cross-sectional survey. Rheumatology 44: 211–218.
Kain M, Novais E, Vallim C, Millis M, Kim Y 2011 Periacetabular Osteotomy After Failed Hip Arthroscopy for Labral Tears in Patients with Acetabular Dysplasia. Journal of Bone and Joint Surgery American 93: 57–61.
Kaku N, Tsumura H, Taira H, Sawatari T, Torisu T 2004 Biomechanical study of load transfer of the pubic ramus due to pelvic inclination after hip joint surgery using a three-

dimensional finite element model. Journal of Orthopaedic Science 9: 264–269.
Karam M, Gao Y, McKinley T 2011a Assessment of Walking Pattern Pre and Post Periacetabular Osteotomy. The Iowa orthopaedic journal 31: 83–89.
Karam MD, Gao Y, McKinley T 2011b Assessment of walking pattern pre and post peri-acetabular osteotomy. The Iowa orthopaedic journal 31: 83–89.
Katoh M, Yamasaki H 2009 Comparison of reliability of isometric leg muscle strength measurements made using a Hand-Held dynamometer with and without a restraining Belt. Journal of Physical Therapy Science 21: 37–42.
Kemp JL, Collins NJ, Roos EM, Crossley KM 2013 Psychometric properties of patient-reported outcome measures for hip arthroscopic surgery. American Journal of Sports Medicine 41: 2065–2073.
Kerr A, Durward B, Kerr KM 2004 Defining phases for the sit-to-walk movement. Clinical Biomechanics 19: 385–390.
Kim CH, Kim JW 2020 Periacetabular osteotomy vs. total hip arthroplasty in young active patients with dysplastic hip: Systematic review and meta-analysis. Orthopaedics and Traumatology: Surgery and Research 106: 1545–1551.
Kim WK, Kim DK, Seo KM, Kang SH 2014 Reliability and validity of isometric knee extensor strength test with hand-held dynamometer depending on its fixation: A pilot study. Annals of Rehabilitation Medicine 38: 84–93.
Klit J, Hartig-Andreasen C, Jacobsen S, Søballe K, Troelsen A 2014 Periacetabular osteotomy: Sporting, social and sexual activity 9-12 years post surgery. HIP International 24: 27–31.
Kraeutler MJ, Garabekyan T, Pascual-Garrido C, Mei-Dan O 2016 Hip instability: A review of hip dysplasia and other contributing factors. Muscles, Ligaments and Tendons Journal 6: 343–353.
Kralj M, Mavčič B, Antolič V, Iglič A, Kralj-Iglič V 2005 The Bernese periacetabular osteotomy: Clinical, radiographic and mechanical 7-15-year follow-up of 26 hips. Acta Orthopaedica 76: 833–840.
De La Rocha A, Sucato D, Tulchin K, Podeszwa DA 2012 Treatment of Adolescents with a Periacetabular Osteotomy After Previous Pelvic Surgery. Clinical Orthopaedics 470: 2583–2590.
Larsen JB, Mechlenburg I, Jakobsen SS, Thilleman TM, Søballe K 2020 14-Year Hip Survivorship After Periacetabular Osteotomy: a Follow-Up Study on 1,385 Hips. Acta Orthopaedica 91: 299–305.
Lee KJ, Park SJ, Lee SJ, Naito M, Kwon SY 2015 Biomechanical study on the efficacy of the periacetabular osteotomy using Patient-specific finite element analysis. International Journal of Precision Engineering and Manufacturing 16: 823–829.
Leunig M, Ganz R 2007a (iii) Bernese periacetabular osteotomy. Current Orthopaedics 21: 100–108.
Leunig M, Ganz R 2007b Bernese periacetabular osteotomy. Current Orthopaedics 21: 100–108.
Leunig M, Siebenrock KA, Ganz R 2001 Rationale of periacetabular osteotomy and background work. Journal of Bone and Joint Surgery 83A: 438–448.
Lu TW, O’Connor JJ 1999 Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. Journal of Biomechanics 32: 129–134.
Mandeville D, Osternig LR, Chou LS 2007 The effect of total knee replacement on dynamic support of the body during walking and stair ascent. Clinical Biomechanics 22: 787–794.
Martins J, da Silva JR, da Silva; MRB, Bevilaqua-Grossi D 2017 Reliability and Validity of

the Belt-Stabilized Handheld Dynamometer in Hip- and Knee-Strength Tests. Journal of Athletic Training 52: 809–819.

Matheney T, Kim Y, Zurakowski D, Matero C, Millis M 2009 Intermediate to Long-Term Results Following the Bernese Periacetabular Osteotomy and Predictors of Clinical Outcome. 2113–2123.

Matta J, Stover M, Siebenrock K 1999 Periacetabular osteotomy through the Smith-Petersen approach. Clinical Orthopaedics and Related Research 21–32.

McCrory JL, White SC, Lifeso RM 2001 Vertical ground reaction forces: Objective measures of gait following hip arthroplasty. Gait and Posture 14: 104–109.

Michaeli DA, Murphy SB, Hipp JA 1997 Comparison of predicted and measured contact pressures in normal and dysplastic hips. Medical Engineering and Physics 19: 180–186.

Millis MB, Murphy SB, Poss R 1995 Osteotomis about the hip for the prevention and treatment of osteoarthrosis. Journal of Bone and Joint Surgery American 77: 626–647.

Miura N, Tagomori K, Ikutomo H, Nakagawa N 2018a Asymmetrical loading during sit-to-stand movement in patients 1 year after total hip arthroplasty. Clinical Biomechanics 57: 89–92.

Miura N, Tagomori K, Ikutomo H, Nakagawa N, Masuhara K 2018b Asymmetrical loading during sit-to-stand movement in patients 1 year after total hip arthroplasty. Clinical Biomechanics 57: 89–92.

Mizner RL, Snyder-Mackler L 2005 Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. Journal of Orthopaedic Research 23: 1083–1090.

Moore KL, Dalley AF, Agur AMR 2014 Clinically Oriented Anatomy. Baltimore: Lippincott Williams & Wilkins.

Murphy RJ, Armiger RS, Lepistö J, Mears SC, Taylor RH, Armand M 2015 Development of a biomechanical guidance system for periacetabular osteotomy. International Journal of Computer Assisted Radiology and Surgery 10: 497–508.

Murphy S, Deshmukh R 2002a Periacetabular Osteotomy. 168–174.

Murphy SB, Deshmukh R 2002b Periacetabular Osteotomy: Preoperative Radiographic Predictors of Outcome. Clinical Orthopaedics and Related Research 405: 168–174.

Murphy SB, Ganz R, Muller ME 1995 The Prognosis in Untreated Dysplagia of the Hip. The Journal of bone and joint surgery British volume 77: 985–989.

Nadeau S, McFadyen BJ, Malouin F 2003 Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: What are the challenges compared to level walking? Clinical Biomechanics 18: 950–959.

Nawabi DH, Degen RM, Fields KG, McLawhorn A, Ranawat AS, Sink EL, Kelly BT 2016 Outcomes after Arthroscopic Treatment of Femoroacetabular Impingement for Patients with Borderline Hip Dysplasia. American Journal of Sports Medicine 44: 1017–1023.

Niknafs N, Murphy RJ, Armiger RS, Lepistö J, Armand M 2013 Biomechanical Factors in Planning of Periacetabular Osteotomy. Frontiers in Bioengineering and Biotechnology 1: .

Nishimura M, Takahira N, Fukushima K, Yamamoto T, Moriya M, Uchiyama K 2015 Early gait analysis after curved periacetabular osteotomy for acetabular dysplasia. Orthopedic Research and Reviews 25.

Nishino T, Ishii T, Chang F, Yanai T, Watanabe A, Ogawa T, Mishima H, Nakai K, Ochiai N 2010 Effect of gradual weight-bearing on regenerated articular cartilage after joint distraction and motion in a rabbit model. Journal of Orthopaedic Research 28: 600–606.

Pedersen ENG, Alkjær T, Søballe K, Simonsen EB 2006 Walking pattern in 9 women with

hip dysplasia 18 months after periacetabular osteotomy. Acta Orthopaedica 77: 203–208.
Peters CL, Erickson JA, Anderson MB, Anderson LA 2015 Preservation of the Rectus Femoris Origin During Periacetabular Osteotomy Does Not Compromise Acetabular Reorientation. Clinical Orthopaedics and Related Research 473: 608–614.
Pisters MF, Veenhof C, Meeteren NLUVAN, Ostelo RW, Bakker DHDE, Schellevis OISG, Dekker J 2007 Long-Term Effectiveness of Exercise Therapy in Patients With Osteoarthritis of the Hip or Knee : A Systematic Review. Arthritis and Rheumatism 57: 1245–1253.
Pizzolato C, Reggiani M, Saxby DJ, Ceseracciu E, Modenese L, Lloyd DG 2017 Biofeedback for Gait Retraining Based on Real-Time Estimation of Tibiofemoral Joint Contact Forces. IEEE Transactions on Neural Systems and Rehabilitation Engineering 25: 1612–1621.
Ramisetty N, Kwon Y, Mohtadi N 2015 Patient-reported outcome measures for hip preservation surgery--a systematic review of the literature. Journal of Hip Preservation Surgery 2: 15–27.
Reijman M, Hazes JMW, Pols HAP, Koes BW, Bierma-Zeinstra SMA 2005a Acetabular dysplasia predicts incident osteoarthritis of the hip: The Rotterdam study. Arthritis and Rheumatism 52: 787–793.
Reijman M, Hazes JMW, Pols HAP, Koes BW, Bierma-Zeinstra SMA 2005b Acetabular dysplasia predicts incident osteoarthritis of the hip: The Rotterdam study. Arthritis and Rheumatism 52: 787–793.
Samaan MA, Schwaiger BJ, Gallo MC, Link TM, Zhang AL, Majumdar S, Souza RB 2017 Abnormal Joint Moment Distributions and Functional Performance During Sit-to-Stand in Femoroacetabular Impingement Patients. PM and R 9: 563–570.
Schroeder C, Zavala L, Opstedal L, Becker J 2020 Recovery of Lower Extremity Function in the Initial Year Following Periacetabular Osteotomy: A Single Subject Analysis. Physiotherapy Theory and Practice 00: 1–12.
Schwachmeyer V, Damm P, Bender A, Dymke J, Graichen F, Bergmann G 2013 In Vivo Hip Joint Loading during Post-Operative Physiotherapeutic Exercises. PLoS ONE 8: e77807.
Siebenrock KA, Leunig M, Ganz R 2001a Periacetabular osteotomy: the Bernese experience. Instructional course lectures 50: 239–245.
Siebenrock KA, Leunig M, Ganz R 2001b Periacetabular osteotomy: The Bernese experience. Journal of Bone and Joint Surgery - Series A 83: 449–455.
Sophia Fox AJ, Bedi A, Rodeo SA 2009 The basic science of articular cartilage: Structure, composition, and function. Sports Health 1: 461–468.
Steel HH 1973 Triple Osteotomy of the Innominate Bone. The Journal of Bone and Joint Surgery 55: 343–350.
Steppacher SD, Tannast M, Ganz R, Siebenrock KA 2008 Mean 20-year followup of bernese periacetabular osteotomy. Clinical Orthopaedics and Related Research 466: 1633–1644.
Stulberg S 1975 Unrecognized childhood hip disease: a major cause of idiopathic osteoarthritis of the hip. In: Cordell LD, Harris WH, Ramsey PL, MacEwen GD (eds). Proceedings of the Third Open Scientific Meeting of the Hip Society. St Louis, MO: Mosby 212–228.
Stulberg S, Harris W 1974 Acetabular dysplasia and development of osteoarthritis of hip. In: Harris WH (ed.). The Hip. Proceedings of the Second Open Scientific Meeting of the Hip Society. St Louis, MO: Mosby 82–93.
Sucato D, Tulchin K, Shrader M, DeLaRocha A, Gist T, Sheu G 2010a Gait, hip strength and functional outcomes after a ganz periacetabular osteotomy for adolescent hip dysplasia.

Journal of Pediatric Orthopaedics 30: 344–350.
Sucato DJ, Tulchin K, Shrader MW, Delarocha A, Gist T, Sheu G 2010b Gait , Hip Strength and Functional Outcomes After a Ganz Periacetabular Osteotomy for Adolescent Hip Dysplasia. 30: 344–350.
The United States Bone and Joint Inititative 2020 United States Bone and Joint Initiative: The Burden of Musculoskeletal Diseases in the United States (BMUS). Rosemont, IL:
Thomas-Aitken HD, Willey MC, Goetz JE 2018 Joint contact stresses calculated for acetabular dysplasia patients using discrete element analysis are significantly influenced by the applied gait pattern. Journal of Biomechanics 79: 45–53.
Thomeé R, Jonasson P, Thorborg K, Sansone M, Ahlden M, Thomeé C, Karlsson J, Baranto A 2015 Validation of the Copenhagen hip groin outcome score (HAGOS) for pain, symptoms and physical function in patients with hip/groin disability. Physiotherapy 101: e1514–e1515.
Thorborg K, Branci S, Stensbirk F, Jensen J, Holmich P 2014 Copenhagen hip and groin outcome scores (HAGOS) in male soccer: reference values for hip and groin injury free players. British Journal of Sports Medicine 48: 557–559.
Thorborg K, Hölmich P, Christensen R, Petersen J, Roos EM 2011 The Copenhagen Hip and Groin Outcome Score (HAGOS): Development and validation according to the COSMIN checklist. British Journal of Sports Medicine 45: 478–491.
Thorborg K, Tijssen M, Habets B, Bartels EM, Roos EM, Kemp J, Crossley KM, Hölmich P 2015 Patient-Reported Outcome (PRO) questionnaires for young to middle-aged adults with hip and groin disability: A systematic review of the clinimetric evidence. British Journal of Sports Medicine 49: 812.
Tippett S 2006a Returning to Sports After Periacetabular Osteotomy for Developmental Dysplasia of the Hip. North American Journal of Sports Physical Therapy 1: .
Tippett SR 2006b Returning to sports after periacetabular osteotomy for developmental dysplasia of the hip. North American journal of sports physical therapy : NAJSPT 1: 32–9.
Tonnis D 1990 Surgical treatment of congenital dislocation of the hip. Clinical Orthopaedics and Related Research 258: 33–40.
Torio C, Moore B 2016 Statistical Brief #204. National Inpatient Hospital Costs: The Most Expensive Conditions by Payer, 2013. Rockville, MD: Agency for Healthcare Research and Quality .
Trousdale RT, Cabanela ME 2003 Lessons learned after more than 250 periacetabular osteotomies. Acta Orthopaedica Scandinavica 74: 119–126.
Umeda N, Miki H, Ishii T, Yoshikawa H, Sugano N 2009 Progression of osteoarthritis of the knee after unilateral total hip arthroplast: a minimum 10-year follow up study. Archives of Orthopaedic and Trauma Surgery 129: 149–154.
Vanwanseele B, Lucchinetti E, Stüssi E 2002 The effects of immobilization on the characteristics of articular cartilage: Current concepts and future directions. Osteoarthritis and Cartilage 10: 408–419.
Wall PDH, Fernandez M, Griffin DR, Foster NE 2013 Nonoperative Treatment for Femoroacetabular Impingement: A Systematic Review of the Literature. PM and R 5: 418–426.
Wedge JH, Wasylenko MJ 1979 The natural history of congenital disease of the hip. Journal of Bone and Joint Surgery - Series B 61: 334–338.
Weinstein S 1987 Natural history of congenital hip dislocation (CDH) and hip dysplasia. Clinical Orthopaedics and Related Research 62–76.

Wesseling M, Meyer C, Corten K, Desloovere K, Jonkers I 2018 Longitudinal joint loading in patients before and up to one year after unilateral total hip arthroplasty. Gait and Posture 61: 117–124.

White SC, Lifeso RM 2005 Altering asymmetric limb loading after hip arthroplasty using real-time dynamic feedback when walking. Archives of Physical Medicine and Rehabilitation 86: 1958–1963.

Wiberg G 1939 Studies on dysplastic acetabula and congenital subluxation of the hip joint: with special reference to the complication of osteoarthritis. Acta Chirurgica Scandinavica 83: 5–135.

Wilk KE, Reinold MM, Hooks TR 2003 Recent advances in the rehabilitation of isolated and combined anterior cruciate ligament injuries. Orthopedic Clinics 34: P107-137.

Willy RW, Scholz JP, Davis IS 2012 Mirror gait retraining for the treatment of patellofemoral pain in female runners. Clinical Biomechanics 27: 1045–1051.

Winter DA 1980 Overall Principle of Lower Limb Spport During Stance Phase of Gait.pdf.crdownload. Journal of Biomechanics 13: 923–927.

Wong LCY, Chiu WK, Russ M, Liew S 2012 Review of techniques for monitoring the healing fracture of bones for implementation in an internally fixated pelvis. Medical Engineering and Physics 34: 140–152.

