Influence of total hip arthroplasty surgical approach on joint mechanics and muscle function during gait

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LIST OF ABBREVIATIONS

30-CST	30 second Chair Stand Test
6MWT	Six-Minute Walk Test
ATH	Athroplastie totale de la hanche
ANOVA	Analysis of variance
ASIS	Anterior superior iliac spine
CI	Confidence interval
EMG	Electromyography
FMIV	Force maximale isométrique volontaire
GC	Gait cycle
GT	Greater trochanter
HOOS	Hip Disability Osteoarthritis Outcome
LLD	Limb length discrepancy
MVIC	Maximum voluntary isometric contraction
OA	Osteoarthritis
PC	Principle component
PCA	Principle component analysis
PP-scores	Principle pattern-scores
PSIS	Posterior superior iliac spine
ROM	Range of motion
THA	Total hip arthroplasty
VAS	Visual analogue scale
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index

ABSTRACT

The lateral and posterior total hip arthroplasty (THA) surgical approaches are the most commonly used methods to perform a THA. The gluteus medius muscle is more disrupted during the lateral approach versus the gluteus maximus during the posterior approach. Impairments in these muscles following THA may impact lower extremity muscle activation, gait mechanics and physical function. Thus, the primary objective was to determine if lower extremity muscle activation patterns, joint angles and external hip moments during gait and isometric muscle torques differ between lateral and posterior THA approaches one year after surgery and healthy adults. The secondary objective was to compare pain, physical function and spatio-temporal parameters one year after surgery between lateral and posterior THA approaches and healthy adults. The study recruited participants with lateral (n = 19) and posterior (n = 19) THA approaches at one year post-surgery and healthy adults (n = 21). Surface electromyography (EMG), an eight-camera three-dimensional motion capture system, and force plates recorded muscle activation of eight lower extremity muscles, joint angles and external joint moments while participants ambulated at self-selected speeds. An isokinetic dynamometer measured maximum isometric muscle torques during maximum voluntary isometric contraction (MVIC) exercises. Hip pain, symptoms, function of activities of daily living, sport function, quality of life and physical function were measured using Hip disability and Osteoarthritis Outcome Score (HOOS) and performance-based measures. Principal component analysis (PCA) identified difference in EMG, joint angles and joint moment waveform during gait. Lateral THA group had significantly higher amplitudes of gluteus medius gait EMG with large effect size, lowered pelvic obliquity angle excursions during gait and reduced isometric hip abduction torque compared to healthy group. Posterior THA group had significantly higher gluteus maximus muscle, hamstring muscle gait EMG and lowered hip adduction angles

excursion during gait compared to healthy group with large effects for these differences. Both lateral and posterior THA groups had reduced hip flexion, increased medial rotation angle excursion during gait, lower HOOS-sport function and lower HOOS-quality of life compared to healthy group. HOOS-pain and HOOS-function of activities of daily living were reduced in the lateral THA group only compared to healthy group. Few differences were identified between THA groups except for significantly smaller changes in activation of hamstrings gait EMG and increased hip medial rotation angle excursion during gait in the posterior THA group compared to lateral THA group. Groups did not differ for other variables. Thus, at one year post-surgery, patients that have THA using lateral or posterior approaches will have similar gait and clinical outcomes, and both groups will show some deficits compared to healthy adults.

ABREGÉ

Les approches chirurgicales totales latérale et postérieure de l'arthroplastie de la hanche (ATH) sont les méthodes les plus utilisées pour effectuer une ATH. Le muscle moyen fessier est plus perturbé lors de l'approche latérale et le muscle grand fessier est plus perturbé lors de l'approche postérieure de l'ATH. Les altérations de ces muscles consécutives à l'ATH peuvent affecter l'activation des muscles des membres inférieurs, la mécanique de la démarche et la fonction physique. L'objectif principal était donc de déterminer si les modes d'activation des muscles des membres inférieurs, les angles articulaires et les moments articulaires externes de la hanche pendant la démarche et les forces musculaires isométriques diffèrent entre les approches latérale et postérieure de l'ATH un an après la chirurgie et les sujets sains. L'objectif secondaire était de comparer la douleur, la fonction physique et les variables spatio-temporelles un an après la chirurgie entre les approches ATH latérale et postérieure et les sujets sains. L'étude a recruté des patients ayant subi des approches ATH latérale (n = 19) et postérieure (n = 19) et qui en sont à un an post chirurgie, et des sujets sains (n = 21). L'électromyographie de surface (EMG), un système de capture de mouvement tridimensionnel à huit caméras, et des plateformes de force ont enregistré l'activation musculaire de huit muscles des membres inférieurs, des données cinématiques et des données cinétiques pendant que les participants se déplaçaient à des vitesses auto-sélectionnées. Un dynamomètre isocinétique a mesuré les forces musculaires isométriques maximales pendant les exercices de force maximale isométrique volontaire (FMIV). La douleur à la hanche, les symptômes, les activités de la vie quotidienne, l'activité sportive, la qualité de vie et la fonction physique ont été mesurés à l'aide de mesures 'Hip disability and Osteoarthritis Outcome Score' (HOOS) et fondées sur la performance. L'analyse en composantes principales (PCA) a identifié la différence en la forme d'onde du signal EMG, les angles des articulations et les moments des

articulaires externes pendant la marche. Le groupe ATH latéral présentait des amplitudes significativement plus élevées d'EMG du gluteus medius avec un grand effet de taille, une réduction de l'angle de l'obliquité pelvienne lors de la marche et une force l'abduction isométrique de la hanche par rapport au groupe sain. Le groupe ATH postérieur présentait un EMG du muscle grand fessier significativement plus élevé, un EMG des muscles ischio-jambiers et une réduction l'angle d'adduction de la hanche au cours de la marche par rapport au groupe sain avec de larges effets pour ces différences. Les groupes ATH latéral et postérieur présentaient avec une réduction de la hanche en flexion, une plus grande amplitude de la rotation médiale au cours de la démarche, une réduction de fonctions sportives HOOS et une qualité de vie HOOS inférieure à celles du groupe sain. La douleur HOOS et la fonction des activités de la vie quotidienne HOOS ont été réduites dans le groupe ATH latéral uniquement par rapport au groupe sain. Peu de différences ont été identifiées entre les groupes d'ATH, sauf pour des modifications significativement plus faibles de l'activation des muscles ischio-jambiers et une augmentation de l'angle de rotation vers l'intérieur pendant la marche dans le groupe ATH postérieur par rapport au groupe latéral. Les groupes ne différaient pas pour les autres variables. Ainsi, un an après l'ATH, les patients ayant subi une approche latérale ou postérieure présenteront une démarche et des résultats cliniques similaires, et les deux groupes présenteront des déficits par rapport aux adultes en bonne santé.

DEDICATION

This thesis is dedicated to my parents.

Thank you for believing in me!

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Thank you all.

PREFACE

This thesis is organized in a monograph format in accordance with the guidance of the Faculty of Graduate and Postdoctoral Studies of McGill University. It contains six chapters as follows.

The following section outlines the organization of this thesis.

Chapter 1 introduces the topic of interest.

Chapter 2 presents a review of the existing literature relevant to the area of study.

Chapter 3 provides a detailed account of the methodology used in the study.

Chapter 4 summarizes the findings of the study.

Chapter 5 discusses the results and limitations of the study.

Chapter 6 provides conclusions and summary of the main findings of the study, including its clinical significance, possible implications and future directions.

Chapter 7 presents the list of references contained within this thesis.

This thesis complies with McGill's policy of intellectual property and all ethical standards.

CONTRIBUTION OF AUTHORS

The monograph contained in this thesis is entitled, “Influence of total hip arthroplasty surgical approach on joint mechanics and muscle function during gait.” This research study was done under the supervision of Dr. Shawn Robbins. It took place at the Clinical Integration of Musculoskeletal Biomechanics Lab at Constance Lethbridge Rehabilitation Centre in Montreal, Quebec, Canada, which is part of the Centre for Interdisciplinary Research in Rehabilitation (CRIR).

Dr. Shawn Robbins was responsible for the study design and obtaining ethics approval. He also created the Matlab and Visual 3D code used in the data processing. Dr. John Antonio, Dr. Olga Huk and Dr. David Zukor at the Jewish General Hospital referred participants to the study. Philippe Dixon, Daniela Chan-Víquez, and Susan Mengxiao, assisted with the data collection. Terry Wang assisted with data collection and data processing. Larissa Fedorowich assisted with data collection and participant recruitment. Chaira Sabatino, translated the french version of the abstract. I, Sharleen Krislyn Gomes, was the main contributor and lead author of the content of this thesis. My contributions include the screening of participants, data collection and processing, statistical analysis, interpretation of findings, figures/tables/appendices and formulation of conclusions and clinical implications. Dr. Shawn Robbins reviewed this thesis and provided feedback.

STATEMENT OF ORIGINALITY

This thesis contains material solely written by me except where references are made. Elements of this master's thesis provide original contributions to understanding the influence of total hip arthroplasty surgical approach on the recovery of muscle function and joint mechanics during gait as well as muscle strength and physical function at one year following THA surgery.

CHAPTER 1: BACKGROUND

1.1. OSTEOARTHRITIS

1.1.1. Definition and prevalence

The centres for disease control defines osteoarthritis (OA) as a disease characterized by degeneration of cartilage and its underlying bone within a joint as well as bony overgrowth (Centre for Disease Control, 2018). OA is the most common form of arthritis and is ranked eleventh in the world on the list of leading causes of disability or years lived with disability (Cross et al., 2014). In the United States, among adults more than 45 years, the prevalence of hip OA in particular ranges between 3-9% for symptomatic hip OA (defined as radiographic OA with hip symptoms) and 27% for radiographic hip OA (Jordan et al., 2009). Globally, the prevalence of hip OA in 2010 has been estimated at 0.85% and 2.9 million years lived with disability (Cross et al., 2014; Vos et al., 2012).

1.1.2. Effects of OA

OA is a debilitating condition characterized by pain and stiffness, and results in a substantial degree of physical disability. OA pain is usually chronic in nature progressing from activity related to constant pain with intermittent intense spells (Hawker et al., 2008). Additionally, patients with hip and knee OA have been found to have significantly greater increases in pain/ discomfort in response to physical activity and respond to activities of stable intensity with increasingly severe pain, impairing performance (Wideman et al., 2014). Another consequence of hip OA is the reduction in strength and mass of major muscles especially the hip abductors, adductors, and flexors (Arokoski et al., 2002; Rasch, Bystrom, Dalen, & Berg, 2007). Finally, limitations in hip range of motion (ROM) due to OA (especially medial rotation) hinders mobility,

ambulatory capacity and performance of functional activities (stairclimbing, walking, sit to stand etc.) (Abhishek & Doherty, 2013; Altman et al., 1991).

1.1.3. Effects of OA on gait

Hip OA causes abnormal loading at the hip, affecting gait (Tateuchi et al., 2017). Therefore, patients with hip OA exhibit altered gait parameters including muscle activation, hip joint angles and moments, and spatio-temporal parameters.

1.1.3.a. Spatio-temporal parameters

A recent literature review and meta-analysis of 30 studies compared spatio-temporal parameters of gait between patients with hip OA and healthy adults (Constantinou, Barrett, Brown, & Mills, 2014). At self-selected gait speeds, patients with hip OA had reduced speed (large effect), cadence (moderate effect), step length (large effect), stride length (large effect) and swing duration (large effect) on affected leg compared to healthy adults. Furthermore, stance duration (small effect), double support time (large effect) and step width (moderate effect) were greater on the affected leg of patients with hip OA compared to healthy adults. The mean self-selected gait speed in patients with hip OA (mean = 0.95 m/s) was 26% lower than that of the healthy adults (mean = 1.29 m/s). Patients with hip OA also demonstrated ipsilateral reduced step length and swing duration on the affected leg versus unaffected leg (Constantinou et al., 2014). These finding thus suggest the presence of gait adaptations in patients with hip OA most notably in terms of reduced self-selected gait speed and reduced gait symmetry.

1.1.3.b. Joint angles

Hip joint ROMs during ambulation are reduced in patients with severe hip OA (Rutherford et al., 2015a). In a cross-sectional study comparing three-dimensional hip joint angles, patients

with severe hip OA ambulated with significantly reduced overall hip extension and abduction angles ($p < 0.05$) compared to patients with moderate hip OA and healthy adults (Rutherford et al., 2015a). Furthermore, they had decreased hip joint excursion for all angles ($p < 0.03$) (Rutherford et al., 2015a). A study by Schmitt et al. reported, patients with severe hip OA had significantly reduced peak hip extension angle ($p < 0.001$) compared to healthy adults, confirming the existence of limitations in hip extension during the stance phase of gait (Schmitt, Vap, & Queen, 2015). This is a common alteration observed in patients with hip OA and could be due to hip flexion contracture or hip extensor muscle weakness (Eitzen, Fernandes, Nordsletten, & Risberg, 2012). Patients with severe hip OA also exhibit altered pelvis and trunk angles during ambulation (Bolink et al., 2015; Constantinou, Loureiro, Carty, Mills, & Barrett, 2017; Leigh, Osis, & Ferber, 2016; Meyer et al., 2015; Zeni, Pozzi, Abujaber, & Miller, 2015). Three-dimensional pelvic angles in patients with moderate to severe hip OA analyzed during gait using either a single inertial sensor or optical systems demonstrated lower pelvic obliquity ROM (mean = 5.6° versus 8.0°, $p = 0.01$), lower peak pelvic obliquity angle during stance (mean = 2.7° versus 5.1° , $p = 0.006$) and lower peak pelvic obliquity angle during midstance (mean = −0.64° versus 0.76°, $p < 0.001$ where positive is pelvic drop) compared to healthy adults ($n = 20$) (Bolink et al., 2015; Constantinou et al., 2017; Leigh et al., 2016). Contradicting these finding, significantly greater peak pelvic obliquity angle ($p = 0.003$) and pelvic obliquity ROM ($p = 0.019$) has been reported on the affected leg of patients with severe hip OA compared to their unaffected leg (mean difference = 1.8° and 0.6° respectively) (Zeni et al., 2015). Increased lateral lean of the trunk toward the affected side (lateral trunk lean) during the stance phase of gait is commonly seen in patients with severe hip OA (Meyer et al., 2015; Zeni et al., 2015). For instance, principal component analysis identified increased lateral trunk lean over the affected side during the stance

phase of gait in patients with severe hip OA ($n = 20$) compared to healthy adults ($n = 17$, $p < 0.001$) (Meyer et al., 2015). This is a compensatory mechanism for weakness present in hip abductor muscles and involves shifting the body's centre of mass toward the stance limb. This shortens the moment arm between the ground reaction force and the hip joint centre, decreasing the external hip adduction torque (Levangie & Norkin, 2005; Oatis, 2009).