Wyles CC, Heidenreich MJ, Jeng J, Larson DR, Trousdale RT, Sierra RJ 2017 The John Charnley Award: Redefining the Natural History of Osteoarthritis in Patients With Hip Dysplasia and Impingement. Clinical Orthopaedics and Related Research 475: 336–350.

Yasunaga Y, Yamasaki T, Ochi M 2012 Patient selection criteria for periacetabular osteotomy or rotational acetabular osteotomy. Clinical Orthopaedics and Related Research 470: 3342–3354.

Yeung M, Kowalczuk M, Simunovic N, Ayeni OR 2016 Hip arthroscopy in the setting of hip dysplasia: A systematic review. Bone and Joint Research 5: 225–231.

Youdas JW, Kotajarvi BJ, Padgett DJ, Kaufman KR 2005 Partial weight-bearing gait using conventional assistive devices. Archives of Physical Medicine and Rehabilitation 86: 394–398.

Zhao X, Chosa E, Totoribe K, Deng G 2010 Effect of periacetabular osteotomy for acetabular dysplasia clarified by three-dimensional finite element analysis. Journal of Orthopaedic Science 15: 632–640.

Zou Z, Chávez-Arreola A, Mandal P, Board TN, Alonso-Rasgado T 2013 Optimization of the position of the acetabulum in a ganz periacetabular osteotomy by finite element analysis. Journal of Orthopaedic Research 31: 472–479.

CHAPTER FOUR

RECOVERY OF LOWER EXTREMITY FUNCTION IN THE INITIAL YEAR FOLLOWING PERIACETABULAR OSTEOTOMY: A SINGLE SUBJECT ANALYSIS

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

Author: Cailyn Schroeder, RD, LN

Contributions: Primary investigator and developer of study methodology. Primary processor and analyzer of study data. Author of manuscript.

Co-Author: Laura Opstedal, PT, DPT

Contributions: Provided clinical input for study methodology. Reviewed study design, results, analysis, and final manuscript.

Co-Author: David Graham, PhD

Contributions: Assisted with data analysis and development of conclusions and final manuscript. Provided recommendations for changes to aspects of data analysis and final manuscript.

Co-Author: James Becker, PhD

Contributions: Assisted with development of study methodology, data analysis, and development of conclusions and final manuscript. Provided recommendations for changes to all aspects of study from design to final manuscript.

Manuscript Information

Cailyn Schroeder, RD, LN, Laura Opstedal, DPT, David Graham, PhD, James Becker, PhD

Physiotherapy Theory and Practice

Status of Manuscript:
_X_ Prepared for submission to a peer-reviewed journal
____ Officially submitted to a peer-reviewed journal
____ Accepted by a peer-reviewed journal
____ Published in a peer-reviewed journal

Taylor and Francis Group, LLC

Return of Gait Symmetry Following Real-time Biofeedback Gait Retraining in Periacetabular Osteotomy: A Single Subject Analysis

Cailyn Schroeder, BS[1], Laura Opstedal, DPT[2], David Graham, PhD[1], James Becker, PhD[1]

[1]Department of Health and Human Development, Montana State University, Bozeman, MT, USA

[2]Build Physio & Performance, Bozeman, MT, USA

Corresponding Author
Dr. James Becker
Department of Health and Human Development
219 Herrick Hall
Montana State University,
Bozeman, MT 59717
Email: james.becker4@montana.edu

Ethical Statement: All protocols in this study were approved by the Institutional Review Board at Montana State University. Written informed consent was obtained from the participant prior to participating in the study.

Funding: This study was supported by the Ellen Kreighbaum Movement Science Laboratory Endowment at Montana State University.

ABSTRACT

Background: Symmetric limb function during gait may take up to 1 year to return following periacetabular osteotomy (PAO). **Purpose:** Implement gait intervention between 6 and 12 weeks post operatively in an attempt to improve limb symmetry at the 12-week timepoint. **Methods:** Hip joint kinematics, moments, and vertical ground reaction forces, as well as symmetry between limbs during gait were assessed at 6 and 12 weeks following bilateral PAO – one with gait intervention, and one without. **Results:** Limb symmetry across dependent variables was not improved in the gait retraining intervention PAO compared to the control PAO. **Conclusions:** Future research should examine the effect of timeline post operatively on gait intervention as well as assessing other forms of intervention to improve return of limb symmetry.

Key Words: Gait analysis; hip preservation surgery; rehabilitation; activities of daily living

Word Count: 5,265

INTRODUCTION

Hip dysplasia is a condition in which the coverage of the femoral head by the acetabulum of the pelvis is decreased leading to joint instability and altered loading of the joint during common locomotive tasks such as walking and running (Leunig, and Ganz, 2007b). The altered loading of the joint may present as increased stress placed on the hip joint and may ultimately lead to the development of joint injury or chronic degeneration i.e. osteoarthritis (Michaeli, et al., 1997; Jacobsen, and Sonne-Holm, 2005a; Reijman, et al., 2005b). A periacetabular osteotomy (PAO) is a highly invasive surgery used to improve hip dysplasia (Siebenrock, et al., 2001a) by improving the coverage of the femoral head, re-adjusting the load bearing, and helping to prolong the onset of osteoarthritis (Ganz, Klaue, Son Vinh, and Mast, 1988; Leunig, and Ganz, 2007; Millis, Murphy, and Poss, 1995; Steppacher, Tannast, Ganz, and Siebenrock, 2008). There are several techniques to performing a PAO with the most common being the Bernese PAO. This involves surgical transection of the pubic ramus, freeing the acetabulum from the ilium, then reorienting and fixing the acetabular fragment in a position to improve coverage of the femoral head (Ganz, Klaue, Vinh, and Mast, 1988b). Benefits to the Bernese PAO over other osteotomies are the maintenance of acetabular blood flow, facilitation of extensive acetabular reorientation, maintenance of pelvic rim shape, and allowance for the posterior column to remain intact which allows for immediate crutch walking following surgery with minimal internal fixation (Ganz, et al., 1988b; Siebenrock, et al., 2001a; Leunig, and Ganz, 2007a), however, the surgery is invasive and recovery periods can be long.

A larger proportion of the literature regarding PAO focuses on computer guidance for planning and improving surgery or on computer simulations of joint stress following surgery (Zhao, et al., 2010; Niknafs, et al., 2013; Zou, et al., 2013; Thomas-Aitken, et al., 2018). In contrast, relatively little is known regarding the impact PAO has on hip biomechanics and hip function during activities of daily living. Prior to PAO, patients have been shown to demonstrate decreased hip range of motion, decreased hip extensor moments during walking, and decreased hip abductor moments, deficits which slowly return to normative values following surgery (Pedersen, et al., 2006; Sucato, et al., 2010b; Jacobsen, et al., 2014; Gahramanov, et al., 2017). It has also been shown that for other activities of daily living requiring greater muscle force, it may take up to one year for muscle strength and support moments to return to baseline values (Schroeder, Zavala, Opstedal, and Becker, 2020). There is also little known about how the rehabilitation protocols or timelines following PAO influences gait patterns in the short to longer term (1-12 months), as most postoperative assessments occur at six months following surgery. However, patients are usually cleared for 100% weight bearing between six- and eight-weeks following surgery, thus understanding the rehabilitation process in this window may be impactful in developing effective rehabilitation protocols (Ganz, et al., 1988b; Siebenrock, et al., 2001a; Trousdale, and Cabanela, 2003).

Schroeder et al. (2020) noted in a clinical case study, increased loading of the contralateral limb was present at both six and twelve weeks post operatively during a sit to walk activity following PAO. This increased loading of the non-surgical limb also occurs following hip and knee arthroplasty (McCrory, White, and Lifeso, 2001; Mizner, and Snyder-Mackler, 2005; Wesseling, et al., 2018). Such alterations in limb loading raise concerns in the development or progression of osteoarthritis in joints of the contralateral limb. Increased loading of the contralateral limb can be addressed through gait retraining strategies. White and Lifeso (White, and Lifeso, 2005) reported that real-time biofeedback of ground reaction forces measured on an instrumented treadmill improved loading rate symmetry during gait in patients following THA. Similar results have been reported in runners, where training with real-time feedback on running mechanics has been shown to reduce knee loading (Willy, Scholz, and Davis, 2012). Together, these studies demonstrate that reduction of asymmetry and improvement of mechanics during activity are possible with intervention. Using the six to twelve-week window of time following PAO to implement a gait retraining protocol could have positive implications in reducing time to return to baseline, and reducing the amount of time spent in altered loading patterns following surgery, further reducing the risk of developing osteoarthritis in this population. Importantly, because patients are usually cleared for 100% weight bearing between six- and eight-weeks following surgery, thus understanding the rehabilitation process in this window may be impactful in developing effective rehabilitation protocols (Ganz, et al., 1988a; Siebenrock, et al., 2001a; Trousdale, and Cabanela, 2003)

Therefore, the purpose of this study was to examine return of gait function following a two week real time biofeedback intervention task in a patient undergoing bilateral PAO separated by 18 months. Kinematic and kinetic motion capture analyses of gait were assessed at six weeks (6WK) and twelve weeks (12WK) following each PAO operation. It was hypothesized that compared to a baseline recovery, gait retraining would result in reduced gait asymmetry 12weeks following surgery.

MATREIALS AND METHODS

Participant Description

A single participant (24 yrs female, height: 1.80m, mass: 77kg) who had undergone bilateral PAO separated by 18 months participated in this study. The participant was diagnosed with hip dysplasia due to a shallowing of the acetabulum on the left side from three prior arthroscopic left hip surgeries including a labral repair resulting from femoroacetabular impingement, one capsular plication, and a second labral repair. The patient underwent the first PAO, on the left side, approximately five months following the last labral repair. The second PAO, on the right side, was conducted approximately 18 months following the first PAO. All procedures performed in this study were approved by the Institutional Review Board and written informed consent was provided by the participant prior to any data collection (Appendix C).

Both operations were performed using a Bernese PAO with a modified Smith-Peterson approach. This approach includes osteomizing the anterior superior iliac spine, keeping the sartorius and respective tendons intact. The acetabulum is resected using cuts made through both ischium tables of the pelvis, a transverse cut across the ilium, and a cut downward toward the posterior inferior pubis. The acetabulum in both operations was then anterior-laterally oriented to improve coverage of the femoral head. Three screws were used to secure the fragment with a fourth screw used to reattach the anterior superior iliac spine. Radiographic imaging showing the new orientation of both acetabulums, and screw placement, following bilateral PAO is shown in Figure 1.

Figure 1: *Radiographic images of the pelvis following bilateral PAO.*

Upon completion of each surgery, physical therapy was implemented using a prescribed protocol from the orthopedic unit conducting the surgery. Full details of the protocol have been previously described (Schroeder, et al., 2020) and are only described in brief here. Weight bearing was initiated at 25% immediately post operatively and progressed to 100% weight bearing by six weeks. At this point the patient was cleared to walk without crutches and cleared to perform limited exercise during the first two weeks. At 12 weeks post operatively, the exercise was progressed to closed chain single limb exercises.

Motion Analysis

At six weeks and 12 weeks following both PAO surgeries, the participant completed walking gait analysis in a motion capture laboratory. The participant was instructed to walk across the room, at a self-selected pace. Ten trials were recorded with 10 seconds of rest between each trial. Whole body kinematics were captured using a 10-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) sampling at 100Hz for surgery 1 and 200Hz for surgery 2 and ground reaction forces were captured using 3 force plates (AMTI, Watertown, MA) sampling at 1000Hz. Trials were discarded and repeated if the subject did not hit each force plate squarely with a single foot during stride. Fifty-one reflective markers in surgery one and sixty-five reflective markers in surgery two were placed on bony landmarks using a modified Helen Hayes marker set. Prior to walking trials, a static trial was collected for calibration with the patient standing in a T-pose position with palms facing down.

Marker trajectories and ground reaction forces filtered in Cortex (Motion Analysis Corp., Santa Rosa, CA) using zerolag, low pass Butterworth filters with cutoff frequencies of 6 and 15 Hz, respectively. Data was then exported into OpenSim (SimTK, Stanford, CA) in conjunction with custom MATLAB scripts (Version 2019a, The Math Works, USA) where a scalable anatomic model was used for analysis. The model used was previously described by Hamner et al. (2010) and consisted of 17 bodies, 17 joints, 94 muscle actuators, and 36 degrees of freedom (pelvis: 6, neck: 3, lumbar joints: 3, hip: 3, shoulder joints: 3, wrist: 2, elbow: 1, radioulnar: 1, knee: 1, and ankle: 1). A wrap object was embedded within the model to prevent non-physiologic moment arms for the erector spinae muscle during trunk flexion (Daggfeldt, and Thorstensson, 2003; Graham, et al., 2014).

Spatial temporal variables of step length and average whole body center of mass velocity (whole body COM velocity) were calculated at each time point for each surgery. The following individual discrete variables were then calculated at each time point, for each surgery, during the stance phase: peak pelvic tilt, peak pelvic obliquity , peak pelvic rotation , hip extension, adduction, and rotation angles peak hip extensor moment, peak hip adduction moment , peak hip internal rotation moment , and vertical ground reaction forces (vGRF). This approach was specifically chosen as it follows the assessment of hip joint mechanics used to evaluate gait in hip osteoarthritis (Constantinou, 2017).

Scaling of the model and inverse kinematics were performed by fitting the anatomical model to measured 3D marker positions, placing high weighting on virtual markers which defined the joint centers of the hip, knee, and ankle (Lu, and O'Connor, 1999). Joint centers were estimated from experimental marker trajectories: regression equations of Harrington et al. (2007) were used for the hip joint center, while knee and ankle joint centers were identified by the midpoints of the femoral condyles and medial and lateral malleoli respectively. Joint moments were determined using the inverse dynamics tool in OpenSim (Delp, et al., 2007). Internal sagittal plane joint moments of the hip were calculated using

Newtonian-Euler inverse dynamics with moments being expressed in the coordinate system of the proximal segment and extensor moments being positive (Winter, 1980).

Gait Intervention

Gait retraining sessions were conducted between six- and 12-week time points over the course of 11 sessions implemented over two weeks. Sessions were completed on days where the patient did not attend physical therapy. Biofeedback was provided as vertical ground reaction forces displayed in real-time by plantar pressure insoles (Tekscan, Inc., Boston, MA) fitted to the insole of the patient's shoes while the patient walked on a treadmill (Figure 2). The vertical ground reaction force curves for each foot were displayed on a screen in front of the treadmill for the patient to see. The patient was instructed to walk with a goal of making the left and right curves as similar in magnitude and shape as possible.

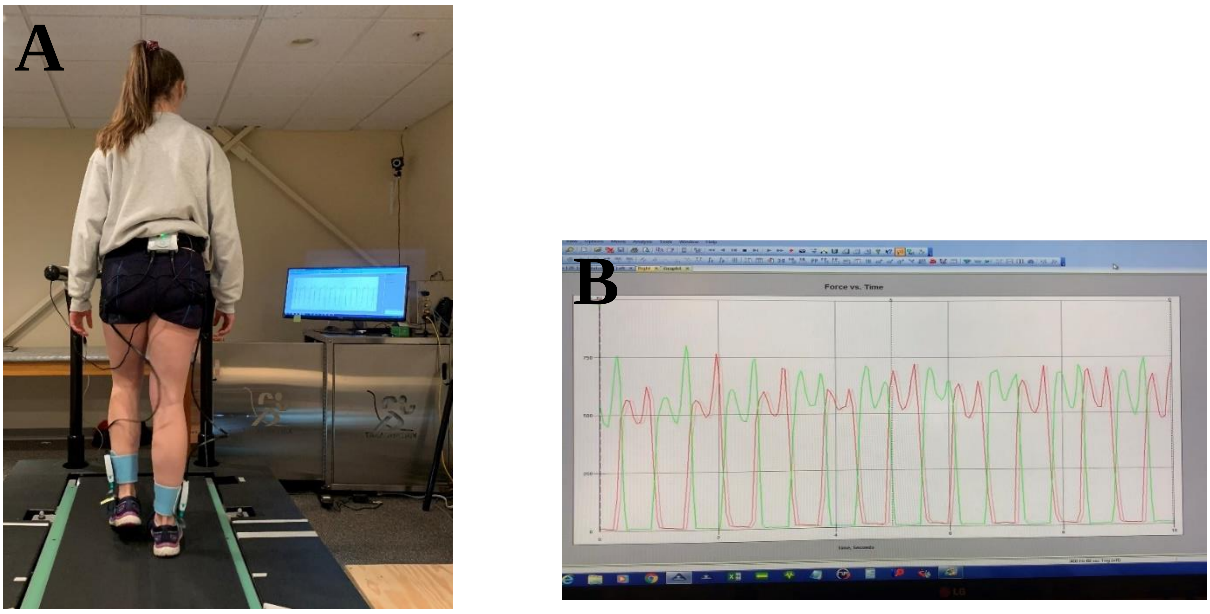

Figure 2: *Image of gait intervention set up (A), Ground reaction force curves being displayed in real-time (B).*

Feedback exposure and treadmill walk time followed a protocol previously described that gradually increases both feedback and walk time during initial sessions, then gradually decreases feedback time while continuing to increase walk time (Willy, et al., 2012). In this study, feedback and walk time were increased over the first six sessions then feedback was gradually decreased over the remaining five sessions as shown in Figure 3.

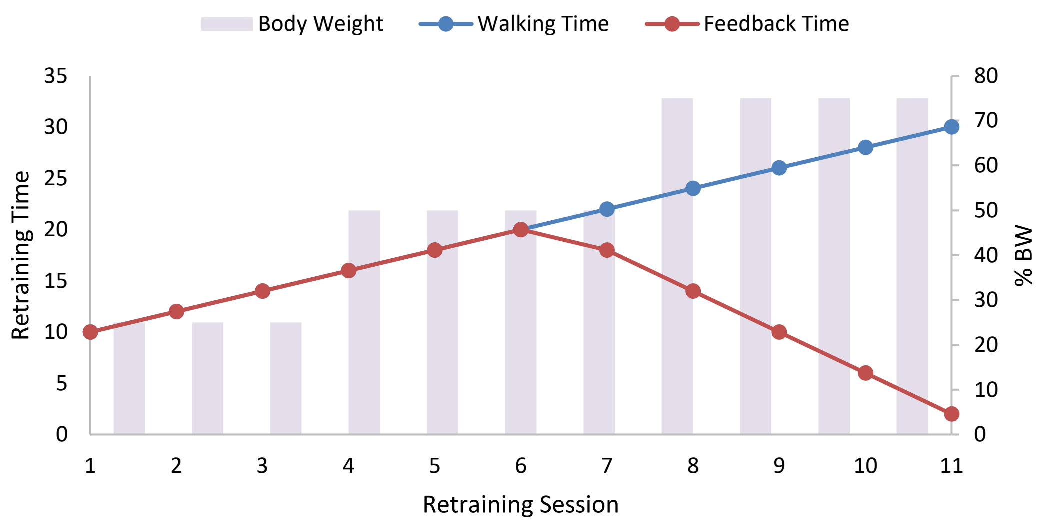

Figure 3: *Real-time Biofeedback Gait Retraining Protocol*

Data and Statistical Analysis

Following each surgery, joint angles and ground reaction forces were normalized to 100% of stance phase and limb symmetry index (LSI) was used to calculate symmetry at each time point using the following equation (Carpes, Mota, and Faria, 2010):

$$LSI = \frac{surgical\ limb\ -\ non\ surgical\ limb}{(surgical\ limb + non\ surgical\ limb) * 0.5} * 100$$

Mean LSI values across stance phase were then calculated. Differences in discrete peak variables and mean LSI across stance phase between timepoints and surgeries were evaluated using Model Statistics, an approach designed for single subject analyses (Dufek, Bates, Stergiou, and James, 1995b; Bates, 1996). This method uses a weighting factor that considers the number of trials and desired alpha level. The pooled standard deviation is multiplied by the weighting factor to provide a critical difference value. When compared to the difference in means, if the difference in means is greater than the critical difference value, it is with confidence that the two measurements are statistically different at the desired alpha level. An alpha level of $p<.01$ was used to minimize chance of Type I error. Effect sizes (*d*) were also calculated to assist with interpretation of results. Interpretation of effect sizes were in accordance with Hopkins (2006) with small effects defined as 0.2 or lower, medium effects 0.63-1.15, or large effects defined as greater than 1.15.

RESULTS

Spatial-temporal Gait Characteristics

Following surgery one, there was an increase in step length and an increase in whole body COM velocity from 6WK to 12WK time points (*d*=7.10, *d*=13.91 respectively). However, following surgery two, there was no difference in step length and whole-body COM velocity across timepoints (6WK *d*=0.23, 12WK *d*=1.05). Means for both variables across surgeries are demonstrated in Table 1.

Table 1. Means (± standard deviation) for Step Length and Whole-Body COM Velocity

	Surgery 1		**Surgery 2**	
	6 Weeks	12 Weeks	6 Weeks	12 Weeks
Step Length (m)	0.73 (±0.013)	0.82 (±0.013)	0.81 (±0.023)	0.80 (±0.039)
COM Velocity (m/s)	1.15 (±0.027)	1.55 (±0.029)	1.48 (±0.035)	1.45 (±0.022)

Kinematic Gait Characteristics and Mean Limb Asymmetry

In surgery one peak pelvic tilt was not different between limbs at 6 weeks (*d*=0.82) but was different at 12 weeks (*d*=2.01) with pelvic tilt being greater when in stance phase on the non-surgical limb. Peak pelvic tilt during surgery two noted no differences between limbs at both six and 12 weeks (*d*=0.15, *d*=0.14 respectively). There were no differences in peak pelvic obliquity between limbs at six- and 12-weeks during surgery one (*d*=0.43, *d*=0.44 respectively) and surgery two (*d*=0.87, *d*=0.39 respectively). No differences were demonstrated in pelvic rotation at either time point for surgery one (6 weeks: *d*=0.02, 12 weeks: *d*=1.2) and surgery two (6 weeks: *d*=0.03, 12 weeks: *d*=0.38) Mean peak values at each time point can be found in Table 1.

Ensemble averages for hip kinematics following each surgery are displayed in Figure 4. There were not differences in mean asymmetry for hip extension, hip abduction, and hip rotation between timepoints following surgery one (*d*=1.57, *d*=1.01, *d*=1.29 respectively) and surgery two (*d*=0.63, d=0.70, *d*=0.95 respectively). However, each variable at each time point had a moderate to high effect size.

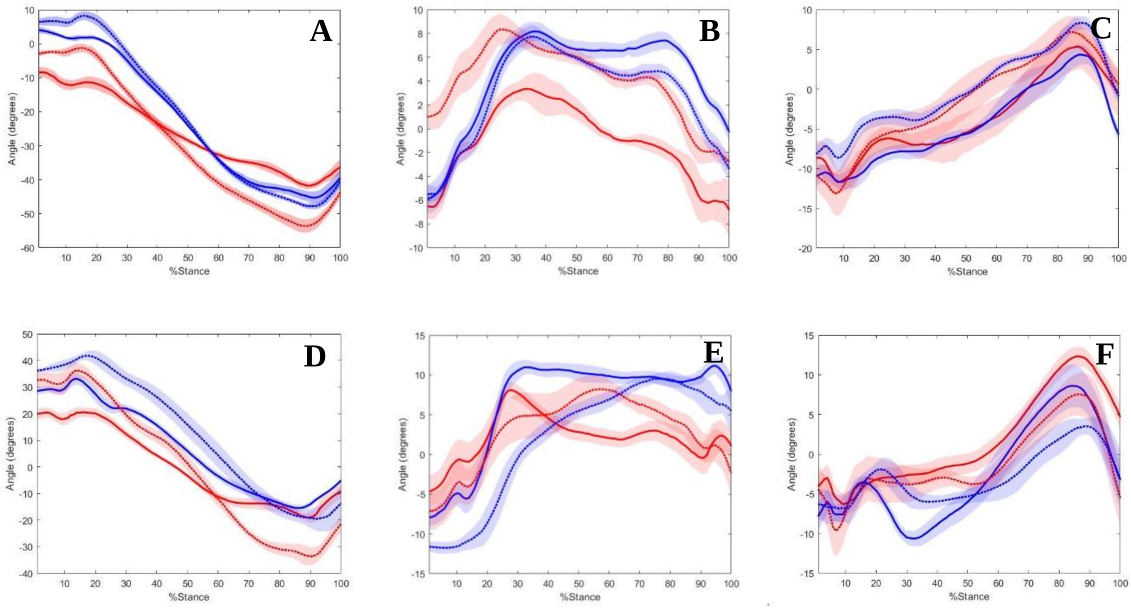

Figure 4: *Ensemble averages of hip kinematics. Top row left to right: Surgery 1 flexion/extension (A), abduction/adduction (B), and internal rotation (C). Bottom row left to right: Surgery 2 flexion/extension (D), abduction/adduction (E), and internal rotation (F). Red lines denote six-week time points while blue lines denote 12-week time points. Solid lines represent surgical limb while dotted lines represent non-surgical limb.*

Ensemble averages of vGRF at each time point for each surgery are displayed in Figure 5. No differences were demonstrated in vGRF symmetry between timepoints for either surgery, however, similar to hip kinematics, both surgeries demonstrated moderate effect sizes in vGRF between timepoints (d=0.84; d=0.84 respectively).

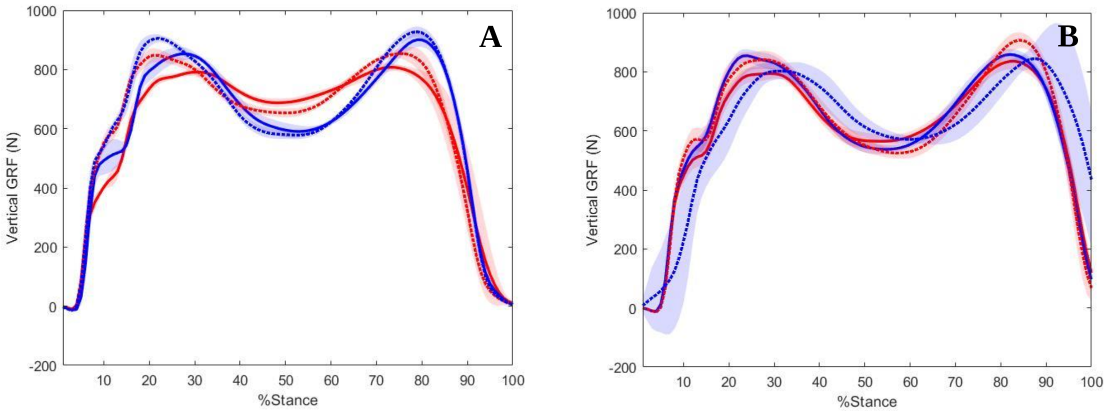

Figure 5: *Ensemble averages of vGRF (Surgery 1 (A), Surgery 2 (B). Red lines denote six-week time points while blue lines denote 12-week time points. Solid lines represent surgical limb while dotted lines represent non-surgical limb.*

Peak Hip Joint Moments

Peak hip extensor moments during surgery one were not different in the surgical limb compared to the non-surgical limb at six or 12 weeks (*d*=1.68, *d*=0.94 respectively). Peak hip extensor moments during surgery two were also not different between limbs at 6 or 12 weeks (*d*=0.73, *d*=0.26 respectively). Peak hip abductor moments during surgery one were increased in the non-surgical limb compared to the surgical limb at six weeks (*d*=6.13) and 12 weeks (*d*=4.00). However, peak hip abductor moments during surgery two were not different between limbs at six or 12 weeks (*d*=1.48, *d*=0.30 respectively). Peak hip rotator moments were not different between limbs at six and 12 weeks in surgery one (*d*=0.33, *d*=0.42 respectively). Peak hip rotator moments in surgery two were greater in the non-surgical limb compared to surgical limb at 6 weeks (*d*=2.23) but no difference was shown at 12 weeks (*d*=0.54). Mean peak hip extensor, abductor, and rotator moments are shown in Table 2.

Table 2. Mean peaks for internal hip joint moments and peak pelvic angles (± standard deviation) during stance phase across surgical time points for both surgical (S) and non-surgical (NS) limbs.

	Surgery 1		Surgery 2	
	6 Weeks	12 Weeks	6 Weeks	12 Weeks
Hip Internal Joint Moments (Nm)				
Peak Extension Moment	S: 297.56 (±108.82) NS: 166.35 (±46.90)	S: 141.44 (±22.26) NS: 160.56 (±18.27)	S: 164.42 (±47.38) NS: 205.30 (±63.95)	S: 111.69 (±73.49) NS: 98.66 (±26.32)
Peak Abduction Moment	S: 282.80 (±134.15) NS: 1070.96 (±122.62)	S: 578.52 (±134.27) NS: 1169.74 (±161.24)	S: 411.20 (±251.76) NS: 744.46 (±195.78)	S: 770.05 (±189.27) NS: 826.11 (±177.26)
Peak Internal Rotation Moment	S: 1424.57 (±927.63) NS: 1654.78 (±446.27)	S: 1203.10 (±258.53) NS: 1037.59 (±511.67)	S: 771.82 (±167.62) NS: 1662.39 (±628.69)	S: 867.93 (±701.06) NS: 1203.00 (±519.42)
Pelvis Angle (degrees)				
Peak Tilt	S: 0.98 (±1.21) NS: 0.16 (±0.76)	S: 5.75 (±0.98) NS: 7.14 (±0.38)	S: 4.28 (±1.21) NS: 4.47 (±1.20)	S: 7.08 (±0.85) NS: 7.21 (±0.86)
Peak Obliquity	S: -21.84 (±0.93) NS: -21.40 (±1.10)	S: -20.20 (±0.91) NS: -20.59 (±0.84)	S: 9.16 (±1.99) NS: 7.34 (±2.16)	S: 12.61 (±1.57) NS: 13.17 (±1.25)
Peak Rotation	S: -82.55 (±1.79) NS: -82.50 (±2.27)	S: -85.71 (±2.18) NS: -83.81 (±0.90)	S: -84.54 (±1.68) NS: -84.47 (±2.19)	S: -84.95 (±1.43) NS: -85.59 (±1.82)

DISCUSSION

The current case study describes changes in gait kinematics and hip joint kinetics with and without a gait intervention including real time feedback during the six to 12 week recovery period following PAO. We found no significant improvement in gait symmetry or gait parameters during surgical recovery when including a real time biofeedback gait intervention compared to surgical recovery without such a gait intervention. However, there were several observations that warrant discussion.

Hip joint moments tended to be greater in the non-surgical limb at all time points except for peak hip extensor moment at 12 weeks in surgery two. This favoring of the non-surgical limb is in agreement with hip moments found at similar post-operative time points during sit to walk by Schroeder et al. (2020). Increased loading of the non-surgical limb has also been observed during a sit to stand task following total hip arthroplasty, with patients displaying asymmetric loading up to one year following surgery (Abujaber, et al., 2015; Miura, et al., 2018b). Addressing such asymmetric loading, especially in tasks requiring high muscular effort such as sit-to-stand or walk should be considered in development of rehabilitation protocols. It should be noted however, that it is unknown if the relatively short altered loading period of one year does indeed increase risk of developing osteoarthritis. Interestingly, the increased loading on the non-surgical limb was less apparent in vGRF than in hip moments, as vGRFs under each limb did not substantially differ between surgical and non-surgical limbs at any time point. It is currently unknown if, compared to joint moments, vGRF is a sensitive enough measure to assess improvements in asymmetry following surgery. This may be a worthwhile area for future research to examine as vGRF can now be easily measured by in clinic force plate devices.

PAO rehabilitation protocols described in the literature tend to vary considerably (Tippett, 2006b; Ito, et al., 2014; Adler, et al., 2016)but the common element across all protocols is the inclusion of weight bearing activities in the six to eight weeks post PAO. However, return to symmetry during this time frame, to the authors' knowledge, has not been evaluated and given the potential for joint loading to be differentially expressed with altered limb symmetry it presents a clear need for future evaluation. Realtime biofeedback interventions similar to the one in the current study have been shown to improve biomechanics and reduce pain following total hip arthroplasty (White and Lifeso, 2005) and following running injuries (Willy, et al., 2012). However, this was not the case in the current study as there were no improvements to mean LSI from six to 12 weeks with gait intervention, compared to rehabilitation without the gait intervention. While this presents an apparent contradiction, it would be possible that the feedback presented to the participant was ineffectual, that is, trying to achieve symmetry in GRF is counterproductive when considering the internal forces experienced by the participant. Given that the ultimate goal of rehabilitation is to normalize the internal loads experienced by the joint, it may be more relevant to provide real time feedback of the internal loading during gait. Pizzolato and colleagues (2017) recently demonstrated that internal loads can be effectively measured in real time and that the participant can modify said loads using varied movement strategies. Allowing the participant to manipulate the motion relative to the internal loads could be more effective and yield a different outcome than presented here. Amount of time receiving feedback may also be a contributing factor. Our retraining protocol was modeled after those previously used to treat running injuries (Willey et al., 2012) and included eight sessions conducted over two weeks. However, White and Lifeso (2005) used more retraining sessions conducted over a period of eight weeks. It may be that compared to overuse running injuries, for a more invasive surgery such as TKA or PAO, longer durations of gait retraining might be required.

A number of factors should be considered when interpreting the results of this case study. Firstly, this is a single subject analysis and thus results presented here may not be generalizable to other PAO patients. Secondly, this participant had bilateral PAO and we cannot determine if the prior surgery and surgical history on the limb in surgery one influenced the outcomes following surgery two. Prior to surgery one, the patient was a collegiate athlete and did not return to the same level of activity following surgery one and prior to surgery two, thus it is unknown whether this alteration in physical training regimen impacted results. Third, during surgery two the subject also developed an infection and hematoma of the surgical wound with the first six weeks following surgery. It is unknown if this complication had substantial impact on the healing process and had any effect on the resulting outcomes at either time point.