1.1.3.c. Joint moments

Altered hip moments during gait have been frequently reported in patients with hip OA. Patients with severe hip OA ($n = 19$) have reported significantly ($p < 0.05$) lower mean and peak extension, adduction, medial rotation and lateral rotation moments on the affected side in the OA group compared to healthy adults ($n = 19$) (Constantinou et al., 2017; Hurwitz, Hulet, Andriacchi, Rosenberg, & Galante, 1997). Likewise, patients with mild to moderate hip OA have also exhibited significantly reduced external hip flexion moments at mid and terminal stance phases of gait (mean difference = −0.08 Nm/kg and −0.18 Nm/kg respectively, $p < 0.001$) compared to healthy adults (Eitzen et al., 2012). Furthermore, the affected hip in patients with moderate to severe hip OA has found to exhibit lower external peak hip adduction, flexion, medial rotation and lateral rotation moments compared to the unaffected hip (Farkas et al., 2018; Schmidt et al., 2017). Such decrease in hip moments indicates decreased loads acting on the hip joint as well adoption of compensatory strategies, such as lateral trunk lean, that decrease demands on the weakened hip muscles in patients with moderate to severe OA (Hurwitz et al., 1997).

1.1.3.d. Muscle activation during gait

Patients with moderate and severe hip OA demonstrate alterations in muscle activation patterns of the affected lower extremity (Dwyer, Stafford, Mattacola, Uhl, & Giordani, 2013;

Horstmann, Listringhaus, Haase, Grau, & Mundermann, 2013; Rutherford, Moreside, & Wong, 2015a, 2015b; Schmidt et al., 2016). Patients with severe hip OA (n = 20) have significantly prolonged gluteus maximus ($p = 0.04$) and increased gluteus medius activation ($p < 0.001$) during the midstance phase of gait compared to patients with moderate hip OA (n = 20) and healthy adults (n = 20) (Rutherford et al., 2015a). Also, patients with moderate hip OA (n = 20) have significantly higher hamstring and quadriceps electromyography (EMG) amplitude on the affected leg during mid/ late stance phases of gait compared to their unaffected leg ($p = 0.02$) (Rutherford et al., 2015b). Another study has also reported significantly higher gluteus medius EMG during gait on the affected side in patients with severe hip OA, during both the stance ($p = 0.02$) and swing ($p = 0.001$) phases compared to healthy adults (Dwyer et al., 2013). Lastly, tensor fascia latae mean EMG muscle activity in the affected leg of patients with severe hip OA has also found to be significantly greater ($p = 0.01$, $d = 0.57$), compared to the unaffected side. Thus, patients with hip OA exhibit increased muscle activation patterns in the affected leg during ambulation compared to the unaffected leg or healthy adults.

1.2. TOTAL HIP ARTHROPLASTY

1.2.1. Description

Total hip arthroplasty (THA), also called total hip replacement, is the definitive cost-effective treatment for end stage hip OA (Daigle, Weinstein, Katz, & Losina, 2012; Pivec, Johnson, Mears, & Mont, 2012). It involves removal of the damaged bone and cartilage and replacing them with prosthetic components (Jolles & Bogoch, 2006).

- The damaged femoral head is removed and replaced with a metal stem that is placed into the hollow centre of the femur. The femoral stem may be either cemented or "press fit" into the bone.
- A metal or ceramic ball is placed on the upper part of the stem. This ball replaces the damaged femoral head that was removed.
- The damaged cartilage surface of the socket (acetabulum) is removed and replaced with a metal socket. Screws or cement are sometimes used to hold the socket in place.
- A plastic, ceramic, or metal spacer is inserted between the new ball and the socket to allow for a smooth gliding surface (Foran, 2015).

1.2.2. Prevalence of THA

There are more than one million THA procedures performed worldwide per year with a crude incidence rate in 2007 of 118.8 (118.4–119.2) per 100,000 persons per year (de Fatima de Pina, Ribeiro, & Santos, 2011; Zagra, 2017). In the past five years there has been an increase in the incidence of THA hospitalizations in Canada by 17.8%, with more than 55,500 THAs being performed in 2016-2017 alone (Canadian Institute for Health Information, 2018). Considering the increasing prevalence of this surgery, it is important to maximize patient outcomes and minimize adverse events.

1.2.3. Surgical approaches

Different THA surgical approaches have been described in the literature. The 2015 National Joint Registry annual report for England, Wales, Northern Ireland and the Isle of Man, identified the posterior and direct lateral approaches as the most common THA approaches used, respectively accounting for 62% and 36% of THA cases (Palan & Manktelow, 2018). In contrast,

2008-2009 THA usage rates in Canada have identified higher usage of the lateral THA approach (60%) compared to the posterior THA approach (36%) (Burnett, 2010). A survey among 292 orthopedic surgeons of the American Academy of Orthopedic Surgeons did not identify substantial difference with respect to surgeon preference toward usage of the posterior (45%) and lateral (42%) THA approaches (Chechik, Khashan, Lador, Salai, & Amar, 2013). However, the survey identified significant preference of posterior THA approach between region; North American surgeons favored the posterior approach more often than European surgeons (69 % compared to 36 % respectively), and surgeons from other countries (69 % compared to 45 % respectively). Thus, there is a variation in the surgical approach usage not only between continents but also between countries in the same continent and differences in findings could be due to sampling methods used. Also, differences seen in THA surgical approach usage rates between region could be influenced by surgeon training (Chechik et al., 2013; Moretti & Post, 2017).

1.2.4. Surgical approach descriptions

The primary goal of THA is to achieve maximum reduction in pain, optimize function, and minimize adverse events. The THA approaches have therefore been modified since they were first introduced to achieve this goal. They differ mainly in the way surgeons access the joint.

1.2.4.a. Direct lateral approach

The direct lateral approach is performed through a longitudinal skin incision centred over the greater trochanter of the femur (Hardinge, 1982; Petis, Howard, Lanting, & Vasarhelyi, 2015). The exposed gluteal fascia and iliotibial band are split to visualize the tendon and muscle fibers of the gluteus medius. Next, the insertion of the gluteus medius is split down to the greater trochanter and prolonged distally to the vastus ridge leaving a cuff of gluteus medius tendon for repair

following the procedure. The gluteus minimus and joint capsule are then split either in line with the neck of the femur or in line with the tendinous fibers of the gluteus minimus. Some surgeons may perform a capsulectomy to facilitate dislocating the hip. The surgeon then dislocates the femoral head by laterally rotating and flexing the hip and knee (Petis et al., 2015). Following fixation of the prosthetic component, the gluteus medius and minimus are repaired and routine closure of surgical site performed. The gluteus medius and minimus remain the most disrupted muscle during this approach.

1.2.4.b. Posterior approach

In contrast, the posterior THA approach spares the gluteus medius muscle but splits the gluteus maximus to access the hip joint (Burnett, 2010; Hoppenfeld, DeBoer, & Buckley, 2012; Petis et al., 2015). The approach uses a curved incision centred on the femoral diaphysis. The incision continues proximally to the greater trochanter, curves toward the posterior superior iliac spine. The fascia latae overlying the gluteus maximus is then incised in the line of the incision and the fibers of the gluteus maximus are split by blunt dissection exposing the short lateral rotators and piriformis tendons. Further, these are detached close to their femoral insertion and reflected to expose the posterior hip joint capsule which is incised. The hip joint is flexed and medially rotated to dislocate the femoral head. Once the joint surfaces are replaced with prosthetic implants, the short lateral rotators, posterior joint capsule, gluteus maximus and fascia latae are repaired along with the closure of the surgical site.

1.2.4.c. Anterolateral approach

This approach is less commonly used and is similar to the lateral approach. As many studies have compared this approach to the lateral and posterior THA approaches we are briefly discussing

it here. In this approach the incision is centred over the greater trochanter and lateral to the tensor fascia latae. The anterior one-third of the gluteus medius and minimus are detached from the greater trochanter to allow for femoral dislocation and adequate exposure to the joint, with a capsulectomy performed (Burnett, 2010; Hardinge, 1982; Mulliken, Rorabeck, Bourne, & Nayak, 1998). At closure, the gluteus medius and minimus tendons are reattached to their insertions. During surgery, lateral hip rotator muscles are not detached.

1.2.5. Muscles involved following THA and their function

The fibers of the gluteus medius and minimus muscles are most violated during the lateral THA approach whereas those of the gluteus maximus, piriformis and short lateral rotators are most disrupted following the posterior THA approach.

The gluteus maximus, along with being a powerful hip extensor also abducts (superior fibers) and laterally rotates the hip (Oatis, 2009). During gait, the gluteus maximus plays an important role in decelerating the forward movement of the hip and knee prior to initial contact with the ground as well as assists in initiating hip extension as weight bearing begins (Oatis, 2009). The gluteus medius and gluteus minimus primarily abduct the hip and stabilize the pelvis during single leg stance activities (Levangie & Norkin, 2005). During gait they produce a counter torque necessary to control the downward drop of the pelvis over the swinging leg. They also support hip and knee extension during single leg support phase of gait (Levangie & Norkin, 2005).

CHAPTER 2: LITERATURE REVIEW

2.1. OUTCOMES FOLLOWING THA

The most reported outcomes of THA relate to pain and mobility. These may be influenced by the surgical approach used. Although, both lateral and posterior THA approaches involve splitting of muscles, the structures involved, the degree to which the muscles are split, post-surgical joint stability, and risk of complications have shown to differ between approaches. These could result in differing adverse events, clinical and functional outcomes (Berstock, Blom, & Beswick, 2015; Jolles & Bogoch, 2006; Masonis & Bourne, 2002; Petis et al., 2015).

2.1.1. Adverse events

Adverse events following a THA mainly include dislocation, nerve injury, limb length discrepancy (LLD), fracture, heterotrophic ossification, stem malposition, aseptic loosening, infection, and deep vein thrombosis (Mears, 1999; Petis et al., 2015; Pivec et al., 2012). Dislocation following THA has a deleterious effect on patient outcomes. A systematic review of the literature, reported a dislocation rate of 3.23% among those with posterior THA as compared to that of 0.55% among those with lateral THA approach (Masonis & Bourne, 2002). Damage to the posterior hip joint structures during the posterior THA approach surgery has found to influence this dislocation rate. A meta-analysis of the posterior approach reported 8.21 times higher risk of dislocation without a posterior soft tissue repair compared with repair (Kwon et al., 2006). Agreeing with these results, among THAs performed using the posterior approach, a lower dislocation rate (2.03%) was identified when posterior structures were repaired as compared to when not repaired (3.95%) (Masonis & Bourne, 2002). Additionally, comparable dislocation rates have been identified between the direct lateral approach (0.43%), and posterior approach with soft tissue

repair (1.01%) versus without repair (4.36%) ((Kwon et al., 2006). Finally, two more recent systematic reviews and meta- analysis studies have reported no significant difference in dislocation rate between posterior and direct lateral surgical approach (relative risk = 0.35, 95% confidence intervals = 0.04 to 3.22 and Peto odds ratio = 0.37, 95% confidence interval = 0.09 to 1.48, p = 0.16) (Berstock et al., 2015; Jolles & Bogoch, 2006). Thus, if the posterior hip joint soft tissue is adequately repaired, the risk of dislocation using a posterior approach can be reduced, reproducing similar dislocation rates for both posterior and direct lateral approaches.

Development of a peripheral nerve injury following THA is a rare but potentially devastating complication following THA. Nerve injury can occur under several different circumstances, including direct trauma during dissection or placement of devices (Schmalzried, Amstutz, & Dorey, 1991). One systematic review and meta-analysis and a more recent longitudinal study have compared nerve injury rate between posterior and lateral THA approaches (Chomiak et al., 2015; Jolles & Bogoch, 2006). The meta-analysis study identified significant differences in incidence rate of nerve palsies or injuries between lateral and posterior THA approaches (relative risk = 0.16; 95%, Confidence interval = 0.03 to 0.83) with the posterior THA group (1 of 43 participant) demonstrating less risk of nerve injury compared to the lateral THA group (10 of 49 participants) (Jolles & Bogoch, 2006). In agreement, a recent longitudinal study involving a total of 70 patients with THA (direct lateral, posterior and anterolateral approaches), identified more frequent lesion to gluteal nerve following a direct lateral approach compared to the posterior approach (52% versus 46%) with higher incidence of partially denervated gluteus medius (81.8% versus 53%), gluteus maximus (29% versus 71.4%), and tensor fasciae latae (48% versus 14%) at three to nine months post-surgery (Chomiak et al., 2015). Thus, posterior THA approach causes lower nerve injury compared to lateral THA approach surgery.