In conclusion, this case study documented one of the first gait interventions in addition to standard rehabilitation protocols, as an attempt to achieve improved limb symmetry during the immediate recovery following PAO. Although no improvements were noted between the outcomes following the surgery with gait intervention and the surgery without, results suggest further research is warranted to determine whether such a gait intervention with alternative feedback mechanisms would provide similar outcomes in a larger patient population. The ineffectiveness of this intervention, if shown on a larger scale, would also prompt examination of other modes of intervention such as the use of an antigravity treadmill, or assessment of intervention at other time points during the recovery process. In order to improve outcomes and understand areas to address in the rehabilitation process, further investigation of biomechanical outcomes following PAO in various activities, including gait, is needed during the immediate six months to one year following surgery.

Acknowledgements
The authors would like to acknowledge Christopher Casillas, and Allison Hoffee for their assistance in data collection, Justin Whitten for his assistance in processing, and to acknowledge the University of Utah Medical Center where the surgery was performed for sharing medical reports and radiographic images.

Conflicts of Interest
The authors have no financial disclosures or conflicts of interest to report.

References

Abujaber SB, Marmon AR, Pozzi F, Rubano JJ, Zeni JA 2015 Sit-To-Stand Biomechanics Before and After Total Hip Arthroplasty. Journal of Arthroplasty 30: 2027–2033.

Adler KL, Cook PC, Frcs C, Geisler PR, Yen Y, Giordano BD 2015 Current Concepts in Hip Preservation Surgery : Part II — Rehabilitation. Sports Health: A Multidisciplinary Approach 8: 57–64.

Adler KL, Cook PC, Geisler PR, Yen YM, Giordano BD 2016 Current Concepts in Hip Preservation Surgery: Part II—Rehabilitation. Sports Health 8: 57–64.

Andriacchi T, Andersson G, Fermier R, Stern D, Galante J 1980 A study of lower-limb mechanics during stair-climbing. The Journal of Bone and Joint Surgery 62: 749–757.

Armand M, Lepistö J, Tallroth K, Elias J, Chao E 2005 Outcome of periacetabular osteotomy: Joint contact pressure calculation using standing AP radiographs, 12 patients followed for average 2 years. Acta Orthopaedica 76: 303–313.

Bates BT 1996 Single-subject methodology: an alternative approach. Medicine and Science in Sports and Exercise 28: 631–638.

Behrens P, Bitter T, Kurz B, Russlies M 2006 Matrix-associated autologous chondrocyte transplantation/implantation (MACT/MACI)-5-year follow-up. Knee 13: 194–202.

Beltran LS, Rosenberg ZS, Mayo JD, De Tuesta MD, Martin O, Neto LP, Bencardino JT 2013 Imaging evaluation of developmental hip dysplasia in the young adult. American Journal of Roentgenology 200: 1077–1088.

Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, Duda GN 2001 Hip contact forces and gait patterns from routine activities. Journal of Biomechanics 34: 859–871.

Bohannon RW 1997 Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. Age and Ageing 26: 15–19.

Boje J, Caspersen CK, Jakobsen SS, Søballe K, Mechlenburg I 2019 Are changes in pain associated with changes in quality of life and hip function 2 years after periacetabular osteotomy? A follow-up study of 321 patients. Journal of Hip Preservation Surgery 6: 69–76.

Cady RB 2006 Developmental dysplasia of the hip: Definition, recognition, and prevention of late sequelae. Pediatric Annals 35: 92–101.

Carpes FP, Mota CB, Faria IE 2010 On the bilateral asymmetry during running and cycling - A review considering leg preference. Physical Therapy in Sport 11: 136–142.

Chan A, McCaul KA, Cundy PJ, Haan EA, Byron-Scott R 1997 Perinatal risk factors for developmental dysplasia of the hip. Archives of Disease in Childhood: Fetal and Neonatal Edition 76: 94–100.

Choi S 2015 Total hip arthroplasty. Decision-Making in Orthopedic and Regional Anesthesiology: A Case-Based Approach 95–100.

Chou LS, Kaufman KR, Hahn ME, Brey RH 2003 Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. Gait and Posture 18: 125–133.

Clohisy JC, Barrett SE, Gordon JE, Delgado ED, Schoenecker PL 2005 Periacetabular osteotomy for the treatment of severe acetabular dysplasia. Journal of Bone and Joint Surgery - Series A 87: 254–259.

Clohisy JC, Dobson MA, Robison JF, Warth LC, Zheng J, Liu SS, Yehyawi TM, Callaghan JJ 2011 Radiographic structural abnormalities associated with premature, natural hip-joint

failure. Journal of Bone and Joint Surgery - Series A 93: 3–9.
Clohisy JC, Schutz AL, St L, Bs J, Schoenecker PL, Wright RW 2009 A Systematic Literature Review. 2041–2052.
Coobs BR, Xiong A, Clohisy JC 2015 Contemporary Concepts in the Young Adult Hip Patient: Periacetabular Osteotomy for Hip Dysplasia. Journal of Arthroplasty 30: 1105–1108.
Cross M, Smith E, Hoy D, Nolte S, Ackerman I, Fransen M, Bridgett L, Williams S, Guillemin F, Hill CL, Laslett LL, Jones G, Cicuttini F, Osborne R, Vos T, Buchbinder R, Woolf A, March L 2014 The global burden of hip and knee osteoarthritis: Estimates from the Global Burden of Disease 2010 study. Annals of the Rheumatic Diseases 73: 1323–1330.
Crowe J, Mani V, Ranawat C 1979 Total hip replacement in congenital dislocation and dysplasia of the hip. The Journal of Bone and Joint Surgery 61: 15–23.
Daggfeldt K, Thorstensson A 2003 The mechanics of back-extensor torque production about the lumbar spine. Journal of Biomechanics 36: 815–825.
Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, Guendelman E, Thelen DG 2007 OpenSim: Open-source software to create and analyze dynamic simulations of movement. IEEE Transactions on Biomedical Engineering 54: 1940–1950.
Diamond LE, Wrigley T V., Hinman RS, Hodges PW, O’Donnell J, Takla A, Bennell KL 2016 Isometric and isokinetic hip strength and agonist/antagonist ratios in symptomatic femoroacetabular impingement. Journal of Science and Medicine in Sport 19: 696–701.
Domb BG, Stake CE, Finch NA, Cramer TL 2014 Return to sport after hip arthroscopy: Aggregate recommendations from high-volume hip arthroscopy centers. Orthopedics 37: e902–e905.
Dufek J, Bates B, Stergiou N, James CR 1995a Interactive effects between group and single subject response patterns. Human Movement Science 14: 301–323.
Dufek JS, Bates BT, Stergiou N, James CR 1995b Interactive effects between group and single-subject response patterns. Human Movement Science 14: 301–323.
Eitzen I, Fernandes L, Nordsletten L, Snyder-mackler L, Arna M 2014 Gait & Posture Weight-bearing asymmetries during Sit-To-Stand in patients with mild-to-moderate hip osteoarthritis. Gait & Posture 39: 683–688.
Ezoe M, Naito M, Asayama I 2006 Muscle Strength Improves after Abductor-sparing. Clinical Orthopaedics and Related Research 444: 161–168.
Gahramanov A, İnanıcı F, Çağlar Ö, Aksoy C, Tokgözoğlu AM, Güner S, Baki A, Atilla B 2017 Functional results in periacetabular osteotomy: Is it possible to obtain a normal gait after the surgery? HIP International 27: 449–454.
Gala L, Clohisy JC, Beauĺe PE 2016 Hip dysplasia in the young adult. Journal of Bone and Joint Surgery - American Volume 98: 63–73.
Ganz R, Klaue K, Son Vinh T, Mast J 1988a A New Periacetabular Osteotomy for the Treatment of Hip Dysplasias: Technique and Preliminary Results. Clinical Orthopaedics and Related Research 232: 26–36.
Ganz R, Klaue K, Vinh TS, Mast JW 1988b A New Periacetabular Osteotomy for the Treatment of Hip Dysplasias. Clinical Orthopaedics and Related Research 232: 26–36.
Givens-Heiss DL, Krebs DE, Riley PO, Strickland EM, Fares M, Hodge WA, Mann RW, Oatis CA 1992 In vivo acetabular contact pressures during rehabilitation, Part II: Postacute phase. Physical Therapy 72: 700–710.
Graham DF, Carty CP, Lloyd DG, Lichtwark GA, Barrett RS 2014 Muscle contributions to recovery from forward loss of balance by stepping. Journal of Biomechanics 47: 667–

674.
Grant AD, Sala DA, Davidovitch RI 2012 The labrum: Structure, function, and injury with femoro-acetabular impingement. Journal of Children's Orthopaedics 6: 357–372.
Hamner SR, Seth A, Delp SL 2010 Muscle contributions to propulsion and support during running. Journal of Biomechanics 43: 2709–2716.
Hansen W, Shim VB, Obst S, Lloyd DG, Newsham-West R, Barrett RS 2017 Achilles tendon stress is more sensitive to subject-specific geometry than subject-specific material properties: A finite element analysis. Journal of Biomechanics 56: 26–31.
Harrington ME, Zavatsky AB, Lawson SEM, Yuan Z, Theologis TN 2007 Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging. Journal of Biomechanics 40: 595–602.
Harris JD, Mitchell RJ, Qadeer A, Gerrie BJ, Mcculloch PC 2017 Patient Reported Outcomes and Symptomatic Impingement in US Women's Professional Soccer. The Orthopaedic Journal of Sports Medicine 5: 1.
Hartofilakidis G, Karachalios T, Stamos KG 2000 Epidemiology, Demographics, and Natural History of Congenital Hip Disease in Adults. Orthopedics 23: 823–827.
Henak CR, Abraham CL, Anderson AE, Maas SA, Ellis BJ, Peters CL, Weiss JA 2014 Patient-specific analysis of cartilage and labrum mechanics in human hips with acetabular dysplasia. Osteoarthritis and Cartilage 22: 210–217.
Hopkins W 2006
Inman VT 1947 Functional Aspects of the Abductor Muscles of the Hip. The Journal of Bone and Joint Surgery 29: 607–619.
Ito H, Tanino H, Sato T, Nishida Y, Matsuno T 2014 Early weight-bearing after periacetabular osteotomy leads to a high incidence of postoperative pelvic fractures. BMC Musculoskeletal Disorders 15: 1–7.
Jacobs C, Uhl TL, Seeley M, Sterling W, Goodrich L 2005 Strength and fatigability of the dominant and nondominant hip abductors. Journal of Athletic Training 40: 203–206.
Jacobsen JS, Nielsen DB, Sørensen H, Søballe K, Mechlenburg I 2014 Joint kinematics and kinetics during walking and running in 32 patients with hip dysplasia 1 year after periacetabular osteotomy. Acta Orthopaedica 85: 592–599.
Jacobsen JS, Søballe K, Thorborg K, Bolvig L, Jakobsen S, Hölmich P, Mechlenburg I, Jacobsen JS, Søballe K, Thorborg K, Bolvig L 2019 Patient-reported outcome and muscle – tendon pain after periacetabular osteotomy are related : 1- year follow-up in 82 patients with hip dysplasia Patient-reported outcome and muscle – tendon pain after periacetabular osteotomy are related : 1-year follow. Acta Orthopaedica 90: 40–45.
Jacobsen JS, Thorborg K, Hölmich P, Bolvig L, Storgaard Jakobsen S, Søballe K, Mechlenburg I 2018 Does the physical activity profile change in patients with hip dysplasia from before to 1 year after periacetabular osteotomy? Acta Orthopaedica 89: 622–627.
Jacobsen S, Sonne-Holm S 2005a Hip dysplasia: A significant risk factor for the development of hip osteoarthritis. A cross-sectional survey. Rheumatology 44: 211–218.
Jacobsen S, Sonne-Holm S 2005b Hip dysplasia: A significant risk factor for the development of hip osteoarthritis. A cross-sectional survey. Rheumatology 44: 211–218.
Kain M, Novais E, Vallim C, Millis M, Kim Y 2011 Periacetabular Osteotomy After Failed Hip Arthroscopy for Labral Tears in Patients with Acetabular Dysplasia. Journal of Bone and Joint Surgery American 93: 57–61.
Kaku N, Tsumura H, Taira H, Sawatari T, Torisu T 2004 Biomechanical study of load transfer of the pubic ramus due to pelvic inclination after hip joint surgery using a three-

dimensional finite element model. Journal of Orthopaedic Science 9: 264–269.
Karam M, Gao Y, McKinley T 2011a Assessment of Walking Pattern Pre and Post Periacetabular Osteotomy. The Iowa orthopaedic journal 31: 83–89.
Karam MD, Gao Y, McKinley T 2011b Assessment of walking pattern pre and post periacetabular osteotomy. The Iowa orthopaedic journal 31: 83–89.
Katoh M, Yamasaki H 2009 Comparison of reliability of isometric leg muscle strength measurements made using a Hand-Held dynamometer with and without a restraining Belt. Journal of Physical Therapy Science 21: 37–42.
Kemp JL, Collins NJ, Roos EM, Crossley KM 2013 Psychometric properties of patient-reported outcome measures for hip arthroscopic surgery. American Journal of Sports Medicine 41: 2065–2073.
Kerr A, Durward B, Kerr KM 2004 Defining phases for the sit-to-walk movement. Clinical Biomechanics 19: 385–390.
Kim CH, Kim JW 2020 Periacetabular osteotomy vs. total hip arthroplasty in young active patients with dysplastic hip: Systematic review and meta-analysis. Orthopaedics and Traumatology: Surgery and Research 106: 1545–1551.
Kim WK, Kim DK, Seo KM, Kang SH 2014 Reliability and validity of isometric knee extensor strength test with hand-held dynamometer depending on its fixation: A pilot study. Annals of Rehabilitation Medicine 38: 84–93.
Klit J, Hartig-Andreasen C, Jacobsen S, Søballe K, Troelsen A 2014 Periacetabular osteotomy: Sporting, social and sexual activity 9-12 years post surgery. HIP International 24: 27–31.
Kraeutler MJ, Garabekyan T, Pascual-Garrido C, Mei-Dan O 2016 Hip instability: A review of hip dysplasia and other contributing factors. Muscles, Ligaments and Tendons Journal 6: 343–353.
Kralj M, Mavčič B, Antolič V, Iglič A, Kralj-Iglič V 2005 The Bernese periacetabular osteotomy: Clinical, radiographic and mechanical 7-15-year follow-up of 26 hips. Acta Orthopaedica 76: 833–840.
De La Rocha A, Sucato D, Tulchin K, Podeszwa DA 2012 Treatment of Adolescents with a Periacetabular Osteotomy After Previous Pelvic Surgery. Clinical Orthopaedics 470: 2583–2590.
Larsen JB, Mechlenburg I, Jakobsen SS, Thilleman TM, Søballe K 2020 14-Year Hip Survivorship After Periacetabular Osteotomy: a Follow-Up Study on 1,385 Hips. Acta Orthopaedica 91: 299–305.
Lee KJ, Park SJ, Lee SJ, Naito M, Kwon SY 2015 Biomechanical study on the efficacy of the periacetabular osteotomy using Patient-specific finite element analysis. International Journal of Precision Engineering and Manufacturing 16: 823–829.
Leunig M, Ganz R 2007a (iii) Bernese periacetabular osteotomy. Current Orthopaedics 21: 100–108.
Leunig M, Ganz R 2007b Bernese periacetabular osteotomy. Current Orthopaedics 21: 100–108.
Leunig M, Siebenrock KA, Ganz R 2001 Rationale of periacetabular osteotomy and background work. Journal of Bone and Joint Surgery 83A: 438–448.
Lu TW, O'Connor JJ 1999 Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. Journal of Biomechanics 32: 129–134.
Mandeville D, Osternig LR, Chou LS 2007 The effect of total knee replacement on dynamic support of the body during walking and stair ascent. Clinical Biomechanics 22: 787–794.
Martins J, da Silva JR, da Silva; MRB, Bevilaqua-Grossi D 2017 Reliability and Validity of

the Belt-Stabilized Handheld Dynamometer in Hip- and Knee-Strength Tests. Journal of Athletic Training 52: 809–819.

Matheney T, Kim Y, Zurakowski D, Matero C, Millis M 2009 Intermediate to Long-Term Results Following the Bernese Periacetabular Osteotomy and Predictors of Clinical Outcome. 2113–2123.

Matta J, Stover M, Siebenrock K 1999 Periacetabular osteotomy through the Smith-Petersen approach. Clinical Orthopaedics and Related Research 21–32.

McCrory JL, White SC, Lifeso RM 2001 Vertical ground reaction forces: Objective measures of gait following hip arthroplasty. Gait and Posture 14: 104–109.

Michaeli DA, Murphy SB, Hipp JA 1997 Comparison of predicted and measured contact pressures in normal and dysplastic hips. Medical Engineering and Physics 19: 180–186.

Millis MB, Murphy SB, Poss R 1995 Osteotomis about the hip for the prevention and treatment of osteoarthrosis. Journal of Bone and Joint Surgery American 77: 626–647.

Miura N, Tagomori K, Ikutomo H, Nakagawa N 2018a Asymmetrical loading during sit-to-stand movement in patients 1 year after total hip arthroplasty. Clinical Biomechanics 57: 89–92.

Miura N, Tagomori K, Ikutomo H, Nakagawa N, Masuhara K 2018b Asymmetrical loading during sit-to-stand movement in patients 1 year after total hip arthroplasty. Clinical Biomechanics 57: 89–92.

Mizner RL, Snyder-Mackler L 2005 Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. Journal of Orthopaedic Research 23: 1083–1090.

Moore KL, Dalley AF, Agur AMR 2014 Clinically Oriented Anatomy. Baltimore: Lippincott Williams & Wilkins.

Murphy RJ, Armiger RS, Lepistö J, Mears SC, Taylor RH, Armand M 2015 Development of a biomechanical guidance system for periacetabular osteotomy. International Journal of Computer Assisted Radiology and Surgery 10: 497–508.

Murphy S, Deshmukh R 2002a Periacetabular Osteotomy. 168–174.

Murphy SB, Deshmukh R 2002b Periacetabular Osteotomy: Preoperative Radiographic Predictors of Outcome. Clinical Orthopaedics and Related Research 405: 168–174.

Murphy SB, Ganz R, Muller ME 1995 The Prognosis in Untreated Dysplagia of the Hip. The Journal of bone and joint surgery British volume 77: 985–989.

Nadeau S, McFadyen BJ, Malouin F 2003 Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: What are the challenges compared to level walking? Clinical Biomechanics 18: 950–959.

Nawabi DH, Degen RM, Fields KG, McLawhorn A, Ranawat AS, Sink EL, Kelly BT 2016 Outcomes after Arthroscopic Treatment of Femoroacetabular Impingement for Patients with Borderline Hip Dysplasia. American Journal of Sports Medicine 44: 1017–1023.

Niknafs N, Murphy RJ, Armiger RS, Lepistö J, Armand M 2013 Biomechanical Factors in Planning of Periacetabular Osteotomy. Frontiers in Bioengineering and Biotechnology 1: .

Nishimura M, Takahira N, Fukushima K, Yamamoto T, Moriya M, Uchiyama K 2015 Early gait analysis after curved periacetabular osteotomy for acetabular dysplasia. Orthopedic Research and Reviews 25.

Nishino T, Ishii T, Chang F, Yanai T, Watanabe A, Ogawa T, Mishima H, Nakai K, Ochiai N 2010 Effect of gradual weight-bearing on regenerated articular cartilage after joint distraction and motion in a rabbit model. Journal of Orthopaedic Research 28: 600–606.

Pedersen ENG, Alkjær T, Søballe K, Simonsen EB 2006 Walking pattern in 9 women with

hip dysplasia 18 months after periacetabular osteotomy. Acta Orthopaedica 77: 203–208.
Peters CL, Erickson JA, Anderson MB, Anderson LA 2015 Preservation of the Rectus Femoris Origin During Periacetabular Osteotomy Does Not Compromise Acetabular Reorientation. Clinical Orthopaedics and Related Research 473: 608–614.
Pisters MF, Veenhof C, Meeteren NLUVAN, Ostelo RW, Bakker DHDE, Schellevis OISG, Dekker J 2007 Long-Term Effectiveness of Exercise Therapy in Patients With Osteoarthritis of the Hip or Knee : A Systematic Review. Arthritis and Rheumatism 57: 1245–1253.
Pizzolato C, Reggiani M, Saxby DJ, Ceseracciu E, Modenese L, Lloyd DG 2017 Biofeedback for Gait Retraining Based on Real-Time Estimation of Tibiofemoral Joint Contact Forces. IEEE Transactions on Neural Systems and Rehabilitation Engineering 25: 1612–1621.
Ramisetty N, Kwon Y, Mohtadi N 2015 Patient-reported outcome measures for hip preservation surgery--a systematic review of the literature. Journal of Hip Preservation Surgery 2: 15–27.
Reijman M, Hazes JMW, Pols HAP, Koes BW, Bierma-Zeinstra SMA 2005a Acetabular dysplasia predicts incident osteoarthritis of the hip: The Rotterdam study. Arthritis and Rheumatism 52: 787–793.
Reijman M, Hazes JMW, Pols HAP, Koes BW, Bierma-Zeinstra SMA 2005b Acetabular dysplasia predicts incident osteoarthritis of the hip: The Rotterdam study. Arthritis and Rheumatism 52: 787–793.
Samaan MA, Schwaiger BJ, Gallo MC, Link TM, Zhang AL, Majumdar S, Souza RB 2017 Abnormal Joint Moment Distributions and Functional Performance During Sit-to-Stand in Femoroacetabular Impingement Patients. PM and R 9: 563–570.
Schroeder C, Zavala L, Opstedal L, Becker J 2020 Recovery of Lower Extremity Function in the Initial Year Following Periacetabular Osteotomy: A Single Subject Analysis. Physiotherapy Theory and Practice 00: 1–12.
Schwachmeyer V, Damm P, Bender A, Dymke J, Graichen F, Bergmann G 2013 In Vivo Hip Joint Loading during Post-Operative Physiotherapeutic Exercises. PLoS ONE 8: e77807.
Siebenrock KA, Leunig M, Ganz R 2001a Periacetabular osteotomy: the Bernese experience. Instructional course lectures 50: 239–245.
Siebenrock KA, Leunig M, Ganz R 2001b Periacetabular osteotomy: The Bernese experience. Journal of Bone and Joint Surgery - Series A 83: 449–455.
Sophia Fox AJ, Bedi A, Rodeo SA 2009 The basic science of articular cartilage: Structure, composition, and function. Sports Health 1: 461–468.
Steel HH 1973 Triple Osteotomy of the Innominate Bone. The Journal of Bone and Joint Surgery 55: 343–350.
Steppacher SD, Tannast M, Ganz R, Siebenrock KA 2008 Mean 20-year followup of bernese periacetabular osteotomy. Clinical Orthopaedics and Related Research 466: 1633–1644.
Stulberg S 1975 Unrecognized childhood hip disease: a major cause of idiopathic osteoarthritis of the hip. In: Cordell LD, Harris WH, Ramsey PL, MacEwen GD (eds). Proceedings of the Third Open Scientific Meeting of the Hip Society. St Louis, MO: Mosby 212–228.
Stulberg S, Harris W 1974 Acetabular dysplasia and development of osteoarthritis of hip. In: Harris WH (ed.). The Hip. Proceedings of the Second Open Scientific Meeting of the Hip Society. St Louis, MO: Mosby 82–93.
Sucato D, Tulchin K, Shrader M, DeLaRocha A, Gist T, Sheu G 2010a Gait, hip strength and functional outcomes after a ganz periacetabular osteotomy for adolescent hip dysplasia.

Journal of Pediatric Orthopaedics 30: 344–350.
Sucato DJ, Tulchin K, Shrader MW, Delarocha A, Gist T, Sheu G 2010b Gait , Hip Strength and Functional Outcomes After a Ganz Periacetabular Osteotomy for Adolescent Hip Dysplasia. 30: 344–350.
The United States Bone and Joint Inititative 2020 United States Bone and Joint Initiative: The Burden of Musculoskeletal Diseases in the United States (BMUS). Rosemont, IL:
Thomas-Aitken HD, Willey MC, Goetz JE 2018 Joint contact stresses calculated for acetabular dysplasia patients using discrete element analysis are significantly influenced by the applied gait pattern. Journal of Biomechanics 79: 45–53.
Thomeé R, Jonasson P, Thorborg K, Sansone M, Ahlden M, Thomeé C, Karlsson J, Baranto A 2015 Validation of the Copenhagen hip groin outcome score (HAGOS) for pain, symptoms and physical function in patients with hip/groin disability. Physiotherapy 101: e1514–e1515.
Thorborg K, Branci S, Stensbirk F, Jensen J, Holmich P 2014 Copenhagen hip and groin outcome scores (HAGOS) in male soccer: reference values for hip and groin injury free players. British Journal of Sports Medicine 48: 557–559.
Thorborg K, Hölmich P, Christensen R, Petersen J, Roos EM 2011 The Copenhagen Hip and Groin Outcome Score (HAGOS): Development and validation according to the COSMIN checklist. British Journal of Sports Medicine 45: 478–491.
Thorborg K, Tijssen M, Habets B, Bartels EM, Roos EM, Kemp J, Crossley KM, Hölmich P 2015 Patient-Reported Outcome (PRO) questionnaires for young to middle-aged adults with hip and groin disability: A systematic review of the clinimetric evidence. British Journal of Sports Medicine 49: 812.
Tippett S 2006a Returning to Sports After Periacetabular Osteotomy for Developmental Dysplasia of the Hip. North American Journal of Sports Physical Therapy 1: .
Tippett SR 2006b Returning to sports after periacetabular osteotomy for developmental dysplasia of the hip. North American journal of sports physical therapy : NAJSPT 1: 32–9.
Tonnis D 1990 Surgical treatment of congenital dislocation of the hip. Clinical Orthopaedics and Related Research 258: 33–40.
Torio C, Moore B 2016 Statistical Brief #204. National Inpatient Hospital Costs: The Most Expensive Conditions by Payer, 2013. Rockville, MD: Agency for Healthcare Research and Quality .
Trousdale RT, Cabanela ME 2003 Lessons learned after more than 250 periacetabular osteotomies. Acta Orthopaedica Scandinavica 74: 119–126.
Umeda N, Miki H, Ishii T, Yoshikawa H, Sugano N 2009 Progression of osteoarthritis of the knee after unilateral total hip arthroplast: a minimum 10-year follow up study. Archives of Orthopaedic and Trauma Surgery 129: 149–154.
Vanwanseele B, Lucchinetti E, Stüssi E 2002 The effects of immobilization on the characteristics of articular cartilage: Current concepts and future directions. Osteoarthritis and Cartilage 10: 408–419.
Wall PDH, Fernandez M, Griffin DR, Foster NE 2013 Nonoperative Treatment for Femoroacetabular Impingement: A Systematic Review of the Literature. PM and R 5: 418–426.
Wedge JH, Wasylenko MJ 1979 The natural history of congenital disease of the hip. Journal of Bone and Joint Surgery - Series B 61: 334–338.
Weinstein S 1987 Natural history of congenital hip dislocation (CDH) and hip dysplasia. Clinical Orthopaedics and Related Research 62–76.

Wesseling M, Meyer C, Corten K, Desloovere K, Jonkers I 2018 Longitudinal joint loading in patients before and up to one year after unilateral total hip arthroplasty. Gait and Posture 61: 117–124.
White SC, Lifeso RM 2005 Altering asymmetric limb loading after hip arthroplasty using real-time dynamic feedback when walking. Archives of Physical Medicine and Rehabilitation 86: 1958–1963.
Wiberg G 1939 Studies on dysplastic acetabula and congenital subluxation of the hip joint: with special reference to the complication of osteoarthritis. Acta Chirurgica Scandinavica 83: 5–135.
Wilk KE, Reinold MM, Hooks TR 2003 Recent advances in the rehabilitation of isolated and combined anterior cruciate ligament injuries. Orthopedic Clinics 34: P107-137.
Willy RW, Scholz JP, Davis IS 2012 Mirror gait retraining for the treatment of patellofemoral pain in female runners. Clinical Biomechanics 27: 1045–1051.
Winter DA 1980 Overall Principle of Lower Limb Spport During Stance Phase of Gait.pdf.crdownload. Journal of Biomechanics 13: 923–927.
Wong LCY, Chiu WK, Russ M, Liew S 2012 Review of techniques for monitoring the healing fracture of bones for implementation in an internally fixated pelvis. Medical Engineering and Physics 34: 140–152.
Wyles CC, Heidenreich MJ, Jeng J, Larson DR, Trousdale RT, Sierra RJ 2017 The John Charnley Award: Redefining the Natural History of Osteoarthritis in Patients With Hip Dysplasia and Impingement. Clinical Orthopaedics and Related Research 475: 336–350.
Yasunaga Y, Yamasaki T, Ochi M 2012 Patient selection criteria for periacetabular osteotomy or rotational acetabular osteotomy. Clinical Orthopaedics and Related Research 470: 3342–3354.
Yeung M, Kowalczuk M, Simunovic N, Ayeni OR 2016 Hip arthroscopy in the setting of hip dysplasia: A systematic review. Bone and Joint Research 5: 225–231.
Youdas JW, Kotajarvi BJ, Padgett DJ, Kaufman KR 2005 Partial weight-bearing gait using conventional assistive devices. Archives of Physical Medicine and Rehabilitation 86: 394–398.
Zhao X, Chosa E, Totoribe K, Deng G 2010 Effect of periacetabular osteotomy for acetabular dysplasia clarified by three-dimensional finite element analysis. Journal of Orthopaedic Science 15: 632–640.
Zou Z, Chávez-Arreola A, Mandal P, Board TN, Alonso-Rasgado T 2013 Optimization of the position of the acetabulum in a ganz periacetabular osteotomy by finite element analysis. Journal of Orthopaedic Research 31: 472–479.

CHAPTER FIVE

CONCLUSIONS & FUTURE DIRECTIONS

The PAO is proven to be a successful intervention to improve coverage of the head of the femur in those with hip dysplasia. However, it was unknown how this surgical procedure affects the contralateral limb and what the window of rehabilitation immediately following surgery looks like from a biomechanics standpoint across a range of activities of daily living. Because patients are cleared to return to full weight bearing at 6-8 weeks postoperatively, it is imperative to understand the biomechanical outcomes during a variety of tasks they may encounter in this window, because the loads experienced by the joints are directly related to each specific movement pattern. Importantly, as patients begin resumption of walking without assistance, it is also critical to understand how varied methods of rehabilitation may assist with return of limb symmetry. This is particularly important because patients exhibit asymmetric gait patterns for up to one year following surgery, including increased loading of the contralateral limb which may increase risk of developing secondary conditions such as osteoarthritis or need for subsequent surgical procedure in that limb.

In the first study, Chapter Three, the research question addressed the assessment of other activities of daily living by examining the sit-to-walk at various timepoint pre and post PAO. Data collections were performed preoperatively and at 6 weeks, 12 weeks, 6 months, and 13 months postoperatively. Patient reported outcomes demonstrated severe problems of the hip upon baseline, though improved by the 12-week time point. By 6 months all domains of the survey had returned to normal ranges except sports and recreation and overall quality of life. At 13 months following surgery, physical activity and quality of life continued to be lower than normative levels. Prior to surgery, the patient was a collegiate athlete and thus the physical limitation following PAO may cause the patient to perceive returning to preferred physical activity and quality of life differently than a patient in the general population. Hip adduction strength was weaker in the surgical limb compared to non-surgical limb at baseline. All muscle groups returned to normal between limbs by 6 months except the adductors, which took until 13 months to be similar between limbs and reach baseline levels. Preoperatively the patient demonstrated greater joint moments on the non-surgical limb, although there were no differences in how the hip, knee, or ankle contributed to total support moment. After surgery, joint moments in the surgical limb were reduced and the distribution changed which the hip contributing less to total support and the knee contributing more to total support, likely to compensate for the decreased ability of the surgical hip to contribute. In the non-surgical limb, contribution distribution did not change although joint moments were increased in this limb. This increased joint moment in the non-surgical limb and surgical knee, if not addressed in the rehabilitation process, could have consequences for the articular cartilages within the joints and potentially lead to increased risk of problems such as osteoarthritis later. Consideration of interventions or adjustments to the rehabilitation process may reduce asymmetry between limbs prior to 1 year or may reduce the overloading of the non-surgical limb.

The purpose of study two was to examine gait symmetry following PAO surgery using two rehabilitation strategies and is described in Chapter Four. Gait analysis was conducted a 6 and 12 weeks postoperatively for two PAO surgeries. Following both surgeries the same rehabilitation plan was followed, however, following surgery two only, additional gait retraining sessions using real time biofeedback of ground reaction forces was used. The inclusion of gait retraining with feedback did not improve measures of symmetry when compared to surgery one. Hip joint moments were all greater in the non-surgical limbs at all time points except for peak hip extensor moment at the 12 week point of surgery two. Increased loading in the non-surgical limb was less apparent in the vertical ground reaction forces, as absolute loads were only slightly different between limbs at each timepoint.

Within study two we hypothesized that gait retraining using feedback would improve bilateral symmetry, however we found no difference. This contrasts what was reported in study one, a sit-to-walk task which is a more muscularly demanding activity. It is currently unclear as to why symmetry was not improved but it is possible that the feedback mode (observing real time vertical ground reaction force) is not a valid measure with respect to the dynamics experienced at the hip during gait. It could be possible that the feedback presented to the participant was ineffectual, that is, trying to achieve symmetry in ground reaction force is counterproductive when considering the internal forces experienced by the participant. Given that the goal of rehabilitation is to normalize the internal loads experienced by the joint, it may be more relevant to provide real time feedback of the internal loading during gait. Pizzolato and colleagues (2017) recently demonstrated that internal loads can be effectively measured in real time and that the participant can modify said loads using varied movement strategies. Allowing the participant to manipulate the motion relative to the internal loads could be more effective to yield a different outcome than presented here.