Limb length discrepancy (LLD) of more than 2 cm following THA has found to cause gait abnormalities (Giles & Taylor, 1981; Gofton & Trueman, 1971). Studies have compared the presence of LLD following posterior and lateral THA approaches. However, a meta-analysis study failed to report a significant difference in LLD between surgical approaches (Peto odds ratio: 1.05, $p = 0.91$) (Berstock et al., 2015). Similarly, a recent prospective randomized controlled trial failed to conclude significant difference (Fisher $p = 0.363$) in the occurrence of LLD of more than 2 cm following the posterior (50%) and lateral (43%) THA approaches (Witzleb, Stephan, Krummenauer, Neuke, & Gunther, 2009). Thus, the incidence of any LLD following THA was not found to be significantly different between approaches.

Other significant adverse events including intraoperative fractures, heterotopic ossification, stem malposition, infection, aseptic loosening, and deep vein thrombosis are rare but known to occur following THA (Petis et al., 2015; Pivec et al., 2012). One retrospective review of 372 primary THAs revealed 15 intraoperative greater trochanter fractures (4.0%) using a lateral approach (Hendel, Yasin, Garti, Weisbort, & Beloosesky, 2002). Although not significant, a trend toward a reduced risk of heterotopic ossification (Peto odds ratio = 0.4, $p = 0.13$) and stem malposition (Peto odds ratio = 0.24, $p = 0.02$) has been reported following the posterior THA approach compared with to the lateral THA approach. However, due to paucity and absence of data, it is difficult to draw firm conclusions on whether surgical approach influences the prevalence of these adverse events (Berstock et al., 2015; Jolles & Bogoch, 2006).

2.1.2. Clinical outcomes

2.1.2.a. Operation time and blood loss

Operation time and blood loss can influence patient recovery following THA. Two studies identified lower mean operation time (mean difference = -27 to -29 minutes, $p \leq 0.001$ to 0.05) among patients who underwent THA using posterior approach compared to those with lateral THA (Ji, Kim, Lee, Ha, & Koo, 2012; Weale, Newman, Ferguson, & Bannister, 1996). Posterior THA group also had significantly lower mean blood loss (mean difference = 169 ml, $p \leq 0.001$) compared to the lateral THA group (Weale et al., 1996). Thus posterior THA approach appears to be more efficient compared to the lateral THA approach. No other studies were identified that compared these outcomes between lateral and posterior THA surgical approaches.

2.1.2.b. Pain

Pain intensity following THA is an important clinical outcome and THA successfully reduces pain associated with hip OA. At 12 months post-THA for severe hip OA, Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) - pain scores improved significantly more in patients who had surgery compared to hip OA patients who did not have surgery ($p < 0.001$) (Hamel, Toth, Legedza, & Rosen, 2008). Pain following THA has been compared between the lateral and posterior THA approaches. A meta-analysis of studies up to 2006 comparing the lateral and the posterior THA approaches reported that the risk of experiencing pain of more than 3 of 10 on a visual analogue scale (VAS) was similar (relative risk = 0.59, 95% Confidence interval = 0.17 to 2.03) between lateral and posterior THA approaches (Jolles & Bogoch, 2006). Similarly, a recent randomized controlled trial reported change in pain at twelve months after THA, relative to preoperative levels using Hip Disability Osteoarthritis Outcome pain subscale (HOOS-pain),

and found no difference ($p > 0.05$) in improvement between patients that had a lateral ($n = 20$) or posterior THA ($n = 20$) (Rosenlund, Broeng, Holsgaard-Larsen, Jensen, & Overgaard, 2017). However, a recent prospective study reported a significantly lower HOOS-pain scores, for lateral ($n = 431$) compared to posterolateral ($n = 421$) THA groups with small between group differences (mean difference = -3.6 out of 100, 95% Confidence interval = -6.3 to -0.9) up to three years after THA (Amlie et al., 2014). Despite differences being small, the presence of contrasting results makes it difficult to determine whether this was due to the surgical approach or preoperative pain levels (Fortin et al., 1999).

2.1.2.c. Hip joint ROM

Recovery in hip ROM is an important outcome following THA as this will influence joint function and performance during functional activities. Twelve months following THA, hip ROM tested ($n=15$) using a goniometer, reported similar results on operated and unoperated leg ($p = 0.81$) (Trudelle-Jackson, Emerson, & Smith, 2002). However, compared to healthy adults some deficits may persist and this could be influenced by surgical approach. One study compared passive hip ROM between lateral and posterior THA approaches. The study, identified significantly increased average passive hip medial rotation ROM in extension (mean difference = 16 degrees, 95% Confidence interval = 8.64° to 23.36°) for patients operated on by the posterior approach ($n = 28$) compared to lateral approach ($n =21$) at two years follow-up (Barber, Roger, Goodman, & Schurman, 1996). No significant difference in ranges was identified for other motions (Barber et al., 1996).

2.1.2.d. Physical function

Following THA, patients demonstrate improvements in physical function. At 12 months post-THA for severe hip OA, WOMAC-physical function scores improved significantly more in patients who had surgery compared to hip OA patients who did not have surgery ($p < 0.001$) (Hamel et al., 2008). However, some impairment persists beyond six months (Fortin et al., 1999). Surgical approach may influence these improvements in physical function and performance following THA, but results of studies are inconsistent. Two studies identified similar changes in physical function, physical activity, and quality of life, between posterior and lateral THA groups up to 12 months post-surgery using self-report outcome measures including the HOOS-physical function short form ($p = 0.20$, $d = 0.3$), HOOS-quality of life ($p = 0.30$, $d = 0.2$) the Harris Hip Score ($p = 0.08$), WOMAC-physical function ($p \geq 0.1$), Short-Form 36 Questionnaire-physical scale ($p \geq 0.43$) and Tegner activity scores (Wilcoxon $p = 0.08$) (Rosenlund et al., 2017; Witzleb et al., 2009). The studies concluded that patients treated with posterior approach did not improve more than patients treated with the lateral approach at three to twelve months postoperatively. Similarly, a cross-sectional study comparing the direct lateral ($n = 12$), posterior ($n = 18$) and anterolateral ($n = 11$) THA approaches on the Timed Up and Go test, Sit-to-Stand test and self-selected walking speed test scores (performance-based tests) at approximately 12 months post-THA reported no statistically significant differences between THA groups (Queen et al., 2014). In contrast, at one to three years after THA, patients who underwent the lateral THA approach reported significantly worse self-report outcomes on all HOOS subscales compared to the patients who underwent the posterior THA approach (Amlie et al., 2014). Specifically, significantly lowered scores on activities of daily living (mean difference = -4.0, 95% Confidence interval = -6.8 to -1.3), sport/ recreation (mean difference = -4.6, 95% Confidence interval = -8.6 to -0.6) and quality of life (mean difference = -3.7, 95% Confidence interval

= -7.2 to -0.3) subscales were observed among patients with the lateral THA approach. Thus, inconsistent findings and lack of reporting of physical function following THA using performance-based measures makes it difficult to determine whether THA surgical approach impacts recovery of physical function and performance following THA.

2.1.2.e. Muscle strength

Muscle weakness is a common concern following THA (Petis et al., 2015). Abductor muscle weakness may be due to OA related changes, post-THA gluteus medius tendon failure, or irreparable muscle tears (Petis et al., 2015). Several studies have been performed comparing muscle strength following THA using the lateral and posterior approaches, however results are inconsistent. Two previous studies found that patients that had a lateral THA approach had significantly decreased isometric hip abduction (mean difference = -0.20 Nm/kg, 95% Confidence interval = -0.4 to 0.0, d = 0.6) and flexion (mean difference = -0.20 Nm/kg, 95% Confidence interval = -0.4 to 0.0, d = 0.2) strength at 12 months after surgery (Rosenlund, Broeng., Overgaard, Jensen, & Holsgaard-Larsen, 2016), and lower one repetition maximum for leg press (91% versus 100%, $p < 0.01$) and hip abduction (117% versus 139%, $p < 0.01$) at six week after surgery (Winther et al., 2016) compared to patients that had a posterior THA. In contrast, two other studies have found no significant difference in hip abductor muscle strength between the lateral and posterior THA surgical approaches (Barber et al., 1996; Downing, Clark, Hutchinson, Colclough, & Howard, 2001). Isometric hip abductor muscle strength measured using either a hand-held or isokinetic dynamometer reported similar strength ratios (i.e. normalized strength of the reconstructed side to that of the unoperated side) ($p = 0.67$) and strength gains ($p \geq 0.75$) at three, 12 months and more than two years after lateral and posterior THA approaches (Downing et al., 2001; Kiyama, Naito, Shinoda, & Maeyama, 2010). Also, visual observation of Trendelenburg test

(drop in contralateral pelvis during single leg stance indicates positive test and weakness in ipsilateral hip abductors) performed in three prospective studies and one retrospective study did not detect statistically significant difference in occurrence of positive Trendelenburg test between lateral and posterior THA approaches ($p \geq 0.20$ or Fisher $p = 0.07$) at three months, 12 months and more than two years after THA (Downing et al., 2001; Kiyama et al., 2010; Witzleb et al., 2009)

Inconsistency in findings could be due to the difference in muscle strength testing procedures as well as the time of testing following THA. Thus, although abductor muscle dysfunction persists immediately following THA, there is no irrefutable evidence that suggests a difference in muscle function exists between THA approaches long-term.

2.2. TOTAL HIP ARTHROPLASTY AND GAIT

Despite improvements, gait abnormalities have been found in patients following THA. Patients fail to reach levels of able-bodied individuals with asymmetries in gait present up to one year (Queen et al., 2011; Rosenlund, Broeng, Overgaard, Jensen, & Holsgaard-Larsen, 2016).

2.2.1. Effects of THA on OA related gait impairments

THA has found to partially reverse impairments in gait caused by OA. A meta-analysis study reported significant moderate to large increase in walking speed (standardized mean differences = 0.97, $p < 0.001$), step length (standardized mean differences = 0.90, $p < 0.001$) and stride length (standardized mean differences = 0.63, $p < 0.001$) at six months post-THA compared to preoperative levels. Walking speed continued to increase with large changes up to 12 months post-THA (standardized mean differences = 1.28, $p < 0.001$) (Bahl et al., 2018). However, step width and cadence did not change significantly following THA even at six months post-THA (Bahl et al., 2018).

Bahl et al. also reported, significant increase in hip flexion/ extension ROM (standardized mean differences = 1.07, $p = 0.006$), abduction/ adduction ROM (standardized mean differences = 1.03, $p = 0.01$) and medial/ lateral rotation ROM (standardized mean differences = 0.5, $p = 0.05$) compared to preoperative level (Bahl et al., 2018). Postoperative external hip flexion, extension and medial rotation moments have also reported to be significantly improved at 12 months post-THA compared to preoperative levels ($p < 0.01$) (Foucher, Hurwitz, & Wimmer, 2007). However, abduction, adduction and external rotation moments did not significantly change after THA surgery ($p > 0.13$) (Foucher et al., 2007).

THA leg muscle activation during gait has also found to differ postoperatively compared to preoperative levels. At 12 months post-THA, muscle activation amplitudes for the rectus femoris, sartorius, tensor fascia latae, gluteus maximus and gluteus medius muscles were significantly lower than preoperative levels ($p < 0.001$) (Horstmann et al., 2013). Alternately, postoperative muscle activation amplitudes for the adductor magnus, biceps femoris and semitendinosus muscles were significantly greater than preoperative levels ($p < 0.001$) (Horstmann et al., 2013). Differences in muscle activation during gait following THA compared to preoperative levels could be due to improved strength in the muscle allowing better muscle activation or compensation for persistent weakness in other muscles. Thus, changes in muscle activation after THA depends on the muscle of interest. Regardless, THA positively impacts gait, minimizing impairments caused due to hip OA. However, some deficits remain in comparison to healthy adults.

2.2.2. Comparing gait parameters between patients with THA and healthy adults

Although gait function improves following THA, aberrant preoperative gait patterns may persist (Bahl et al., 2018; Queen et al., 2014). Compared to healthy adults, patients 12 months post-

THA have lower walking speed (standardized mean differences = -0.59, $p = 0.02$) and stride length (standardized mean differences -1.27, $p < 0.001$) (Bahl et al., 2018). Patients with THA also demonstrated greater step width (standardized mean differences = 1.90, $p = 0.004$) but no difference in double support time at three months compared to healthy adults (Bahl et al., 2018). Hip angles remain limited following THA. Patients with THA have decreased angle excursions during gait in hip flexion/ extension (standardized mean differences = -1.16, $p < 0.001$), abduction/ adduction (standardized mean differences = -1.41, $p < 0.001$) between three to 12 months (Bahl et al., 2018). On the other hand, at three and 12 months post-surgery pelvic obliquity angles during gait are similar between patients with THA and healthy adults (standardized mean differences = 0.09, $p = 0.75$) (Bahl et al., 2018). This contradicts results of a study that identified increased ipsilateral lateral trunk lean among patients that had a THA six to 18 months earlier compared to healthy adults ($p \leq 0.006$) (Perron, Malouin, Moffet, & McFadyen, 2000). Differences in findings for this outcome could be due to varying post-THA follow-up period among patients in this study (Perron et al., 2000). Hip adduction moments were also similar between patients with THA three months post-surgery and healthy adults (standardized mean differences = 0.02, $p = 0.92$) (Bahl et al., 2018). Thus, some impairments in gait mechanics are present up to one year post-THA.