There are a number of considerations that should be taken into account regarding the results presented. It is possible that the way joint moments described in study one versus study two contribute to contrasting outcomes between studies. That is, in study one, joint moments were reported relative to body weight as a percentage of total support moment, presenting the joint moment data within study two in a similar fashion may improve the agreement between studies. It is also possible that the performance of the respective limbs (surgical and non-surgical) between studies is influenced by prior events. In particular, the surgical limb from study one became the non-surgical limb in study two. It is possible that both the altered musculoskeletal geometry and the influence of prior rehabilitation had influence over the outcome of study two. In particular, it is unknown how tissue development and healing processes influenced limb function between study one and study two. As such, it remains unknown if there is a more appropriate timepoint during rehabilitation to implement such an intervention. These considerations and that we were unable to demonstrate improvement in asymmetry following gait intervention in this patient, indicates a need for ongoing investigation including: use of joint specific real time feedback modes, a larger study assessing more participants with true surgical and non-surgical limb relationships and expanding the duration of the intervention to coincide with the return to baseline strength demonstrated in study one.

In summary, it can take up to 1 year for muscle strength to return to baseline levels following PAO. In Chapter 3 it was demonstrated that loading in the surgical limb was decreased and that contribution of each joint to the total support moment was altered by decreased contributions of the hip and an increased contributions of the knee although they returned to baseline levels by 6 months post PAO. It was also demonstrated in Chapter 4 that the current gait intervention did not improve asymmetry compared to PAO rehabilitation without intervention. While not significant, there were several components revealing large effect sizes, thus demonstrating the potential to see significant changes if evaluated on a larger scale. When taken together, these studies suggest that there are alterations in lower limb mechanics present following PAO. Both studies demonstrated asymmetry between limbs at timepoints in the rehabilitation process following PAO. This highlights the need to further evaluate rehabilitation protocols to improve effectiveness following a PAO.

This study has a number of inferences that may inform clinical practice such as implementation of gait intervention, or a focus on abductor strengthening, it is important to keep in mind this was a single subject research analysis and larger study populations are necessary to replicate these outcomes. However, given the results of these studies, future studies should examine other activities of daily living which may include sit to stand, stair climbing, and the lifting of objects from differing heights. These activities, much like the sit-to-walk evaluated in Chapter Three, require greater muscular demand, and may shed further light on the strength requirements or deficits following PAO. It would also be worthwhile to further examine interventions, not only in gait but also in returning strength, in an effort to return symmetry between limbs prior to 1 year post operatively. Considerations for future interventions of gait should take into account volume of intervention, timepoint of implementation in the rehabilitation process, and the mode of feedback provided. Increasing the body of literature focusing on lower body mechanics in the immediate 6-month window following PAO surgery would also allow clinicians and surgeons to have a better understanding of biomechanical changes as patients are cleared for full weight bearing activity. Thus, allowing for the enhancement of the current rehabilitation protocols and potentially lead to greater improvement of outcomes following PAO surgery.

REFERENCES CITED

Abujaber SB, Marmon AR, Pozzi F, Rubano JJ, Zeni JA 2015 Sit-To-Stand Biomechanics Before and After Total Hip Arthroplasty. Journal of Arthroplasty 30: 2027–2033.

Adler KL, Cook PC, Frcs C, Geisler PR, Yen Y, Giordano BD 2015 Current Concepts in Hip Preservation Surgery : Part II — Rehabilitation. Sports Health: A Multidisciplinary Approach 8: 57–64.

Adler KL, Cook PC, Geisler PR, Yen YM, Giordano BD 2016 Current Concepts in Hip Preservation Surgery: Part II—Rehabilitation. Sports Health 8: 57–64.

Andriacchi T, Andersson G, Fermier R, Stern D, Galante J 1980 A study of lower-limb mechanics during stair-climbing. The Journal of Bone and Joint Surgery 62: 749–757.

Armand M, Lepistö J, Tallroth K, Elias J, Chao E 2005 Outcome of periacetabular osteotomy: Joint contact pressure calculation using standing AP radiographs, 12 patients followed for average 2 years. Acta Orthopaedica 76: 303–313.

Bates BT 1996 Single-subject methodology: an alternative approach. Medicine and Science in Sports and Exercise 28: 631–638.

Behrens P, Bitter T, Kurz B, Russlies M 2006 Matrix-associated autologous chondrocyte transplantation/implantation (MACT/MACI)-5-year follow-up. Knee 13: 194–202.

Beltran LS, Rosenberg ZS, Mayo JD, De Tuesta MD, Martin O, Neto LP, Bencardino JT 2013 Imaging evaluation of developmental hip dysplasia in the young adult. American Journal of Roentgenology 200: 1077–1088.

Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, Duda GN 2001 Hip contact forces and gait patterns from routine activities. Journal of Biomechanics 34: 859–871.

Bohannon RW 1997 Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. Age and Ageing 26: 15–19.

Boje J, Caspersen CK, Jakobsen SS, Søballe K, Mechlenburg I 2019 Are changes in pain associated with changes in quality of life and hip function 2 years after periacetabular osteotomy? A follow-up study of 321 patients. Journal of Hip Preservation Surgery 6: 69–76.

Cady RB 2006 Developmental dysplasia of the hip: Definition, recognition, and prevention of late sequelae. Pediatric Annals 35: 92–101.

Carpes FP, Mota CB, Faria IE 2010 On the bilateral asymmetry during running and cycling - A review considering leg preference. Physical Therapy in Sport 11: 136–142.

Chan A, McCaul KA, Cundy PJ, Haan EA, Byron-Scott R 1997 Perinatal risk factors for developmental dysplasia of the hip. Archives of Disease in Childhood: Fetal and Neonatal Edition 76: 94–100.

Choi S 2015 Total hip arthroplasty. Decision-Making in Orthopedic and Regional

Anesthesiology: A Case-Based Approach 95–100.

Chou LS, Kaufman KR, Hahn ME, Brey RH 2003 Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. Gait and Posture 18: 125–133.

Clohisy JC, Barrett SE, Gordon JE, Delgado ED, Schoenecker PL 2005 Periacetabular osteotomy for the treatment of severe acetabular dysplasia. Journal of Bone and Joint Surgery - Series A 87: 254–259.

Clohisy JC, Dobson MA, Robison JF, Warth LC, Zheng J, Liu SS, Yehyawi TM, Callaghan JJ 2011 Radiographic structural abnormalities associated with premature, natural hip-joint failure. Journal of Bone and Joint Surgery - Series A 93: 3–9.

Clohisy JC, Schutz AL, St L, Bs J, Schoenecker PL, Wright RW 2009 A Systematic Literature Review. 2041–2052.

Coobs BR, Xiong A, Clohisy JC 2015 Contemporary Concepts in the Young Adult Hip Patient: Periacetabular Osteotomy for Hip Dysplasia. Journal of Arthroplasty 30: 1105–1108.

Cross M, Smith E, Hoy D, Nolte S, Ackerman I, Fransen M, Bridgett L, Williams S, Guillemin F, Hill CL, Laslett LL, Jones G, Cicuttini F, Osborne R, Vos T, Buchbinder R, Woolf A, March L 2014 The global burden of hip and knee osteoarthritis: Estimates from the Global Burden of Disease 2010 study. Annals of the Rheumatic Diseases 73: 1323–1330.

Crowe J, Mani V, Ranawat C 1979 Total hip replacement in congenital dislocation and dysplasia of the hip. The Journal of Bone and Joint Surgery 61: 15–23.

Daggfeldt K, Thorstensson A 2003 The mechanics of back-extensor torque production about the lumbar spine. Journal of Biomechanics 36: 815–825.

Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, Guendelman E, Thelen DG 2007 OpenSim: Open-source software to create and analyze dynamic simulations of movement. IEEE Transactions on Biomedical Engineering 54: 1940–1950.

Diamond LE, Wrigley T V., Hinman RS, Hodges PW, O’Donnell J, Takla A, Bennell KL 2016 Isometric and isokinetic hip strength and agonist/antagonist ratios in symptomatic femoroacetabular impingement. Journal of Science and Medicine in Sport 19: 696–701.

Domb BG, Stake CE, Finch NA, Cramer TL 2014 Return to sport after hip arthroscopy: Aggregate recommendations from high-volume hip arthroscopy centers. Orthopedics 37: e902–e905.

Dufek J, Bates B, Stergiou N, James CR 1995a Interactive effects between group and single subject response patterns. Human Movement Science 14: 301–323.

Dufek JS, Bates BT, Stergiou N, James CR 1995b Interactive effects between group and single-subject response patterns. Human Movement Science 14: 301–323.

Eitzen I, Fernandes L, Nordsletten L, Snyder-mackler L, Arna M 2014 Gait & Posture Weight-bearing asymmetries during Sit-To-Stand in patients with mild-to-moderate hip osteoarthritis. Gait & Posture 39: 683–688.

Ezoe M, Naito M, Asayama I 2006 Muscle Strength Improves after Abductor-sparing. Clinical Orthopaedics and Related Research 444: 161–168.

Gahramanov A, İnanıcı F, Çağlar Ö, Aksoy C, Tokgözoğlu AM, Güner S, Baki A, Atilla B 2017 Functional results in periacetabular osteotomy: Is it possible to obtain a normal gait after the surgery? HIP International 27: 449–454.

Gala L, Clohisy JC, BeauĺeÍe PE 2016 Hip dysplasia in the young adult. Journal of Bone and Joint Surgery - American Volume 98: 63–73.

Ganz R, Klaue K, Son Vinh T, Mast J 1988a A New Periacetabular Osteotomy for the Treatment of Hip Dysplasias: Technique and Preliminary Results. Clinical Orthopaedics and Related Research 232: 26–36.

Ganz R, Klaue K, Vinh TS, Mast JW 1988b A New Periacetabular Osteotomy for the Treatment of Hip Dysplasias. Clinical Orthopaedics and Related Research 232: 26–36.

Givens-Heiss DL, Krebs DE, Riley PO, Strickland EM, Fares M, Hodge WA, Mann RW, Oatis CA 1992 In vivo acetabular contact pressures during rehabilitation, Part II: Postacute phase. Physical Therapy 72: 700–710.

Graham DF, Carty CP, Lloyd DG, Lichtwark GA, Barrett RS 2014 Muscle contributions to recovery from forward loss of balance by stepping. Journal of Biomechanics 47: 667–674.

Grant AD, Sala DA, Davidovitch RI 2012 The labrum: Structure, function, and injury with femoro-acetabular impingement. Journal of Children's Orthopaedics 6: 357–372.

Hamner SR, Seth A, Delp SL 2010 Muscle contributions to propulsion and support during running. Journal of Biomechanics 43: 2709–2716.

Hansen W, Shim VB, Obst S, Lloyd DG, Newsham-West R, Barrett RS 2017 Achilles tendon stress is more sensitive to subject-specific geometry than subject-specific material properties: A finite element analysis. Journal of Biomechanics 56: 26–31.

Harrington ME, Zavatsky AB, Lawson SEM, Yuan Z, Theologis TN 2007 Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging. Journal of Biomechanics 40: 595–602.

Harris JD, Mitchell RJ, Qadeer A, Gerrie BJ, Mcculloch PC 2017 Patient Reported Outcomes and Symptomatic Impingement in US Women's Professional Soccer. The Orthopaedic Journal of Sports Medicine 5: 1.

Hartofilakidis G, Karachalios T, Stamos KG 2000 Epidemiology, Demographics, and Natural History of Congenital Hip Disease in Adults. Orthopedics 23: 823–827.

Henak CR, Abraham CL, Anderson AE, Maas SA, Ellis BJ, Peters CL, Weiss JA 2014 Patient-specific analysis of cartilage and labrum mechanics in human hips with acetabular dysplasia. Osteoarthritis and Cartilage 22: 210–217.

Hopkins W 2006

Inman VT 1947 Functional Aspects of the Abductor Muscles of the Hip. The Journal of Bone and Joint Surgery 29: 607–619.

Ito H, Tanino H, Sato T, Nishida Y, Matsuno T 2014 Early weight-bearing after periacetabular osteotomy leads to a high incidence of postoperative pelvic fractures. BMC Musculoskeletal Disorders 15: 1–7.

Jacobs C, Uhl TL, Seeley M, Sterling W, Goodrich L 2005 Strength and fatigability of the dominant and nondominant hip abductors. Journal of Athletic Training 40: 203–206.

Jacobsen JS, Nielsen DB, Sørensen H, Søballe K, Mechlenburg I 2014 Joint kinematics and kinetics during walking and running in 32 patients with hip dysplasia 1 year after periacetabular osteotomy. Acta Orthopaedica 85: 592–599.

Jacobsen JS, Søballe K, Thorborg K, Bolvig L, Jakobsen S, Hölmich P, Mechlenburg I, Jacobsen JS, Søballe K, Thorborg K, Bolvig L 2019 Patient-reported outcome and muscle – tendon pain after periacetabular osteotomy are related : 1- year follow-up in 82 patients with hip dysplasia Patient-reported outcome and muscle – tendon pain after periacetabular osteotomy are related : 1-year follow. Acta Orthopaedica 90: 40–45.

Jacobsen JS, Thorborg K, Hölmich P, Bolvig L, Storgaard Jakobsen S, Søballe K, Mechlenburg I 2018 Does the physical activity profile change in patients with hip dysplasia from before to 1 year after periacetabular osteotomy? Acta Orthopaedica 89: 622–627.

Jacobsen S, Sonne-Holm S 2005a Hip dysplasia: A significant risk factor for the development of hip osteoarthritis. A cross-sectional survey. Rheumatology 44: 211–218.

Jacobsen S, Sonne-Holm S 2005b Hip dysplasia: A significant risk factor for the development of hip osteoarthritis. A cross-sectional survey. Rheumatology 44: 211–218.

Kain M, Novais E, Vallim C, Millis M, Kim Y 2011 Periacetabular Osteotomy After Failed Hip Arthroscopy for Labral Tears in Patients with Acetabular Dysplasia. Journal of Bone and Joint Surgery American 93: 57–61.

Kaku N, Tsumura H, Taira H, Sawatari T, Torisu T 2004 Biomechanical study of load transfer of the pubic ramus due to pelvic inclination after hip joint surgery using a three-dimensional finite element model. Journal of Orthopaedic Science 9: 264–269.

Karam M, Gao Y, McKinley T 2011a Assessment of Walking Pattern Pre and Post Periacetabular Osteotomy. The Iowa orthopaedic journal 31: 83–89.

Karam MD, Gao Y, McKinley T 2011b Assessment of walking pattern pre and post peri-acetabular osteotomy. The Iowa orthopaedic journal 31: 83–89.

Katoh M, Yamasaki H 2009 Comparison of reliability of isometric leg muscle strength measurements made using a Hand-Held dynamometer with and without a restraining Belt. Journal of Physical Therapy Science 21: 37–42.

Kemp JL, Collins NJ, Roos EM, Crossley KM 2013 Psychometric properties of patient-reported outcome measures for hip arthroscopic surgery. American Journal of Sports Medicine 41: 2065–2073.

Kerr A, Durward B, Kerr KM 2004 Defining phases for the sit-to-walk movement. Clinical Biomechanics 19: 385–390.

Kim CH, Kim JW 2020 Periacetabular osteotomy vs. total hip arthroplasty in young active patients with dysplastic hip: Systematic review and meta-analysis. Orthopaedics and Traumatology: Surgery and Research 106: 1545–1551.

Kim WK, Kim DK, Seo KM, Kang SH 2014 Reliability and validity of isometric knee extensor strength test with hand-held dynamometer depending on its fixation: A pilot study. Annals of Rehabilitation Medicine 38: 84–93.

Klit J, Hartig-Andreasen C, Jacobsen S, Søballe K, Troelsen A 2014 Periacetabular osteotomy: Sporting, social and sexual activity 9-12 years post surgery. HIP International 24: 27–31.

Kraeutler MJ, Garabekyan T, Pascual-Garrido C, Mei-Dan O 2016 Hip instability: A review of hip dysplasia and other contributing factors. Muscles, Ligaments and Tendons Journal 6: 343–353.

Kralj M, Mavčič B, Antolič V, Iglič A, Kralj-Iglič V 2005 The Bernese periacetabular osteotomy: Clinical, radiographic and mechanical 7-15-year follow-up of 26 hips. Acta Orthopaedica 76: 833–840.

De La Rocha A, Sucato D, Tulchin K, Podeszwa DA 2012 Treatment of Adolescents with a Periacetabular Osteotomy After Previous Pelvic Surgery. Clinical Orthopaedics 470: 2583–2590.

Larsen JB, Mechlenburg I, Jakobsen SS, Thilleman TM, Søballe K 2020 14-Year Hip Survivorship After Periacetabular Osteotomy: a Follow-Up Study on 1,385 Hips. Acta Orthopaedica 91: 299–305.

Lee KJ, Park SJ, Lee SJ, Naito M, Kwon SY 2015 Biomechanical study on the efficacy of the periacetabular osteotomy using Patient-specific finite element analysis. International Journal of Precision Engineering and Manufacturing 16: 823–829.