2.2.3. Comparing gait parameters between THA surgical approaches

Recovery in gait following THA could be influenced by surgical approach. This could be attributed to the difference in structures involved during these approaches which in turn could affect gait recovery differently.

2.2.3.a. Spatio-temporal parameters

Five studies compare spatio-temporal gait parameters between lateral and posterior THA groups. Four studies reported similar improvements in several spatio-temporal gait parameters in both lateral and posterior THA groups at six weeks to six months follow-up (Madsen et al., 2004; Petis et al., 2017; Queen et al., 2011). However, one randomized controlled trial found patients with posterior THA approach (n = 23) had small but significant improvement in single leg support time (mean difference = -1.3 %, 95% Confidence interval = -2.1% to -0.4%) and double support time (mean difference = 1.3%, 95% Confidence interval = 0.3% to 2.4%) of the affected leg compared to patients who had the lateral THA approach (n = 24) at 12 months follow-up (Rosenlund et al., 2016). Thus, time of follow-up could be responsible for the discrepancies in findings between studies requiring further investigations to determine whether surgical approach impacts long-term improvements in spatio-temporal gait parameters.

2.2.3.b. Joint angles

There is evidence that dynamic lower limb joint angles during gait also differ between posterior and lateral THA approaches. Three-dimensional gait analysis identified increased ipsilateral lateral trunk lean, anterior pelvic rotation (50% and 63% increase respectively) and a reduced hip sagittal ROM (by 59% for peak hip extension) among patients that had a THA compared to healthy adults irrespective of surgical approach (Perron et al., 2000). Another three-dimensional motion capture study reported significant differences ($p < 0.05$) in pelvic obliquity (frontal plane) excursion angles during gait between lateral and posterior THA approaches. Following the lateral THA approach, overall pelvic obliquity ROM during gait was found to be lower (3.92 degrees versus 6.13 degree) (Whatling et al., 2008). The study also identified significantly lowered sagittal hip ROM during gait in operated leg compared to the unoperated leg

(29.70 degrees versus 39.89 degrees, $p < 0.05$) among patients who underwent the lateral THA approach compared to posterior THA approach (Whatling et al., 2008). Furthermore, a study found that six months following THA, patient who underwent anterolateral approach ($n = 10$) demonstrated more gait deviations, including greater lateral trunk lean (3 degrees versus 1.5 degrees) and lower hip sagittal ROM, compared to patients that had a posterolateral approach (Madsen et al., 2004). Thus, it appears the type of THA surgical approach can impact joint motion during gait up to 6 months post-THA (Madsen et al., 2004; Whatling et al., 2008).

2.2.3.c. Joint kinetics

Joint moments measured during gait have found to differ between lateral and posterior THA approaches. Abductor muscle torque helps neutralize the gravitational hip adductor moment, controlling hip abduction and pelvic obliquity (Levangie & Norkin, 2005). Hence, frontal moments and power (internal abduction) are important variables to consider. Operated THA leg has been found to have significantly lowered ($p < 0.05$) internal abduction power and moments during gait after lateral THA approach ($n = 14$, 0.08 Watt/kg and 3.92 Nm/kg respectively) compared to posterior approach ($n = 13$, 0.25 Watt/kg and 6.13 Nm/kg respectively) (Whatling et al., 2008). Additionally, the study identified significant difference ($p < 0.05$) in internal hip abduction moments 30s into the Trendelenburg test, with lower moments among patients with lateral THA (0.52 ± 0.19 Nm/kg) compared to those with posterior THA (0.95 ± 0.12 Nm/kg) (Whatling et al., 2008). This reduced internal abduction moment in the lateral approach group could suggest dysfunction in the hip abductor muscle or presence of a compensatory mechanism to reduce the load on weak hip abductors. However, one recent study reported no significant difference in hip moments between patients in lateral and posterior THA groups at six and 12 weeks post-THA

(Petis et al., 2017). These discrepancies and lack of research make it difficult for us to draw firm conclusions whether gait hip moments are affected by THA surgical approach.

2.2.3.d. Trendelenburg gait

Trendelenburg gait is characterized by a drop in the contralateral pelvis with a non-compulsory compensatory ipsilateral trunk lean during the stance phase of gait and is indicative of impaired gluteus medius function (Oatis, 2009). THA surgical approach has found to influence the occurrence of postoperative Trendelenburg gait, with the posterior approach at less risk compared to the lateral approach (Berstock et al., 2015; Masonis & Bourne, 2002). A meta-analysis of four studies that visually assessed frequency of Trendelenburg gait, concluded that patients with posterior THA approach (n = 190) were significantly less likely to present with Trendelenburg gait (Peto odds ratio = 0.43, 95% Confidence interval = 0.23 to 0.80, p = 0.008) compared to those with lateral THA approach (n = 188) at a mean follow-up period of 15.5 months (Berstock et al., 2015). Also, the incidence of limp following THA has found to be higher among individuals undergoing lateral or anterolateral THA approach. A review comparing the direct lateral or anterolateral approaches to THA (n = 2,288) with the posterior approach (n =167) reported a limp incidence ranging from 4% to 20% versus 0% to 16% respectively at a mean follow-up of more than 12 months (Masonis & Bourne, 2002). As Trendelenburg gait is generally caused due to hip abductor weakness, such results reinforce conclusions made by previous studies that the lateral THA approach is likely to lead to greater abductor muscle weakness compared to the posterior THA approach. However, Trendelenburg sign, gait or limp following THA have most commonly been assessed by subjective visual inspections of pelvic drop which may not be reliable. Thus, further investigation in pelvic obliquity following THA using more objective assessment methods like three-dimensional motion capture is required.

2.2.3.e. Muscle activation during gait following THA

Appropriate muscle activation patterns during walking are necessary to achieve optimal recovery in gait function following THA. Gait EMG of muscles 12 months post-THA in the operated lower extremity has shown to differ from that of both their unoperated leg and that of healthy adults (Agostini et al., 2014; Horstmann et al., 2013; Perron et al., 2000). At six months after lateral THA approach (n = 55), muscle activation gait EMG waveforms were found to deviate substantially from those of the healthy adults (n = 24) (Horstmann et al., 2013). Compared to the healthy adults, gluteus medius and gluteus maximus muscle activation patterns appeared to be higher and more prolonged during the first 40% and the last 10% of the gait cycle; however, this analysis was only completed by visual observation and was not quantified (Horstmann et al., 2013). The rectus femoris and tensor fascia latae muscles showed an additional EMG activation peak around the end of stance pre and postoperatively among patients with THA in comparison to the healthy adults. EMG activation of the semitendinosus and biceps femoris muscles (hamstrings) during gait was generally higher especially during stance (Horstmann et al., 2013). Additionally, quantitative analysis of gait EMG intensities identified significantly greater postoperative mean gait EMG intensities of the biceps femoris and semitendinosus muscles than preoperative levels ($p < 0.001$), whereas those of gluteus medius, gluteus maximus were significantly lower than preoperative levels ($p < 0.001$) (Horstmann et al., 2013). Similarly, another study that evaluated gait EMG muscle activation timing patterns visually found that patients twelve months after posterior THA approach (n = 20) demonstrated prolonged gluteus medius muscle activity compared to healthy adults (Agostini et al., 2014). The study also identified the occurrence of a third burst of muscle activity in the gluteus medius EMG among the healthy participants at around 50% gait cycle. This burst of muscle activity was found to be delayed to around 65% gait cycle in

patients with THA, possibly indicating a need to abduct the hip when the hip was being unloaded (Agostini et al., 2014). Similar behaviour was observed in muscle activation burst intervals on the sound side possibly suggestive of a developing compensatory strategy to improve gait symmetry (Agostini et al., 2014). Finally, only one study objectively assessed and compared gait EMG muscle activation waveforms between THA surgical approaches (lateral and minimally invasive approaches) (Pospischill, Kranzl, Attwenger, & Knahr, 2010). The study reported that at three months follow-up, about half of the patients in both minimally invasive anterolateral THA (n = 12) and lateral approach (n = 13) groups presented with alterations in hip abductor muscle activity (Pospischill, Kranzl, Attwenger, & Knahr, 2010). This included prolonged gluteus medius and maximus muscle activation over the midstance of gait, which was observed more frequently after lateral approach ($p = 0.08$). Additionally, a significant number of patients in the lateral THA group showed either prolonged or reduced firing of the tensor fasciae latae ($p = 0.02$) (Pospischill et al., 2010). Thus, irrespective of surgical approach, muscle activation patterns during gait in the THA leg have been found to deviate from those of healthy adults. To date, most studies have only analyzed muscle activation patterns during gait after THA by visual observation with no quantitative analysis, and no study specifically compared muscle activation between the lateral and posterior THA approaches. This lack of evidence has made it difficult to draw firm conclusions on differences in muscle function between THA approaches.

2.3. KNOWLEDGE GAPS

THA has proven to successfully alleviate chronic hip joint pain, improve hip joint motion and improve function and quality of life of patients suffering from OA (Bahl et al., 2018; Hamel et al., 2008; Trudelle-Jackson et al., 2002). Additionally, the long-term survivorship of the THA

prosthesis implant ensures it an effective long-term treatment to combat the increasing burden of hip OA (Bedard, Callaghan, Stefl, & Liu, 2015). However, it remains uncertain whether postoperative outcomes are influenced by the surgical approach, and thus further exploration is needed. As results from studies that compare muscle strength between the lateral and posterior THA approaches conflict, firm conclusion on whether surgical approach influences muscle strength cannot be made. Also, information of an individual's muscle activity during functional tasks may complement their strength tests results. However, there are no studies that objectively analyze muscle activation patterns during gait and compare this muscle activity between the lateral and posterior THA approaches. Additionally, despite the lateral and posterior THA approaches being the most common approaches, there is uncertainty whether surgical approach influences the occurrence of long-term muscle, joint and physical function deficits following THA. Also, pelvic obliquity and lateral trunk lean during gait have scarcely been analyzed objectively and compared between patients with lateral and posterior THA approaches. Finally, studies that holistically evaluate physical function following THA using a combination of self-report and performance-based measures are lacking and therefore further exploration is required.

2.4. STUDY OBJECTIVES

The purpose of this study was to compare muscle function and joint mechanics during gait between patients one year after lateral approach THA, posterior approach THA, and healthy adults. We also aimed to compare clinical outcomes between these groups.

Thus, the primary objectives of this thesis were:

- Objective 1: To determine if lower extremity muscle activation patterns during gait differ between lateral or posterior approaches for THA one year after surgery and healthy group.

  We hypothesized that muscle activation waveforms, especially of the gluteus medius and gluteus maximus would differ between THA groups at one year post-THA and healthy group, as well as between lateral and posterior THA group. Lateral THA group would have higher activation of the gluteus medius and posterior THA group would have higher activation of the gluteus maximus compared to participants in the remaining groups.

- Objective 2: To compare if lower extremity isometric muscle torque one year after surgery differ between lateral and posterior THA approaches and healthy group.

  We hypothesized that lateral THA group would present with reduced isometric hip abduction torque compared to posterior THA group at one year post-THA and healthy group. Posterior THA group would present with reduced isometric hip extension torque compared to lateral THA group at one year post-THA and healthy group.

- Objective 3: To determine if hip, pelvis, and trunk angles and external hip moments during gait differ between lateral and posterior THA approaches one year after surgery and healthy group.

  We hypothesized that differences in hip angles and moments would be present between THA group at one year post-THA and healthy group. Specifically, lateral THA group would present with greater pelvic obliquity angle excursion compared to posterior THA group at one year post-THA and healthy group.

The secondary objectives of this research thesis were:

- Objective 4: To compare clinical outcomes, using self-report and performance-based measures, between lateral and posterior THA approaches one year after surgery and healthy group.

  We hypothesized that clinical outcomes would not differ between THA and healthy groups at one year post-THA

- Objective 5: To compare gait speed, stride length and step length between lateral and posterior THA approaches one year after surgery and healthy group.

  We hypothesized that gait speed, stride length and step length would not differ between THA groups at one year after surgery and healthy group.

2.5. RELEVANCE

If surgical approach influences recovery in muscle and joint function during functional activities up to one year post-THA, it is important to modify rehabilitation protocols to make them more specific to address impairment linked with surgical approach. Addressing these deficits early in rehabilitation may help prevent them from persisting long-term. Additionally, the study will also provide surgeons with useful information to aid clinical decision making related to THA surgery and address patient expectation.

CHAPTER 3: METHODS

3.1. STUDY DESIGN AND PARTICIPANTS

A cross-sectional study design was adopted, and convenience sampling was utilized to recruit participants with THA from the Jewish General Hospital, Montreal between September 2016 to April 2018 at their one year follow-up visit with their consulting surgeon. The study was approved by the Research Ethics Committee of the Centre for Interdisciplinary Research in Rehabilitation of Montreal (CRIR) (Appendix 1). Three groups of participants between 50 and 80 years of age were recruited, participants who completed a primary THA using either lateral (n = 19) or posterior (n = 19) surgical approach due to hip OA and healthy adults (n = 21). Exclusion criteria included revision surgery for THA, bilateral THA at the same time, other lower extremity surgeries within one year, severe arthritis in any other lower extremity joint, inflammatory arthritis, neurological conditions (e.g. previous stroke), or severe cardiovascular conditions (e.g. angina). Additional exclusion criteria for the healthy group included lower extremity pain within the last three months, previous lower extremity arthroplasty, and history of hip OA.

Based on the surgical approach used, participants that had a THA were assigned to lateral and posterior groups. THAs were performed by surgeons at the Jewish General Hospital. Two surgeons (Drs. Huk and Zukor) performed the lateral THA approach and one surgeon (Dr. Antoniou) performed the posterior THA approach. The implant components used were a DePuy Trilogy acetabular socket and Trilock Bone Preservation Stem (Zimmer Biomet, Indiana, USA). Potential participants were recruited at their one year follow-up appointment by a member of their healthcare team. To confirm eligibility, interested candidates were then screened (Appendix 2) by a research assistant prior to study enrollment. Healthy adults were recruited on a volunteer basis

by advertising at the Concordia PERFORM centre as well as web page and word of mouth from the local community. Eligible candidates were accordingly scheduled for data collection. EMG was recorded from the THA leg only. For healthy participants, the study leg was randomly selected using a concealed paper draw method. Figure 1 demonstrates the steps involved in the enrollment and screening of study participants.

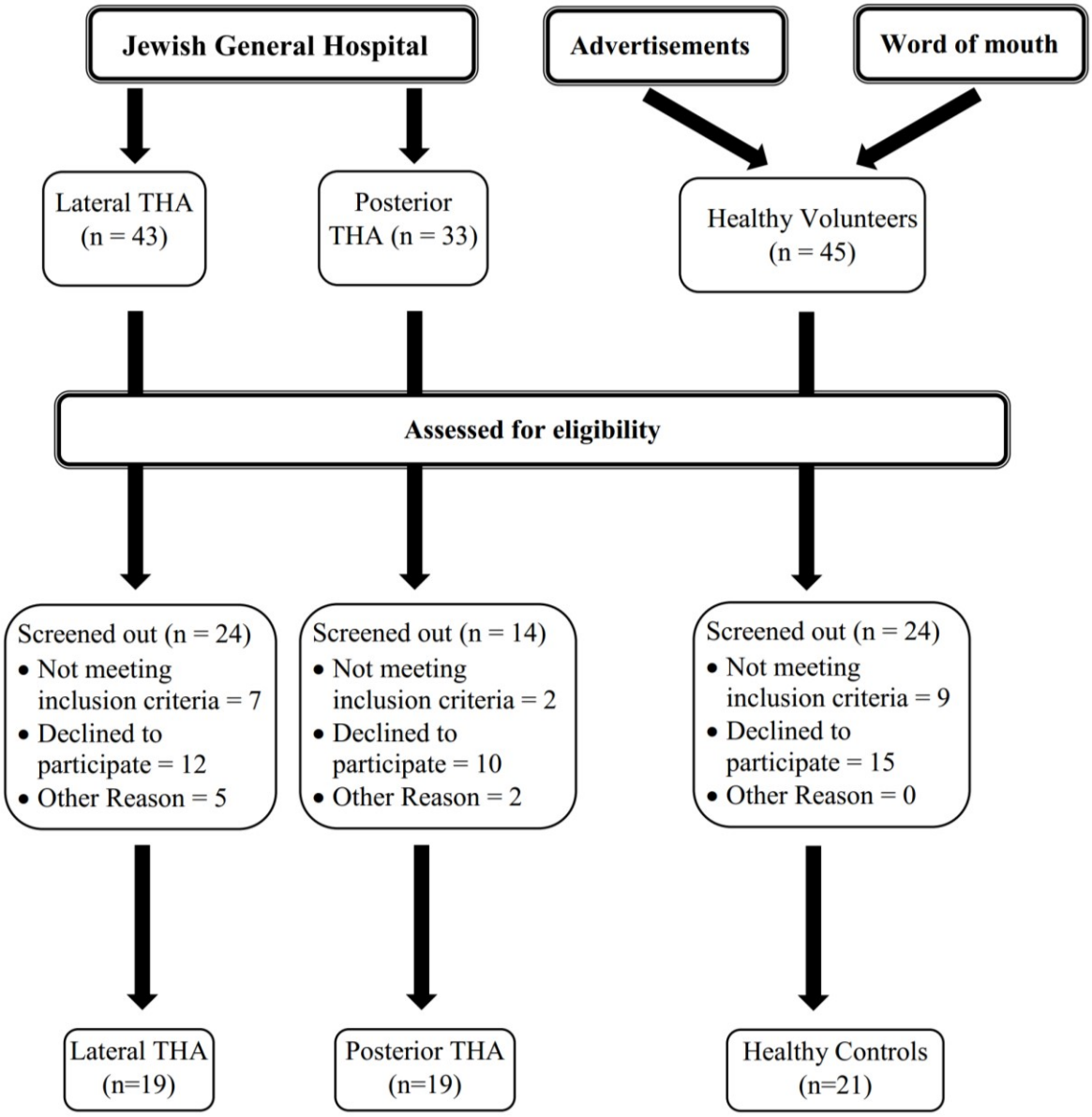

Figure 1: Flow diagram of steps involved in the screening and enrollment of participants.

3.2. SAMPLE SIZE

The calculation of the sample size was based on a previous study that found large effect sizes (Cohen's d > 1.2) for differences in the pelvis obliquity angle and hip moments between patients after THA with either a posterior or lateral approach (Whatling et al., 2008). Thus, to obtain a large effect (f = 0.40) for the planned analysis of variance (ANOVA) comparing the three groups (posterior THA, lateral THA, healthy) we calculated an estimated sample size of 21 participants in each group (N = 63) with an $\alpha = 0.05$ and $\beta = 0.2$. However, due to time restraints we were able to recruit only 59 participants (lateral THA =19 participants, posterior THA = 19 participants and healthy = 21 participants) versus our calculated total sample size of 63 participants.

3.3. DEMOGRAPHICS

Demographic information including age, sex, height, mass and THA surgical information including surgical approach, date of surgery, and operating surgeon were collected from participant medical charts and self-report.

3.4. BIOMECHANICAL DATA COLLECTION

Commercial gait analysis software, Qualisys track manager (Qualisys AB, Gothenburg, Sweden, version 2.8) was used to collect biomechanical data. Gait EMG was acquired using wireless surface EMG electrodes (Trigno, Delsys Inc., Massachusetts, USA; Ag/AgCl, 5 x 1 mm, dual bipolar parallel bar, 10mm interelectrode space). Manufacture's software sampled EMG at 1952 Hz and then unsampled it to 2000 Hz (pre-amplified with an effective signal gain of 909 v/v, common mode rejection ratio > 80dB at 60Hz, overall channel noise of < 0.75uV, and signal resolution 168 nV/bit). Surface EMG electrodes were placed on the study leg consistent with

published guidelines which included shaving and thoroughly cleaning the electrode placement site with alcohol (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000; Hubley-Kozey, Robbins, Rutherford, & Stanish, 2013). Electrodes were placed perpendicular to the orientation of the muscle fibers of the gluteus medius, gluteus maximus, vastus medialis, vastus lateralis, rectus femoris, medial hamstrings (semitendinosus), lateral hamstrings (biceps femoris), and tensor fascia latae based on standardized landmarks (Table 1) (Hermens et al., 2000; Rutherford, Hubley-Kozey, & Stanish, 2011). Muscle palpation and a series of submaximal isometric contractions (squat, single leg stand, hip abduction etc.) specific to the study muscles were then performed to validate the EMG signal.

Kinematic gait data were collected using an eight-camera, three-dimensional optical motion capture system (Oqus 3+, Qualisys AB, Göteborg, Sweden) sampled at 100 Hz. Kinetic data were collected using two synchronized force plates sampled at 2000 Hz (Advanced Mechanical Technology, Inc. Watertown, USA, model BP400600-2000, excitation voltage of 10V and an amplification of 1000 mV). The force plates were embedded in an eight meter walkway aligned with the global coordinates of the motion capture system. Forty reflective markers were placed on the participants. Eighteen markers were attached on bony landmarks bilaterally including acromiums, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), greater trochanter, lateral femoral epicondyle, calcaneus, lateral malleolus, and first and fifth metatarsal heads (Figure 2) (Collins, Ghoussayni, Ewins, & Kent, 2009; Leardini, Biagi, Merlo, Belvedere, & Benedetti, 2011; Leardini et al., 2007; Manca et al., 2010). Rectangular shaped marker clusters consisting of four markers each, one at each corner, were placed bilaterally on the thigh and shank and used to track these segments through all the trials. Six additional markers were

placed over medial femoral epicondyle, medial malleolus and second metatarsal head bilaterally for static calibration trial only and were removed prior to gait trials.

Table 1: The location and orientation of surface electromyogram electrodes over muscles.

Muscle (reference)	Location/ Orientation	
Gluteus maximus (Hermens et al., 2000)	Location	50% of the distance between the sacral vertebrae and the greater trochanter.
	Orientation	In the direction of the line from posterior superior iliac spine to the middle of the posterior aspect of the thigh.
Medial hamstrings (Rutherford et al., 2011)	Location	50% distance from ischial tuberosity to medial joint line of the knee.
	Orientation	In the direction of the line between the ischial tuberosity and the medial epicondyle of the tibia.
Lateral hamstrings (Rutherford et al., 2011)	Location	50% distance from ischial tuberosity to fibular head.
	Orientation	In the direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia.
Gluteus medius (Hermens et al., 2000)	Location	50% distance from top of iliac crest to greater trochanter.
	Orientation	In the direction of the line from the iliac crest to the greater trochanter.
Tensor fascia latae (Hermens et al., 2000)	Location	16% distance from anterior superior iliac spine to the lateral femoral condyle.
	Orientation	In the direction of the line from the anterior superior iliac spine to the lateral femoral condyle.
Vastus medialis (Rutherford et al., 2011)	Location	80% distance from anterior superior iliac spine to medial joint line of knee.
	Orientation	45 degrees lateral and inferior to the line between the anterior superior iliac spine and the joint space in front of the anterior border of the medial ligament.
Vastus lateralis (Rutherford et al., 2011)	Location	70% distance from anterior superior iliac spine to lateral joint line.
	Orientation	45 degrees medial and inferior to the line between the anterior superior iliac spine and the joint space in front of the anterior border of the lateral ligament.
Rectus femoris (Rutherford et al., 2011)	Location	50% distance from anterior superior iliac spine to superior border of patella.
	Orientation	In the direction of the line from the anterior superior iliac spine to the superior part of the patella.

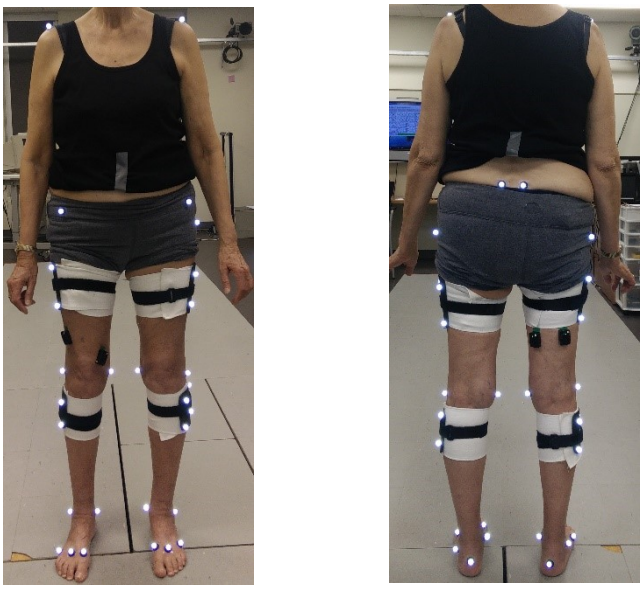

Figure 2: The placement of reflective markers.

3.4.1. Test protocol

Prior to each data collection, ghost markers in the capture volume were eliminated following which the motion capture system was calibrated using a wand of length 750mm (standard deviation of the wand́ length was below 0.8 mm). Following placement of EMG electrodes and previously described reflective markers set (Figure 2) participants were first made to perform one static and two functional calibration trials. The static trial involved the participant standing still on one of the force plates in the capture volume for five seconds with hands across chest. This trial was used to calculate knee, ankle, trunk and pelvis joint centres and measure body mass. In the functional hip trials, participants performed pendular like flexion, extension, abduction and adduction movements of their hip for 15 sec (Camomilla, Cereatti, Vannozzi, & Cappozzo, 2006). This was performed bilaterally and used to determine the hip joint centre (Bell, Pedersen, & Brand, 1990). The participants then performed the gait trials beginning with at least two warm-up trials to establish a natural walking speed and to determine a starting position that

allowed participants to regularly strike the force plates. Next, they performed at least seven gait trials, barefoot at self-selected speed along the eight meter walkway. To avoid alterations in natural gait speed, participants were not prompted to strike the force plate.

On completion of the gait trials, participants performed five maximum voluntary isometric contractions (MVIC) exercises on the study leg. MVIC exercises were performed using an isokinetic dynamometer (Humac Norm, Computer Sports Medicine, Inc., USA.). The exercises performed included: 1) knee extension in sitting with the knee in 45° of flexion; 2) knee flexion in sitting with the knee at 55° of flexion; 3) hip flexion in supine with the hip in 20° of flexion and the knee in flexion; 4) hip abduction in side-lying with the hip in 0° abduction; and 5) hip extension in prone with the hip in 0° (Boren et al., 2011; Rutherford et al., 2011). Each exercise included one practice and two collection trials with 30s rest between trials. A third trial was collected only if an error occurred during collection or if discrepancies of more than 10% were observed in torque values in the first two trials.