Leunig M, Ganz R 2007a (iii) Bernese periacetabular osteotomy. Current Orthopaedics 21: 100–108.

Leunig M, Ganz R 2007b Bernese periacetabular osteotomy. Current Orthopaedics 21: 100–108.

Leunig M, Siebenrock KA, Ganz R 2001 Rationale of periacetabular osteotomy and background work. Journal of Bone and Joint Surgery 83A: 438–448.

Lu TW, O’Connor JJ 1999 Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. Journal of Biomechanics 32: 129–134.

Mandeville D, Osternig LR, Chou LS 2007 The effect of total knee replacement on dynamic support of the body during walking and stair ascent. Clinical Biomechanics 22: 787–794.

Martins J, da Silva JR, da Silva; MRB, Bevilaqua-Grossi D 2017 Reliability and Validity of the Belt-Stabilized Handheld Dynamometer in Hip- and Knee-Strength Tests. Journal of Athletic Training 52: 809–819.

Matheney T, Kim Y, Zurakowski D, Matero C, Millis M 2009 Intermediate to Long-Term Results Following the Bernese Periacetabular Osteotomy and Predictors of Clinical Outcome. 2113–2123.

Matta J, Stover M, Siebenrock K 1999 Periacetabular osteotomy through the Smith-Petersen approach. Clinical Orthopaedics and Related Research 21–32.

McCrory JL, White SC, Lifeso RM 2001 Vertical ground reaction forces: Objective measures of gait following hip arthroplasty. Gait and Posture 14: 104–109.

Michaeli DA, Murphy SB, Hipp JA 1997 Comparison of predicted and measured contact pressures in normal and dysplastic hips. Medical Engineering and Physics 19: 180–186.

Millis MB, Murphy SB, Poss R 1995 Osteotomis about the hip for the prevention and treatment of osteoarthrosis. Journal of Bone and Joint Surgery American 77: 626–647.

Miura N, Tagomori K, Ikutomo H, Nakagawa N 2018a Asymmetrical loading during sit-to-stand movement in patients 1 year after total hip arthroplasty. Clinical Biomechanics 57: 89–92.

Miura N, Tagomori K, Ikutomo H, Nakagawa N, Masuhara K 2018b Asymmetrical loading during sit-to-stand movement in patients 1 year after total hip arthroplasty. Clinical Biomechanics 57: 89–92.

Mizner RL, Snyder-Mackler L 2005 Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. Journal of Orthopaedic Research 23: 1083–1090.

Moore KL, Dalley AF, Agur AMR 2014 Clinically Oriented Anatomy. Baltimore: Lippincott Williams & Wilkins.

Murphy RJ, Armiger RS, Lepistö J, Mears SC, Taylor RH, Armand M 2015 Development of a biomechanical guidance system for periacetabular osteotomy. International Journal of Computer Assisted Radiology and Surgery 10: 497–508.

Murphy S, Deshmukh R 2002a Periacetabular Osteotomy. 168–174.

Murphy SB, Deshmukh R 2002b Periacetabular Osteotomy: Preoperative Radiographic

Predictors of Outcome. Clinical Orthopaedics and Related Research 405: 168–174.

Murphy SB, Ganz R, Muller ME 1995 The Prognosis in Untreated Dysplagia of the Hip. The Journal of bone and joint surgery British volume 77: 985–989.

Nadeau S, McFadyen BJ, Malouin F 2003 Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: What are the challenges compared to level walking? Clinical Biomechanics 18: 950–959.

Nawabi DH, Degen RM, Fields KG, McLawhorn A, Ranawat AS, Sink EL, Kelly BT 2016 Outcomes after Arthroscopic Treatment of Femoroacetabular Impingement for Patients with Borderline Hip Dysplasia. American Journal of Sports Medicine 44: 1017–1023.

Niknafs N, Murphy RJ, Armiger RS, Lepistö J, Armand M 2013 Biomechanical Factors in Planning of Periacetabular Osteotomy. Frontiers in Bioengineering and Biotechnology 1: .

Nishimura M, Takahira N, Fukushima K, Yamamoto T, Moriya M, Uchiyama K 2015 Early gait analysis after curved periacetabular osteotomy for acetabular dysplasia. Orthopedic Research and Reviews 25.

Nishino T, Ishii T, Chang F, Yanai T, Watanabe A, Ogawa T, Mishima H, Nakai K, Ochiai N 2010 Effect of gradual weight-bearing on regenerated articular cartilage after joint distraction and motion in a rabbit model. Journal of Orthopaedic Research 28: 600–606.

Pedersen ENG, Alkjær T, Søballe K, Simonsen EB 2006 Walking pattern in 9 women with hip dysplasia 18 months after periacetabular osteotomy. Acta Orthopaedica 77: 203–208.

Peters CL, Erickson JA, Anderson MB, Anderson LA 2015 Preservation of the Rectus Femoris Origin During Periacetabular Osteotomy Does Not Compromise Acetabular Reorientation. Clinical Orthopaedics and Related Research 473: 608–614.

Pisters MF, Veenhof C, Meeteren NLUVAN, Ostelo RW, Bakker DHDE, Schellevis OISG, Dekker J 2007 Long-Term Effectiveness of Exercise Therapy in Patients With Osteoarthritis of the Hip or Knee : A Systematic Review. Arthritis and Rheumatism 57: 1245–1253.

Pizzolato C, Reggiani M, Saxby DJ, Ceseracciu E, Modenese L, Lloyd DG 2017 Biofeedback for Gait Retraining Based on Real-Time Estimation of Tibiofemoral Joint Contact Forces. IEEE Transactions on Neural Systems and Rehabilitation Engineering 25: 1612–1621.

Ramisetty N, Kwon Y, Mohtadi N 2015 Patient-reported outcome measures for hip preservation surgery--a systematic review of the literature. Journal of Hip Preservation Surgery 2: 15–27.

Reijman M, Hazes JMW, Pols HAP, Koes BW, Bierma-Zeinstra SMA 2005a Acetabular dysplasia predicts incident osteoarthritis of the hip: The Rotterdam study. Arthritis and Rheumatism 52: 787–793.

Reijman M, Hazes JMW, Pols HAP, Koes BW, Bierma-Zeinstra SMA 2005b Acetabular dysplasia predicts incident osteoarthritis of the hip: The Rotterdam study. Arthritis and Rheumatism 52: 787–793.

Samaan MA, Schwaiger BJ, Gallo MC, Link TM, Zhang AL, Majumdar S, Souza RB 2017 Abnormal Joint Moment Distributions and Functional Performance During Sit-to-Stand in Femoroacetabular Impingement Patients. PM and R 9: 563–570.

Schroeder C, Zavala L, Opstedal L, Becker J 2020 Recovery of Lower Extremity Function in the Initial Year Following Periacetabular Osteotomy: A Single Subject Analysis. Physiotherapy Theory and Practice 00: 1–12.

Schwachmeyer V, Damm P, Bender A, Dymke J, Graichen F, Bergmann G 2013 In Vivo Hip Joint Loading during Post-Operative Physiotherapeutic Exercises. PLoS ONE 8: e77807.

Siebenrock KA, Leunig M, Ganz R 2001a Periacetabular osteotomy: the Bernese experience. Instructional course lectures 50: 239–245.

Siebenrock KA, Leunig M, Ganz R 2001b Periacetabular osteotomy: The Bernese experience. Journal of Bone and Joint Surgery - Series A 83: 449–455.

Sophia Fox AJ, Bedi A, Rodeo SA 2009 The basic science of articular cartilage: Structure, composition, and function. Sports Health 1: 461–468.

Steel HH 1973 Triple Osteotomy of the Innominate Bone. The Journal of Bone and Joint Surgery 55: 343–350.

Steppacher SD, Tannast M, Ganz R, Siebenrock KA 2008 Mean 20-year followup of bernese periacetabular osteotomy. Clinical Orthopaedics and Related Research 466: 1633–1644.

Stulberg S 1975 Unrecognized childhood hip disease: a major cause of idiopathic osteoarthritis of the hip. In: Cordell LD, Harris WH, Ramsey PL, MacEwen GD (eds). Proceedings of the Third Open Scientific Meeting of the Hip Society. St Louis, MO: Mosby 212–228.

Stulberg S, Harris W 1974 Acetabular dysplasia and development of osteoarthritis of hip. In: Harris WH (ed.). The Hip. Proceedings of the Second Open Scientific Meeting of the Hip Society. St Louis, MO: Mosby 82–93.

Sucato D, Tulchin K, Shrader M, DeLaRocha A, Gist T, Sheu G 2010a Gait, hip strength and functional outcomes after a ganz periacetabular osteotomy for adolescent hip dysplasia. Journal of Pediatric Orthopaedics 30: 344–350.

Sucato DJ, Tulchin K, Shrader MW, Delarocha A, Gist T, Sheu G 2010b Gait , Hip Strength and Functional Outcomes After a Ganz Periacetabular Osteotomy for Adolescent Hip Dysplasia. 30: 344–350.

The United States Bone and Joint Inititative 2020 United States Bone and Joint Initiative: The Burden of Musculoskeletal Diseases in the United States (BMUS). Rosemont, IL:

Thomas-Aitken HD, Willey MC, Goetz JE 2018 Joint contact stresses calculated for acetabular dysplasia patients using discrete element analysis are significantly influenced by the applied gait pattern. Journal of Biomechanics 79: 45–53.

Thomeé R, Jonasson P, Thorborg K, Sansone M, Ahlden M, Thomeé C, Karlsson J, Baranto A 2015 Validation of the Copenhagen hip groin outcome score (HAGOS) for pain, symptoms and physical function in patients with hip/groin disability. Physiotherapy 101: e1514–e1515.

Thorborg K, Branci S, Stensbirk F, Jensen J, Holmich P 2014 Copenhagen hip and groin outcome scores (HAGOS) in male soccer: reference values for hip and groin injury free players. British Journal of Sports Medicine 48: 557–559.

Thorborg K, Hölmich P, Christensen R, Petersen J, Roos EM 2011 The Copenhagen Hip and Groin Outcome Score (HAGOS): Development and validation according to the COSMIN checklist. British Journal of Sports Medicine 45: 478–491.

Thorborg K, Tijssen M, Habets B, Bartels EM, Roos EM, Kemp J, Crossley KM, Hölmich P 2015 Patient-Reported Outcome (PRO) questionnaires for young to middle-aged adults with hip and groin disability: A systematic review of the clinimetric evidence. British Journal of Sports Medicine 49: 812.

Tippett S 2006a Returning to Sports After Periacetabular Osteotomy for Developmental Dysplasia of the Hip. North American Journal of Sports Physical Therapy 1: .

Tippett SR 2006b Returning to sports after periacetabular osteotomy for developmental dysplasia of the hip. North American journal of sports physical therapy : NAJSPT 1: 32–9.

Tonnis D 1990 Surgical treatment of congenital dislocation of the hip. Clinical Orthopaedics and Related Research 258: 33–40.

Torio C, Moore B 2016 Statistical Brief #204. National Inpatient Hospital Costs: The Most Expensive Conditions by Payer, 2013. Rockville, MD: Agency for Healthcare Research and Quality .

Trousdale RT, Cabanela ME 2003 Lessons learned after more than 250 periacetabular osteotomies. Acta Orthopaedica Scandinavica 74: 119–126.

Umeda N, Miki H, Ishii T, Yoshikawa H, Sugano N 2009 Progression of osteoarthritis of the knee after unilateral total hip arthroplast: a minimum 10-year follow up study. Archives of Orthopaedic and Trauma Surgery 129: 149–154.

Vanwanseele B, Lucchinetti E, Stüssi E 2002 The effects of immobilization on the characteristics of articular cartilage: Current concepts and future directions. Osteoarthritis and Cartilage 10: 408–419.

Wall PDH, Fernandez M, Griffin DR, Foster NE 2013 Nonoperative Treatment for Femoroacetabular Impingement: A Systematic Review of the Literature. PM and R 5: 418–426.

Wedge JH, Wasylenko MJ 1979 The natural history of congenital disease of the hip. Journal of Bone and Joint Surgery - Series B 61: 334–338.

Weinstein S 1987 Natural history of congenital hip dislocation (CDH) and hip dysplasia. Clinical Orthopaedics and Related Research 62–76.

Wesseling M, Meyer C, Corten K, Desloovere K, Jonkers I 2018 Longitudinal joint loading in patients before and up to one year after unilateral total hip arthroplasty. Gait and Posture 61: 117–124.

White SC, Lifeso RM 2005 Altering asymmetric limb loading after hip arthroplasty using real-time dynamic feedback when walking. Archives of Physical Medicine and Rehabilitation 86: 1958–1963.

Wiberg G 1939 Studies on dysplastic acetabula and congenital subluxation of the hip joint: with special reference to the complication of osteoarthritis. Acta Chirurgica Scandinavica 83: 5–135.

Wilk KE, Reinold MM, Hooks TR 2003 Recent advances in the rehabilitation of isolated and combined anterior cruciate ligament injuries. Orthopedic Clinics 34: P107-137.

Willy RW, Scholz JP, Davis IS 2012 Mirror gait retraining for the treatment of patellofemoral pain in female runners. Clinical Biomechanics 27: 1045–1051.

Winter DA 1980 Overall Principle of Lower Limb Spport During Stance Phase of Gait.pdf.crdownload. Journal of Biomechanics 13: 923–927.

Wong LCY, Chiu WK, Russ M, Liew S 2012 Review of techniques for monitoring the healing fracture of bones for implementation in an internally fixated pelvis. Medical Engineering and Physics 34: 140–152.

Wyles CC, Heidenreich MJ, Jeng J, Larson DR, Trousdale RT, Sierra RJ 2017 The John Charnley Award: Redefining the Natural History of Osteoarthritis in Patients With Hip Dysplasia and Impingement. Clinical Orthopaedics and Related Research 475: 336–350.

Yasunaga Y, Yamasaki T, Ochi M 2012 Patient selection criteria for periacetabular osteotomy or rotational acetabular osteotomy. Clinical Orthopaedics and Related Research 470: 3342–3354.

Yeung M, Kowalczuk M, Simunovic N, Ayeni OR 2016 Hip arthroscopy in the setting of hip dysplasia: A systematic review. Bone and Joint Research 5: 225–231.

Youdas JW, Kotajarvi BJ, Padgett DJ, Kaufman KR 2005 Partial weight-bearing gait using conventional assistive devices. Archives of Physical Medicine and Rehabilitation 86: 394–398.

Zhao X, Chosa E, Totoribe K, Deng G 2010 Effect of periacetabular osteotomy for acetabular dysplasia clarified by three-dimensional finite element analysis. Journal of Orthopaedic Science 15: 632–640.

Zou Z, Chávez-Arreola A, Mandal P, Board TN, Alonso-Rasgado T 2013 Optimization of the position of the acetabulum in a ganz periacetabular osteotomy by finite element analysis. Journal of Orthopaedic Research 31: 472–479.

APPENDICES

APPENDIX A

APPROVED INFORMED CONSENT FOR CHAPTER 3

APPROVED
MSU IRB
04/24/2018
Date approved

SUBJECT CONSENT FORM
FOR PARTICIPATION IN HUMAN RESEARCH
AT MONTANA STATE UNIVERSITY

TITLE: Case Study on the Effects and Recovery from Periacetabular Osteotomy Surgery for a Non-traditional Patient.

You are being asked to participate in a research study on the effects and recovery of non-traditional patients receiving periacetabular osteotomy surgery. The purpose of this study is to better understand functional and biomechanical outcomes following the surgical procedure.

INVESTIGATORS:

This research is being conducted by:
Cailyn Schroeder
Undergraduate Student
Phone: (406)868-8915
Email: cailyn_schroeder@yahoo.com

Dr. James Becker
Assistant Professor, Health and Human Development
Phone: (406)994-6854
Email: james.becker4@montana.edu

Linnea Zavala
Master's Student
Phone: (406)425-1434
Email: linnea.zavala@gmail.com

FUNDING AGENCY: Not Applicable

PROCEDURES:
If you agree to participate you will report to Neuromuscular Biomechanics Lab and asked to comply with the following protocols.

Survey:
Upon entering the lab, you will be asked to complete a HAGOS survey to measure hip and groin outcomes. You will also be asked to rate hip pain on a scale of 1-10.

Pre-testing protocol:
Prior to any exercise, EMG electrodes will be placed on various muscles across the body. You will then be run through a battery of muscle contractile tests. Following these tests, electrodes will be removed, and you will then be fitted with reflective markers that will be placed on anatomical landmarks across the body.

Treatment protocol:
Once accurately fitted with markers, you will then begin the data collection. Gait analysis will be conducted by walking across force plates in the lab. Squat analysis will be conducted by standing on the force plates and using a wooden dowel in the front squat position. The Y- balance test will be conducted on each leg.

Time Commitment: The time for your participation in this testing is about 2 hours per visit. Six visits will be required.