3.4.2. Biomechanical data processing

Five gait trials for each leg were first selected on the criteria of clear foot contact with force plate and complete marker set identification. The calibration (static and functional) and gait trials were gap-filled using the polynomial spline interpolation function (maximum 10 frames) on Qualisys track manager and raw kinematic, kinetic and EMG data were further processed and analyzed using custom scripts written in Visual 3D (v5, C-motion Inc., Germantown, USA).

Gait EMG data were band-pass filtered (cut off frequency 20–500 Hz) using a fourth-order, recursive Butterworth filter and then full wave rectified. A linear envelope was created by applying a fourth-order recursive Butterworth low-pass filter. MVIC EMG data were band-pass filtered (cut

off frequency 20–500 Hz) using a recursive fourth-order Butterworth filter and full wave rectified. A 100 ms moving-average window was then created to identify the maximum EMG amplitudes for each muscle during MVIC exercises. Maximum EMG amplitudes, regardless of the MVIC exercise in which it occurred, were used for gait EMG amplitude normalization (% MVIC) (Hubley-Kozey, Deluzio, Landry, McNutt, & Stanish, 2006). Gait EMG was time normalized to 100% of the gait cycle and ensemble averaged over the five trials.

Marker and force plate data were filtered using a low-pass, fourth-order, recursive Butterworth filter with a cut off frequency of 8 Hz and 20 Hz respectively. Three-dimensional joint angles during gait were calculated using a six degrees-of-freedom linked segment model. The orientation of each segment in the model was determined by at least three non-collinear points. A segment coordinate axis system was defined for each segment (Collins et al., 2009).

The lab coordinate system was adjusted to walking direction with X axis oriented medial/ laterally (positive = laterally), Y axis anterior/ posteriorly (positive = anteriorly) and Z axis inferior/ superiorly (positive = superiorly). The pelvic segment coordinate system origin was at the midpoint of the line joining the mid-ASIS (midpoint of the line joining the ASIS markers) and the mid-PSIS (midpoint of the line joining the PSIS markers). Pelvic angles were defined as the orientation of the pelvic segment relative to the lab coordinate system using a Euler ZYX (rotation-obliquity-tilt) rotational sequence. Only pelvic obliquity angle (Y axis, frontal plane) was analyzed as it is controlled by the gluteus medius. A positive pelvic obliquity angle indicated a pelvic drop on the ipsilateral innominate in the frontal plane while the pelvis rises on the contralateral innominate. A negative pelvic obliquity angle indicates pelvic rise on the ipsilateral innominate in the frontal plane while the pelvis drops on the contralateral innominate (Baker, 2001). The origin

of the local segment coordinate system of the trunk was at the midpoint of the line joining the mid-ASIS markers and the mid-acromium markers (Baker, 2001). The lateral trunk lean angle was calculated as the angle between the proximal-distal axis of the frontal plane of the trunk and the vertical axis of the lab (positive = ipsilateral trunk lean, negative = contralateral trunk lean) (Linley, Sled, Culham, & Deluzio, 2010). The hip joint centre was calculated using the functional method and the knee joint centre was calculated as the midpoint between the medial and lateral epicondyle markers (Bell et al., 1990). Hip joint angles were defined as the motion of the thigh segment relative to the pelvis using a Euler XYZ rotational sequence with hip flexion/ extension about the medial-lateral X axis (positive = flexion, negative = extension), adduction/ abduction about the anterior-posterior Y axis (positive = adduction, negative = abduction) and medial/ lateral rotation about vertical Z axis (positive = medial rotation, negative = lateral rotation). Net external hip moments were calculated through inverse dynamics procedure with previously published inertial segment properties and calculated about the joint coordinate system with hip flexion/ extension about the medial-lateral X axis (positive = extension, negative = flexion), abduction/ adduction about the anterior-posterior Y axis (positive = abduction, negative = adduction) and medial/ lateral rotation about vertical Z axis (positive = lateral rotation, negative = medial rotation) (Dempster, 1955; Schache & Baker, 2007). These were amplitude normalized to body mass. Joint angles and external moments were normalized to 100% of the gait cycle and ensemble averaged over the five trials.

Initial gait events (initial contact and toe-off) were computed from force plate contact. Subsequent occurrences of these gait events (off the force plate) were identified using the. kinematic based technique (Stanhope, Kepple, McGuire, & Roman, 1990). Gait cycle was defined as the period between two continuous ipsilateral initial contacts. Spatio-temporal variables were calculated based on gait events. Gait speed was computed by tracking the speed of the forward

progression of posterior superior iliac spine markers. Step length was the distance between initial contact of the study leg to initial contact of the non-study leg. Stride length was the distance between two consecutive initial contacts of study leg. Step length (m/height) and stride length (m/height) were normalized to height to account for differences in height between participants. Stance time (s) was defined as the time between initial contact to toe-off of the study leg and stride time (s) was defined as the time taken to complete one gait cycle. Stance time was represented as a percentage of stride time (% stance).

Torque data from MVIC exercises were filtered using a fourth-order recursive Butterworth filter with a cut off frequency of 10Hz. A 500 ms moving-average window was then created to identify the maximum torque in each MVIC trial. For each exercise, the trial with greater maximum torque was identified as the maximum isometric torque for that exercise.

The primary biomechanical outcome measures were (1) gait EMG of all muscle groups, (2) joint angles during gait including: hip angles, pelvic obliquity angle and ipsilateral trunk lean angle (3) external hip abduction moments during gait (4) maximum isometric hip abduction and extension torque. Secondarily we explored the other variables as well (e.g. external hip extension moment, knee extension torque, spatio-temporal).

3.5. CLINICAL MEASURES

Clinical outcomes included pain, symptoms, function in activities of daily living, function in sport and recreation, and hip-related quality of life were measured using self-report Hip disability and Osteoarthritis Outcome Score questionnaire (HOOS). Physical function was also measured using three performance-based tests including: Six-Minute Walk Test (6MWT), 30-second Chair Stand Test (30-CST), 11-step stair ascend/ descend test (11-step SCT).

3.5.1. HOOS questionnaire

The HOOS (Appendix 3) is a self-report questionnaire that assesses a participant's opinion about their hip and associated problems. It consists of five subscales with 40 items: pain (10 items), other symptoms (5 items; 3 for symptoms and 2 for stiffness), function in activities of daily living (17 items), function in sport and recreation (4 items), and hip-related quality of life (4 items). Based on five standardized answer options (likert boxes) each question is scored from 0 to 4 (0 = none, 1 = mild, 2 = moderate, 3 = severe and 4 = extreme). Scores are summarized for each subscale and transformed to a 0 - 100 scale (0 indicating extreme problems and 100 indicating no problems) (Nilsdotter & Bremander, 2011; Nilsdotter, Lohmander, Klassbo, & Roos, 2003). Among participants with THA, the HOOS has found to have a Cronbach's alpha correlation of r = 0.90 for measuring physical function (Davis et al., 2009). Also, among patients with hip OA or after THA, the HOOS has found to have an internal consistency ranging from 0.82 to 0.98 (Cronbach's alpha coefficient) and a high test-retest reliability, with the intraclass correlation coefficient ranging from 0.78 to 0.91 (de Groot et al., 2007; Klassbo, Larsson, & Mannevik, 2003; Ornetti et al., 2010).

3.5.2. 6MWT

The 6MWT (Appendix 4) is a submaximal exercise test used to assess aerobic capacity and endurance (Bennell, Dobson, & Hinman, 2011). The following instructions were provided to the participants "For this test, do the best you can by going as fast as you can, but do not push yourself to a point of overexertion or beyond what you think is safe for you. Start with both feet on the start line. On start, walk as quickly but as safely as possible up and down the hallway. Continue to cover as much ground as possible over six minutes. Walk continuously if possible, but do not be concerned if you need to slow down or stop to rest. The goal is to feel at the end of the test that no

more ground could have been covered in the six minutes. You can sit down to rest if you require." The 6MWT has shown to have high test-retest reliability (intraclass correlation coefficient = 0.96) in patients after THA (Unver, Kahraman, Kalkan, Yuksel, & Karatosun, 2013). The test has found to have a positive correlation (r = 0.62) with the Short-Form 36 physical function scale indicating adequate validity in measuring this construct among a cardiac rehabilitation population.

3.5.3. 30-CST

The 30-CST (Appendix 4) measures the maximum number of sit-to-stand repetitions from a standard chair (seat height = 46 cm) in 30 seconds. The following instructions were provided to the participants, "For this test, do the best you can by going as fast as you can but do not push yourself to a point of overexertion or beyond what you think is safe for you. Place your hands on the opposite shoulder so that your arms are crossed at the wrists and held close across your chest. Keep your arms in this position for the test. Keep your feet flat on the floor and at shoulder width apart. On the signal to begin, stand up to a full stand position and then sit back down again so as your bottom fully touches the seat. Keep going for 30 seconds and until I say stop." The 30-CST was found to be a reliable measure of functional performance in patients after THA (intraclass correlation coefficient = 0.94; standard error = 0.4 and minimal detectable change at 90% confidence level = 1.2 repetitions) (Unver et al., 2015).

3.5.4. 11-step SCT

The 11-step SCT (Appendix 4) assesses the time taken to ascend and descend a flight of eleven stairs (stair height =16 cm) (Bennell et al., 2011). The instructions were, "For this test, do the best you can by going as fast as you can but do not push yourself to a point of overexertion or beyond what you think is safe for you. Start with both feet on the bottom landing. On start, go to

the top of the stairs as fast but as safe as you can, turn around and return back down and stop with both feet back on the ground landing. Use the rail only if needed." The test has proven to have good inter-rater reliability for clinical use among individuals with total knee arthroplasty, with an intraclass correlation coefficient = 0.94, standard error = 1.14 s and minimum detectable change at 90% confidence level = 2.6 s (Almeida, Schroeder, Gil, Fitzgerald, & Piva, 2010). Among symptomatic individuals with hip/ knee OA, a positive correlation (r = 0.53) was found between the 4-step SCT and the Western Ontario and McMaster Universities Osteoarthritis Index physical function subscale (Bennell et al., 2011).

3.6. TEST PROCEDURE

Testing began once written consent (Appendix 5) and basic demographic information was obtained from the participants. Participants then completed the HOOS questionnaire (Appendix 3) and three physical function tests including 6MWT, 30-CST, 11-step SCT (Appendix 4). Following this, participants changed into tight fitting shorts and shirt so that the passive reflective markers would be placed as closely as possible to the anatomical landmarks. Surface EMG electrodes and reflective makers were placed on the participants and they completed the biomechanical data collection of gait as described above. On completion of the gait trials, participant height was measured. This was followed by the MVIC exercises.

3.7. PRINCIPAL COMPONENT ANALYSIS (PCA)

Principal component analysis of gait data were performed to reduce the multidimensionality of the gait waveforms and identify important waveform characteristics (principal components) (Deluzio, 1997). The extracted principal components (PCs) were further analyzed for group differences. PCA involved creating thirteen separate PCA models, including

EMG waveforms for muscle groups: gluteus medius, gluteus maximus, quadriceps (vastus medialis, vastus lateralis and rectus femoris), hamstrings (medial and lateral hamstrings) and tensor fascia latae; joint angles: hip joint flexion, adduction and medial rotation angles (each angle in a separate analysis), pelvic obliquity and trunk lean angles; and external hip moments: extension, abduction and lateral rotation moments (each moment in a separate analysis) (Hubley-Kozey et al., 2006). The procedure involved first creating an ***X*** matrix of the gait ensemble average waveforms of the variable of interest (e.g. gluteus medius EMG) for all participants (Hubley-Kozey et al., 2006). The covariance matrix of ***X*** was determined, and eigenvectors ***(U)*** and eigenvalues were extracted from the covariance matrix. The eigenvectors are the principal components (PCs) and represent characteristics of the gait waveform data (e.g. amplitude, difference operator, timing difference). Eigenvalues represent described variance in PC-scores. PC-scores were then calculated for each waveform in X. The PC-scores describes how closely individual waveforms match the PC.

$$\text{PC-scores} = (X - \overline{X})*U)$$

Where X = matrix of the gait ensemble average waveforms of the variable of interest
U = principal components or eigenvectors
$\overline{X}$ = mean waveform calculated from X

Data interpretation of the features of a given PC was achieved through visual inspection of PC graphs and the average curves of the participants who had the highest (95th percentile) and lowest (5th percentile) PC-scores. As PCA involves data reduction such that the majority of the variation can be explained by the first few PCs, for each variable only the first three PCs (PC1–PC3) were examined. Previous gait literature has reported these to typically represent more than

80% of the variability in data (Deluzio & Astephen, 2007; Hubley-Kozey et al., 2013). The PC-scores were then used for additional statistical analysis.

3.8. STATISTICAL ANALYSIS

Descriptive statistics were reported for the demographic data (e.g. age, mass, height, BMI, sex), clinical outcomes and gait variables including PCs. Data were assessed for normality of distribution and spread using kurtosis, skewness, Shapiro-Wilk test, normality plots and histograms.

One-way analysis of variances (ANOVA), compared groups (lateral THA, posterior THA, healthy) on demographics, gait PC-scores (e.g. gluteus medius EMG, hip angles), isometric muscle torque, spatio-temporal gait variables, and clinical outcomes. For muscle groups that include more than one muscle (quadriceps, hamstrings), two-way mixed-model ANOVAs compared groups and muscles. Muscle comparisons consisted of vastus lateralis, vastus medialis and rectus femoris for the quadriceps group, and medial hamstrings and lateral hamstrings for the hamstring group. A Bonferroni post hoc procedure was used to test for pairwise differences in variables that revealed significant difference. Mean difference with 95% confidence intervals (95% CI) were also reported for pairwise comparisons. Since HOOS subscale scores on pain, symptoms, activities of daily living, sport/ recreation and quality of life were not normally distributed and were not improved on transformation, the Kruskal-Wallis H test was used to compare HOOS subscores for group effects; following which Man Whitney U test was used to test for pairwise group differences in subscale scores that revealed significant group effects. A significance value of $p = 0.05$ was used for all statistical tests except the Man Whitney U test for which significance value of $p = 0.02$ was used to adjust with Bonferroni correction. Lastly Cohen's d effect sizes were computed and

interpreted as small (d = 0.2), medium (d = 0.5), and large (d = 0.8) based on preset benchmarks (Cohen, 1988). SPSS (version 24) statistical software was used for all statistical analysis.

CHAPTER 4: RESULTS

4.1. CHARACTERISTICS OF THE STUDY SAMPLE

Group descriptive statistics for participant demographics are presented in Table 2. Although participants were similar across groups for age, body mass index and sex, they differed significantly in height and mass (Table 2). Participants in the posterior THA group were significantly taller ($p = 0.02$) and had a higher mass ($p = 0.05$) than participants in healthy group, likely because they had a higher proportion of men.

Table 2: Mean (standard deviation) values for demographic variables. Frequency is provided for sex.

Variable	Healthy (n=21)	Lateral THA (n=19)	Posterior THA (n=19)	Group Effect p value*
Age (years)	63 (8)	67 (7)	62 (7)	0.11
Mass (kg)	71.95 (12.36)	73.98 (13.55)	82.84 (16.29)	0.04
Height (m)	1.65 (0.07)	1.66 (0.11)	1.72 (0.05)	0.01
Body mass index (kg/m^2)	26.56 (4.81)	26.73 (3.12)	27.86 (4.73)	0.59
Sex (frequency)	15 women 6 men	10 women 9 men	6 women 13 men	- -

n = number of participants in group, *p value from one-way analysis of variance, THA = total hip arthroplasty.

4.2. GAIT EMG

Group ensemble average of gait EMG are presented in Figures 3, 5 and 6. Description of gait EMG PCs are presented in Table 3 and group statistics of the muscles are presented in Tables 4, 5 and 6. Muscle, group and interaction effects of hamstring and quadriceps muscle PCs are presented in Table 5. Pairwise comparison of study groups for gait EMG PCs are presented in Appendices 6, 7 and 8. The first three PCs explained approximately 85% to 95% of the variance in the gait EMG waveforms.

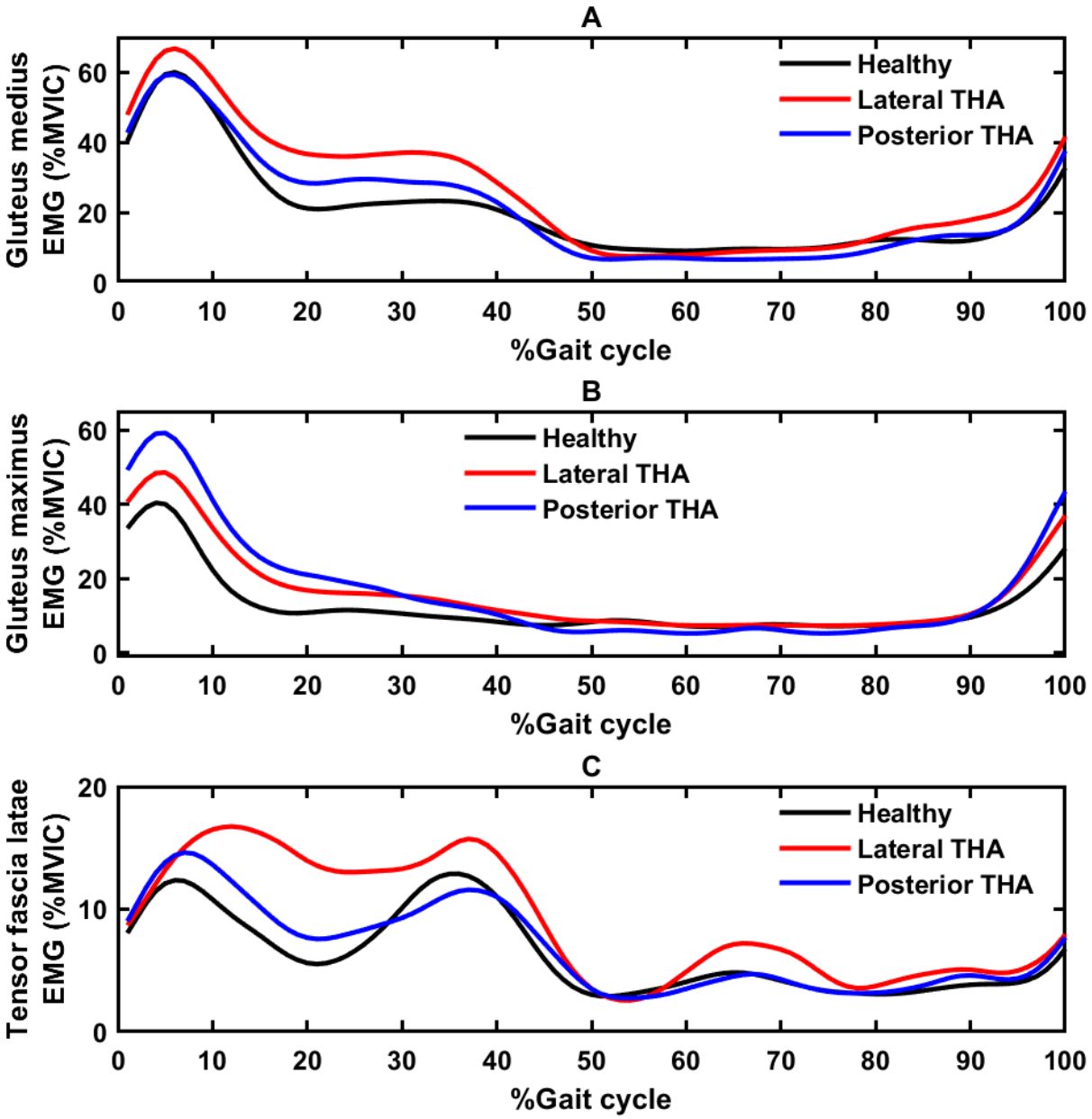

Figure 3: Group ensemble average gait electromyography (EMG) as a percentage of maximum voluntary isometric contraction (% MVIC) over the gait cycle for (A) gluteus medius (B) gluteus maximus and (C) tensor fascia latae muscles. The red, blue and black lines represent lateral THA, posterior THA and healthy groups respectively.

Table 3: Percentage of explained variance and description of the principal components (PCs) for each muscle group.

Muscles	PC	Description	Variance explained (%)
Gluteus Medius	**1**	General shape and overall amplitude (higher scores = greater gluteus medius activation)	80.30
	2	Timing of gluteus medius activation during swing/ loading response (higher scores = earlier gluteus medius activation)	7.60
	3	Amplitude of gluteus medius activation at mid/ terminal stance (higher score = higher gluteus medius activation)	4.28
Gluteus Maximus	**1**	General shape and overall amplitude (higher score = greater gluteus maximus activation)	75.74
	2	Difference in gluteus maximus muscle activation at loading response versus rest of gait (higher score = smaller difference)	11.20
	3	Timing of gluteus maximus activation (higher scores = earlier gluteus maximus activation)	5.09
Hamstrings	**1**	General shape and overall amplitude (higher score = greater hamstring activation)	54.30
	2	Difference in hamstring muscle activation at midstance compared to terminal swing (higher scores = smaller difference)	18.32
	3	Timing of hamstring muscle activation at terminal swing (higher scores = delayed hamstring activation)	7.71
Quadriceps	**1**	General shape and overall amplitude (higher score = greater quadriceps activation)	69.22
	2	Amplitude of quadriceps muscle activation at terminal stance/ preswing compared to loading response (higher scores = smaller difference)	10.33
	3	Difference in muscle activation at terminal stance compared to at preswing/ initial swing (higher scores = greater difference)	7.03
Tensor fascia latae	**1**	General shape and overall amplitude (higher score = greater tensor fascia latae activation)	70.50
	2	Shape of tensor fascia latae muscle activation during late swing and stance (higher scores = delayed activation with prolonged activation during mid/ terminal stance)	14.77
	3	Amplitude of tensor fascia latae activation at preswing/ terminal swing (higher score = higher tensor fascia latae activation)	4.95

4.2.1. Gluteus medius

The gluteus medius EMG differed significantly between groups for PC3 (Table 4). Gluteus medius PC3 represents the amplitude of the muscle activation at mid/ terminal stance (Figure 4A, Table 3). Participants in the lateral group had significantly higher PC3 scores (mean difference = -36.38; 95% CI = -63.96 to -8.80; p = 0.01, Figure 4B) with large effect sizes (d = 1.04) demonstrating that they had higher amplitude of gluteus medius activation during these phases compared to healthy group (Figure 3A). No remaining differences in activation of gluteus medius muscle were identified between study groups (Table 4).

4.2.2. Gluteus maximus

PC2 of the gluteus maximus differed significantly across study groups (Table 4). Gluteus maximus PC2 represents the difference in muscle activation at loading response versus rest of gait (Figure 4C, Table 3). The posterior THA group had significantly lower scores compared to the healthy group (mean difference = 33.58, 95% CI = 3.55 to 63.62; p = 0.02, Figure 4D), with large effect sizes (d = 0.98) indicating that posterior THA group activated their gluteus maximus to a greater extent at loading response compared to the rest of the gait cycle (Figure 3B). No remaining differences in activation of gluteus maximus muscle were identified between study groups (Table 4).

Table 4: Mean (standard deviation) values for gait EMG principal components (PCs).

Muscles (PC-scores)	PCs	Healthy (n = 21)	Lateral THA (n = 19)	Posterior THA (n = 19)	Group Effect p value*
Gluteus medius ‡	**1**	-28.39 (229.90)	39.16 (127.24)	-9.28 (92.22)	0.42
	2	-6.87 (64.60)	8.69 (48.44)	-1.46 (31.31)	0.62
	3	-18.59 (32.35)	17.79 (37.24)	1.78 (34.94)	0.01
Gluteus maximus ‡	**1**	-39.92 (88.00)	6.98 (83.50)	35.04 (126.82)	0.07
	2	13.29 (36.83)	6.30 (44.73)	-20.29 (31.18)	0.02
	3	6.75 (19.11)	-1.07 (29.35)	-6.03 (31.13)	0.33
Tensor fascia latae	**1**	-12.45 (54.43)	19.25 (72.21)	-5.49 (61.81)	0.26
	2	-1.22 (27.96)	6.51 (35.92)	-5.17 (21.80)	0.46
	3	-4.47 (14.86)	6.99 (21.71)	-2.05 (10.60)	0.08

n = number of participants in group, *p value from one-way analysis of variance (ANOVA), THA = total hip arthroplasty, ‡ = missing data on one participant in healthy group for all PCs of gluteus medius and gluteus maximus.

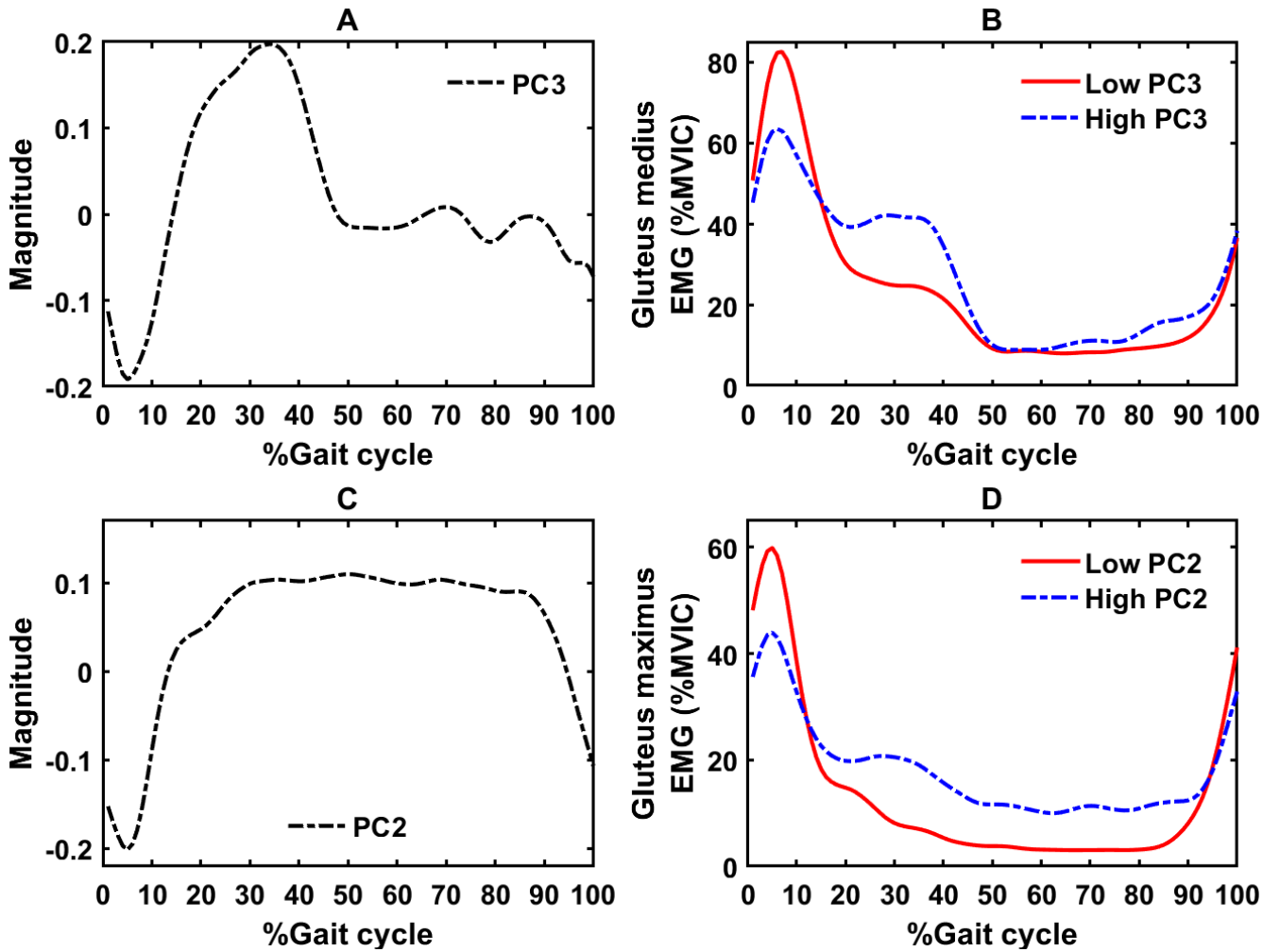

Figure 4: (A) Gluteus medius principal component (PC) 3 (black dashed line) with (B) mean gluteus medius waveforms for a subset of participants that scored high (blue dashed line) and low (red solid line) on PC3. (C) Gluteus maximus PC2 (black dashed line) with (D) mean gluteus maximus waveforms for a subset of participants that scored high (blue dashed line) and low (red solid line) on PC2. EMG was normalized to maximum voluntary isometric contraction (% MVIC).