Confidentiality: In addition, by giving consent you agree to release radiologic imaging from prior to and following the surgical procedure, as well as notes from surgery and notes and treatment protocol from physical therapy. Further information on the release of these medical records is outlined in the "Statement of Authorization" section. Personal information and data will be kept in a locked cabinet. If requested your data will only be given to you.

Benefits: You will learn about biomechanical outcomes regarding periacetabular osteotomy surgery.

Compensation: There is no financial compensation.

Risks:
Risks in this study are minimal. Risks include muscle fatigue and soreness may due to the nature of the exercises, discomfort from removing the adhesive holding on the reflective markers, and a breach of confidentiality. These risks are minimized however by the following steps: not allowing certain movements unless approved by physical therapy protocol, providing rubbing alcohol if desired to help break down the adhesive, and storing any identifying documents in a filing cabinet locked in Dr. Becker's office. If complications do arise during this study, we can refer you to appropriate medical caregivers. However, there is no compensation available from MSU for injury.

Questions:
Your decision whether or not to participate will not jeopardize you in any way. You are free to discontinue participation at any time without negative effects on your relationship with MSU or the researchers. If you have any questions, please ask Cailyn Schroeder (406-868-8915 or cailyn_schroeder@yahoo.com) or Dr. James Becker (406-994-6854 or james.becker4@montana.edu).

Additional questions about the rights of human subjects can be answered by the Chairman of the Institutional Review Board, Dr. Mark Quinn, (406) 994-4707.

Freedom of Consent

I have been given ample opportunity to read this document in its entirety and to ask questions which have been answered to my satisfaction. I hereby consent to become a participant in this study knowing the health risks involved and that I may withdraw my consent at any time, for any reason, and that it will not affect my standing on the team or with MSU. I am covered by a health insurance program. I consent that photographs and/or video may also be taken during data collection sessions. I also understand that project personnel may screen me from this study for any reason deemed appropriate.

APPROVED
MSU IRB
04/24/2018
Date approved

STATEMENT OF AUTHORIZATION

We are asking you to take part in the research described in the attached consent form. To do this research, we need to collect health information that identifies you. We may collect the results of tests, questionnaires and interviews. We may also collect information from your medical record. We will only collect information that is needed for the research. This information is described in the attached consent form. For you to be in this research, we need your permission to collect and share this information.

We will share your health information with people at the hospital who help with the research. We may share your information with other researchers outside of the hospital. We may also share your information with people outside of the hospital who are in charge of the research, pay for or work with us on the research. Some of these people make sure we do the research properly. The "confidentiality" section of the consent form says who these people are. Some of these people may share your health information with someone else. If they do, the same laws that the hospital must obey may not protect your health information.

If you sign this form, we will collect your health information until the end of the research. We may collect some information from your medical records even after your direct participation in the research project ends. We will keep all the information for at least **six years**, in case we need to look at it again. We will protect the information and keep it confidential.

Your information may also be useful for other studies. We can only use your information again if the Institutional Review Board gives us permission. This committee may ask us to talk to you again before doing the research. But the committee may also let us do the research without talking to you again if we keep your health information private.

If you sign this form, you are giving us permission to collect, use and share your health information. You do not need to sign this form. If you decide not to sign this form, you cannot be in the research study. You need to sign this form and the attached consent form if you want to be in the research study. We cannot do the research if we cannot collect, use and share your health information.

If you change your mind later and do not want us to collect or share your health information, you need to send a letter to the researcher listed on the attached consent form. The letter needs to say that you have changed your mind and do not want the researcher to collect and share your health information. You may also need to leave the research study if we cannot collect any more health information. We may still use the information we have already collected. We need to know what happens to everyone who starts a research study, not just those people who stay in it.

APPROVED
MSU IRB
04/24/2018
Date approved

APPENDIX B

HAGOS QUESTIONNAIRE

The Copenhagen Hip and Groin Outcome Score (HAGOS): development and validationaccording to the COSMIN checklist

K Thorborg,[1] P Hölmich,[1] R Christensen,[2,3] J Petersen,[1] EM Roos,[2]

[1]Arthroscopic Centre Amager, Amager Hospital, Faculty of Health Sciences, University ofCopenhagen, Copenhagen, Denmark;
[2]Research Unit for Musculoskeletal Function and Physiotherapy, Institute of Sports Science andClinical Biomechanics, University of Southern Denmark, Odense, Denmark.
[3]The Parker Institute: Musculoskeletal Statistics Unit, Copenhagen University Hospital,Frederiksberg, Copenhagen, Denmark.

Corresponding author:
Kristian Thorborg,
Department of Orthopaedic Surgery,
DK-2300 Copenhagen S, Faculty of Health Sciences, University of Copenhagen, Copenhagen,Denmark. Tel: +45 3234 3247, Fax: +45 3234 3995, E-mail: kristianthorborg@hotmail.com

ABSTRACT

Background Valid, reliable and responsive Patient-Reported Outcome (PRO) questionnaires foryoung to middle-aged, physically active individuals with hip and groin pain are lacking.

Objective To develop and validate a new PRO in accordance with the COnsensus-based Standardsfor the selection of health Measurement INstruments (COSMIN) recommendations, for use in young to middle-aged, physically active patients with longstanding hip and/or groin pain.

Methods Preliminary patient interviews (content validity) included 25 patients. Validity, reliabilityand responsiveness were evaluated in a clinical study including 101 physically active patients (50 women); mean age 36 years, range 18-63.

Results The Copenhagen Hip and Groin Outcome Score (HAGOS) consists of six separate subscales assessing Pain, Symptoms, Physical function in daily living, Physical function in Sport and Recreation, Participation in Physical Activities and hip and/or groin-related Quality of Life. Test-retest reliability was substantial, with Intraclass Correlation Coefficients (ICC) ranging from 0.82-0.91 for the six subscales. The smallest detectable change ranged from 17.7-33.8 points at theindividual level and from 2.7-5.2 points at the group level for the different subscales. Construct validity and responsiveness were confirmed with statistically significant correlation coefficients (0.37-0.73, $p<.01$) for convergent construct validity, and for responsiveness from 0.56-0.69, $p<.01$.

Conclusion HAGOS has adequate measurement qualities for the assessment of symptoms, activitylimitations, participation restrictions and quality of life in physically active, young to middle-aged patients with longstanding hip and/or groin pain, and is recommended for use in interventions where the patient's perspective and health-related quality of life are of primary interest.

Key words: hip, groin, patient-reported outcome, questionnaires, psychometric properties

Trial registration: ClinicalTrials.gov NCT00716729

HAGOS

Today's date:_______/______/_______Date of birth:______/______/_________

Name: ____

INSTRUCTIONS: This questionnaire asks for your view about your hip and/or groin problem. The questions should be answered considering your hip and/or groin functionduring the **past week**.This information will help us keep track of how you feel, and howwell you are able to do your usual activities.

Answer **every** question by ticking the appropriate box. Tick only one box for each question. If a question does not pertain to you or you have not experienced it in the pastweek please make your “best guess” as to which response would be the most accurate.

Symptoms

These questions should be answered considering your hip and/or groin **symptoms** anddifficulties during the **past week**.

S1 Do you feel discomfort in your hip and/or groin?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2 Do you hear clicking or any other type of noise from your hip and/or groin?

Never	Rarely	Sometimes	Often	All the time
☐	☐	☐	☐	☐

S3 Do you have difficulties stretching your legs far out to the side?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S4 Do you have difficulties taking full strides when you walk?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S5 Do you experience sudden twinging/stabbing sensations in your hip and/or groin?

Never	Rarely	Sometimes	Often	All the time
☐	☐	☐	☐	

Stiffness

The following questions concern the amount of stiffness you have experienced during the **past week** in your hip and/or groin. Stiffness is a sensation of restriction orslowness in the ease with which you move your hip and/or groin.

S6 How severe is your hip and/or groin stiffness after first awakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7 How severe is your hip and/or groin stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Pain

P1 How often is your hip and/or groin painful?

Never	Monthly	Weekly	Daily	Always
☐	☐	☐	☐	☐

P2 How often do you have pain in areas other than your hip and/or groin that you think may berelated to your hip and/or groin problem?

Never	Monthly	Weekly	Daily	Always
☐	☐	☐	☐	☐

The following questions concern the amount of pain you have experienced during the **pastweek** in your hip and/or groin. **What amount of hip and/or groin pain have you experienced during the following activities?**

P3 Straightening your hip fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P4 Bending your hip fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P5 Walking up or down stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P6 At night while in bed (pain that disturbs your sleep)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P7 Sitting or lying

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

The following questions concern the amount of pain you have experienced during the **pastweek** in your hip and/or groin. **What amount of hip and/or groin pain have you experienced during the following activities?**

P8 Standing upright

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P9 Walking on a hard surface (asphalt, concrete, etc.)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P10 Walking on an uneven surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Physical function, daily living

The following questions concern your physical function. **For each of the following activities please indicate the degree of difficulty you have experienced in the pastweek due to your hip and/or groin problem.**

A1 Walking up stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2 Bending down, e.g. to pick something up from the floor

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A3 Getting in/out of car

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A4 Lying in bed (turning over or maintaining the same hip position for a long time)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A5 Heavy domestic duties (scrubbing floors, vacuuming, moving heavy boxes etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

The following questions concern your physical function when participating in higher-levelactivities. Answer **every** question by ticking the appropriate box. If a question does not pertain to you or you have not experienced it in the past week please make your "best guess" as to which response would be the most accurate. **The questions should be answered considering what degree of difficulty you have experienced during the following activities in the past week due to problems with your hip and/or groin.**

SP1 Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2 Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3 Twisting/pivoting on a weight bearing leg

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4 Walking on an uneven surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5 Running as fast as you can

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP6 Bringing the leg forcefully forward and/or out to the side, such as in kicking, skating etc.

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP7 Sudden explosive movements that involve quick footwork, such as accelerations, decelerations, change of directions etc.

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP8 Situations where the leg is stretched into an outer position
(such as when the leg is placed as far away from the body as possible)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Participation in physical activities

The following questions are about your ability to participate in your preferred physical activities. Physical activities include sporting activities as well as all other forms of activitywhere you become slightly out of breath. **When you answer these questions consider to what degree your ability to participate in physical activities during the past weekhas been affected by your hip and/or groin problem.**

PA1 Are you able to participate in your preferred physical activities for as long as you would like?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

PA2 Are you able to participate in your preferred physical activities at your normal performance level?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Quality of Life

Q1 How often are you aware of your hip and/or groin problem?

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

Q2 Have you modified your life style to avoid activities potentially damaging to your hip and/or groin?

Not at all	Mildly	Moderately	Severely	Totally
☐	☐	☐	☐	☐

Q3 In general, how much difficulty do you have with your hip and/or groin?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Q4 Does your hip and/or groin problem affect your mood in a negative way?

Not at all	Rarely	Sometimes	Often	All the time
☐	☐	☐	☐	☐

Q5 Do you feel restricted due to your hip and/or groin problem?

Not at all	Rarely	Sometimes	Often	All the time
☐	☐	☐	☐	☐

Thank you very much for completing all the questions in this questionnaire.

APPENDIX C

APPROVED INFORMED CONSENT FOR CHAPTER 4

SUBJECT CONSENT FORM
FOR PARTICIPATION IN HUMAN RESEARCH
AT MONTANA STATE UNIVERSITY

TITLE: Case Study on the Effects and Recovery from Periacetabular Osteotomy Surgery Using and Anti-Gravity Treadmill

You are being asked to participate in a research study on the effects and recovery using an anti-gravity treadmill following periacetabular osteotomy surgery. The purpose of this study is to better understand the functional biomechanical outcomes following the surgical procedure and this form of rehabilitation.

INVESTIGATORS:

This research is being conducted by:

Cailyn Schroeder
Undergraduate Student
Phone: (406)868-8915
Email: cailyn_schroeder@yahoo.com

Dr. James Becker
Assistant Professor, Health and Human Development
Phone: (406)994-6854
Email: james.becker4@montana.edu

David Graham
Assistant Professor, Health and Human Development
Phone: (406)994-4120
Email: david.graham7@montana.edu

FUNDING AGENCY: Not Applicable

PROCEDURES:

If you agree to participate you will report to Neuromuscular Biomechanics Lab and physical therapy sessions and asked to comply with the following protocols.

In the Neuromuscular Biomechanics Lab:

Survey:

Upon entering the lab, you will be asked to complete a HAGOS survey to measure hip and groin outcomes. You will also be asked to rate hip pain on a scale of 1-10.

Gait Analysis:

Surface EMG electrodes will be placed on various muscles across the lower body. You will then complete a battery of muscle strength tests assessing the strength of hip muscles. Following muscle strength testing reflective markers will be placed on bony landmarks on your arms, torso, pelvis, and legs. You will then perform the following activities in the laboratory: walking, chair rising (sit-to-stand). Your motion during these activities will be recorded using motion capture.

During Physical Therapy Sessions Following Surgery

You will walk on an anti-gravity treadmill while seeing real-time feedback of the force under left and right feet. The amount of body weight support will slowly decrease over the six week period to match the rehabilitation guidelines provided by your orthopedic surgeon. The amount of time you walk will slowly be lengthened over the six week period.

Time Commitment: The time for your participation in the laboratory testing is about 2 hours per visit. Two visits will be required, one before and one six weeks following surgery. Each gait retraining session in physical therapy will take about 1 hour. These will be scheduled concurrently with your regular physical therapy appointments.

APPROVED
MSU IRB
12/23/2019
Date approved

Confidentiality: In addition, by giving consent you agree to release radiologic imaging from prior to and following the surgical procedure, as well as notes from surgery and notes and treatment protocol from physical therapy. Further information on the release of these medical records is outlined in the "Statement of Authorization" section. Personal information and data will be kept in a locked cabinet. If requested your data will only be given to you.

Benefits: You will learn about biomechanical outcomes regarding periacetabular osteotomy surgery.

Compensation: There is no financial compensation.

Risks:
Risks in this study are minimal. Risks include muscle fatigue and soreness may due to the nature of the exercises, discomfort from removing the adhesive holding on the reflective markers, and a breach of confidentiality. These risks are minimized however by the following steps: not allowing certain movements unless approved by physical therapy protocol, providing rubbing alcohol if desired to help break down the adhesive, and storing any identifying documents in a filing cabinet locked in Dr. Becker's office. If complications do arise during this study, we can refer you to appropriate medical caregivers. However, there is no compensation available from MSU for injury.

Questions:
Your decision whether or not to participate will not jeopardize you in any way. You are free to discontinue participation at any time without negative effects on your relationship with MSU or the researchers. If you have any questions, please ask Cailyn Schroeder (406-868-8915 or cailyn_schroeder@yahoo.com) or Dr. James Becker (406-994-6854 or james.becker4@montana.edu).

Additional questions about the rights of human subjects can be answered by the Chairman of the Institutional Review Board, Dr. Mark Quinn, (406) 994-4707.

Freedom of Consent

I have been given ample opportunity to read this document in its entirety and to ask questions which have been answered to my satisfaction. I hereby consent to become a participant in this study knowing the health risks involved and that I may withdraw my consent at any time, for any reason, and that it will not affect my standing on the team or with MSU. I am covered by a health insurance program. I consent that photographs and/or video may also be taken during data collection sessions. I also understand that project personnel may screen me from this study for any reason deemed appropriate.

APPROVED
MSU IRB
12/23/2019
Date approved

STATEMENT OF AUTHORIZATION

We are asking you to take part in the research described in the attached consent form. To do this research, we need to collect health information that identifies you. We may collect the results of tests, questionnaires and interviews. We may also collect information from your medical record. We will only collect information that is needed for the research. This information is described in the attached consent form. For you to be in this research, we need your permission to collect and share this information.

We will share your health information with people at the hospital who help with the research. We may share your information with other researchers outside of the hospital. We may also share your information with people outside of the hospital who are in charge of the research, pay for or work with us on the research. Some of these people make sure we do the research properly. The "confidentiality" section of the consent form says who these people are. Some of these people may share your health information with someone else. If they do, the same laws that the hospital must obey may not protect your health information.

If you sign this form, we will collect your health information until the end of the research. We may collect some information from your medical records even after your direct participation in the research project ends. We will keep all the information for at least **six years**, in case we need to look at it again. We will protect the information and keep it confidential.

Your information may also be useful for other studies. We can only use your information again if the Institutional Review Board gives us permission. This committee may ask us to talk to you again before doing the research. But the committee may also let us do the research without talking to you again if we keep your health information private.

If you sign this form, you are giving us permission to collect, use and share your health information. You do not need to sign this form. If you decide not to sign this form, you cannot be in the research study. You need to sign this form and the attached consent form if you want to be in the research study. We cannot do the research if we cannot collect, use and share your health information.

If you change your mind later and do not want us to collect or share your health information, you need to send a letter to the researcher listed on the attached consent form. The letter needs to say that you have changed your mind and do not want the researcher to collect and share your health information. You may also need to leave the research study if we cannot collect any more health information. We may still use the information we have already collected. We need to know what happens to everyone who starts a research study, not just those people who stay in it.

APPROVED
MSU IRB
12/23/2019
Date approved