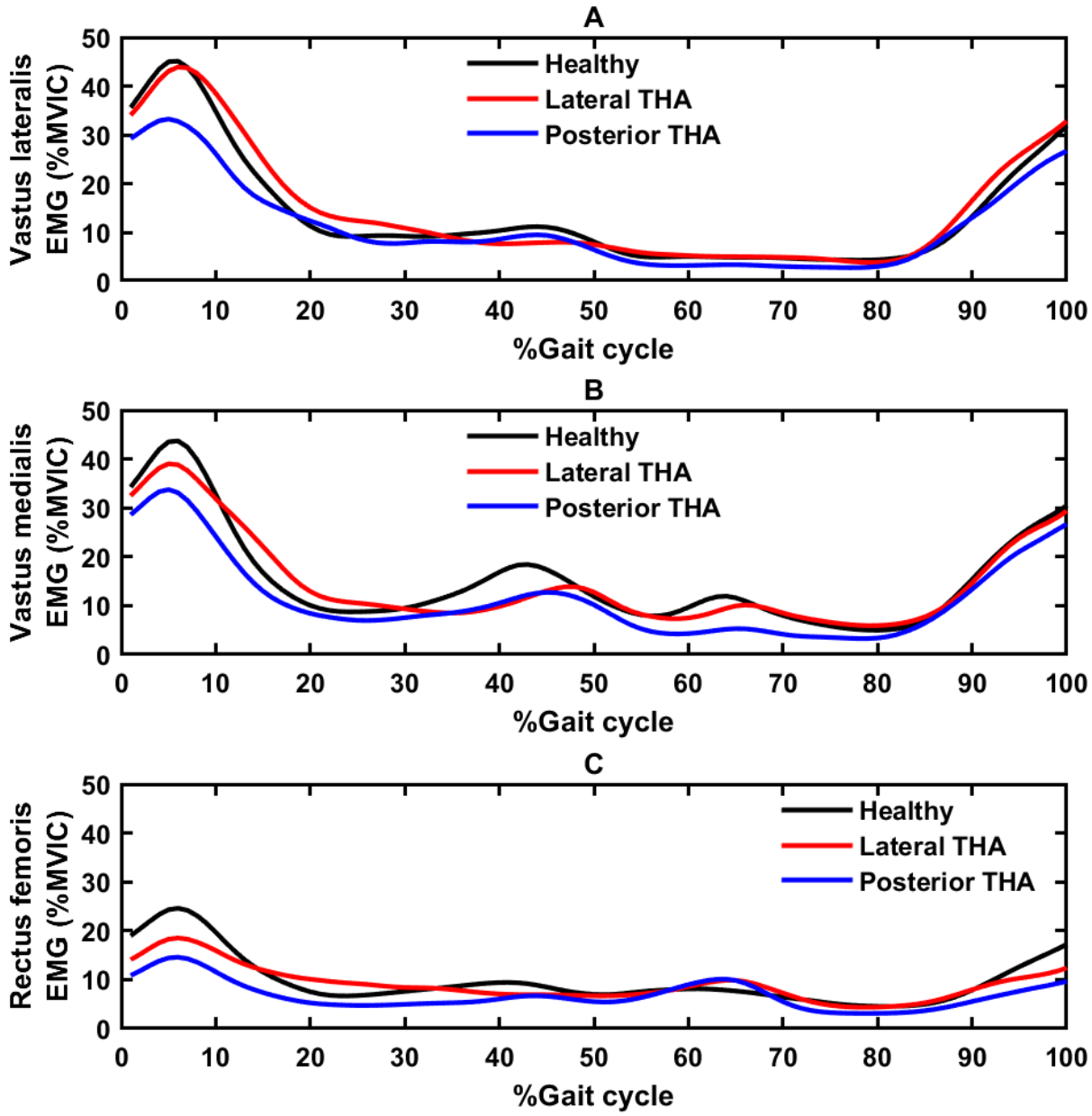

Figure 5: Group ensemble average gait electromyography (EMG) as a percentage of maximum voluntary isometric contraction (% MVIC) over the gait cycle for (A) vastus lateralis (B) vastus medialis and (C) rectus femoris muscles. The red, blue and black lines represent lateral THA, posterior THA and healthy groups respectively.

4.2.3. Tensor fascia latae

PCs for the tensor fascia latae muscle activation did not differ significantly between groups (Table 4, Figure 3C).

4.2.4. Quadriceps

The two-way mixed-model ANOVA for PCs of the quadriceps group found significant muscle effects (Table 5, Figure 5) for all quadriceps muscles, but there were no significant group or group-muscle interaction effects (Table 5, $p > 0.05$).

4.2.5. Hamstrings

The two-way mixed-model ANOVA for PCs of the hamstrings group found significant group and muscle effects for PC2 (Table 5, Figure 6), however, no group-muscle interaction effects (Table 5, $p > 0.05$) were identified. Hamstrings PC2 represents the difference in muscle activation at midstance compared to terminal swing (Figure 7A, Table 3). The lateral hamstrings had higher PC2-scores, which indicated greater activation during midstance (10-40% gait cycle) (Table 6). The posterior THA group had significantly higher PC2-scores compared to the healthy group (mean difference = -31.22, 95% CI = -48.61 to -13.83; $p < 0.001$, Figure 7B) and lateral THA group (mean difference = -22.16, 95% CI = -39.98 to -4.34; $p = 0.02$) with large effect size ($d = 1.34$) and medium effect size ($d = 0.68$) respectively. This indicated that the posterior THA group activated their lateral hamstrings to a greater extent during midstance (Figure 6A). No remaining significant differences in muscle, group or interaction effects were present for activation of the hamstrings muscle during gait (Table 5).

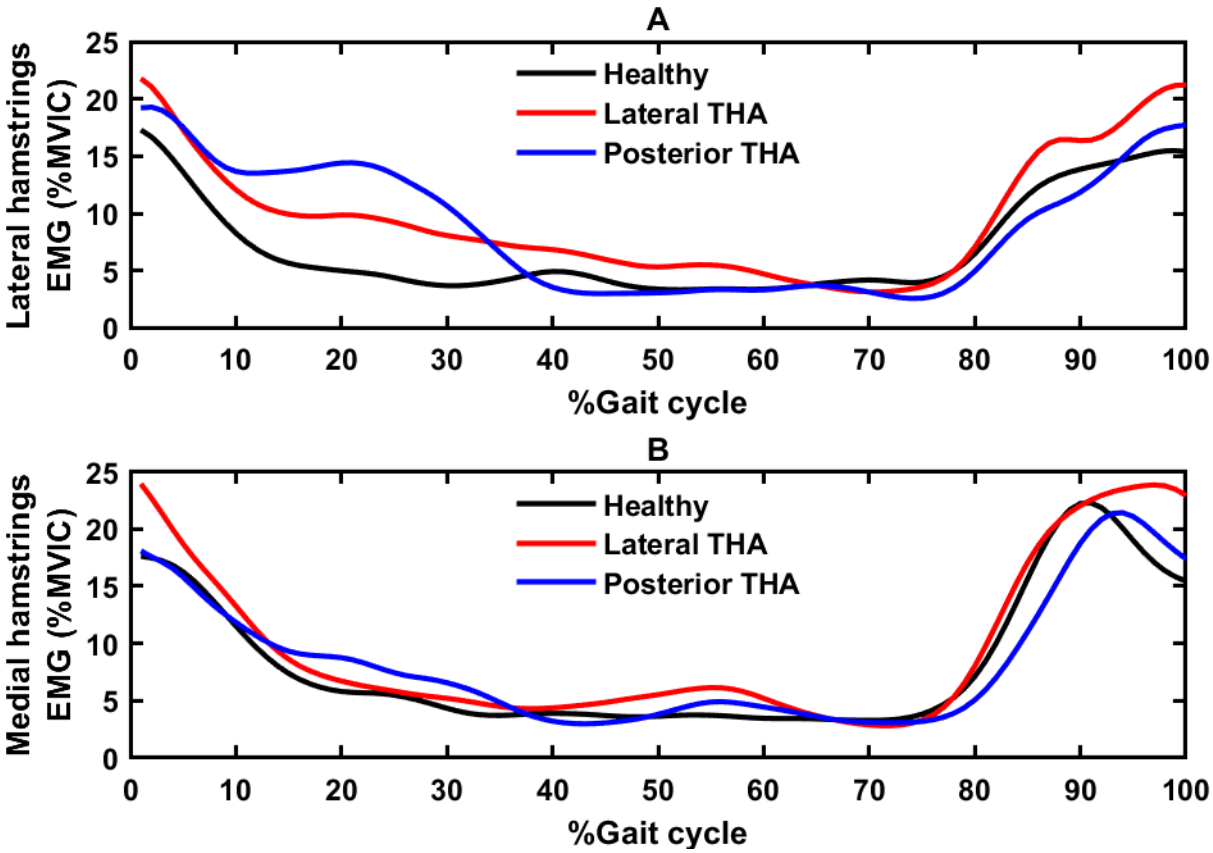

Figure 6: Group ensemble average gait electromyography (EMG) as a percentage of maximum voluntary isometric contraction (% MVIC) over the gait cycle for (A) lateral hamstrings and (B) medial hamstrings muscles. The red, blue and black lines represent lateral THA, posterior THA and healthy groups respectively.

Table 5: Group, muscle and interaction effects for quadriceps and hamstring muscle principal components (PCs) from the two-way analysis of variance.

Muscle group	PC	Group effect p value	Muscle Effect p value	Interaction effect p value
Quadriceps	**1**	0.25	0.00	0.55
	2	0.87	0.00	0.21
	3	0.45	0.00	0.29
Hamstrings	**1**	0.24	0.28	0.50
	2	0.01	0.00	0.13
	3	0.45	0.18	0.42

Table 6: Mean (standard deviation) values for gait EMG principal components (PCs) of hamstring and quadriceps muscle groups.

Muscles			Healthy (n = 21)	Lateral THA (n = 19)	Posterior THA (n = 19)
Quadriceps	**Vastus lateralis** ‡	**1**	36.17 (105.72)	43.89 (93.33)	1.66 (69.61)
		2	-18.46 (29.98)	-24.35 (24.24)	-11.48 (27.43)
		3	8.27 (16.46)	1.46 (21.30)	10.65 (15.41)
	Vastus medialis ‡	**1**	40.81 (138.62)	31.68 (74.34)	0.63 (87.85)
		2	9.66 (65.02)	0.22 (41.39)	0.27 (32.40)
		3	-1.29 (68.65)	-6.15 (30.75)	9.43 (21.47)
	Rectus femoris ‡	**1**	-34.49 (64.26)	-50.53 (53.35)	-72.35 (42.10)
		2	10.19 (16.61)	16.62 (17.54)	17.26 (22.24)
		3	-3.09 (10.08)	-9.89 (17.23)	-9.50 (12.55)
Hamstrings	**Lateral hamstrings**	**1**	-21.22 (47.11)	8.29 (67.59)	1.83 (57.18)
		2	-3.28 (13.40)	5.78 (34.43)	27.94 (30.88)
		3	1.14 (17.89)	2.74 (21.64)	2.63 (22.06)
	Medial hamstrings	**1**	-1.96 (42.09)	15.89 (56.70)	-0.39 (41.21)
		2	-11.96 (23.97)	-15.52 (33.84)	-1.36 (26.01)
		3	-7.51 (18.98)	3.87 (19.39)	-2.20 (19.32)

n = number of participants in group, THA = total hip arthroplasty, ‡ missing data on one participant in posterior THA group for all PCs of vastus lateralis, vastus medialis and rectus femoris.

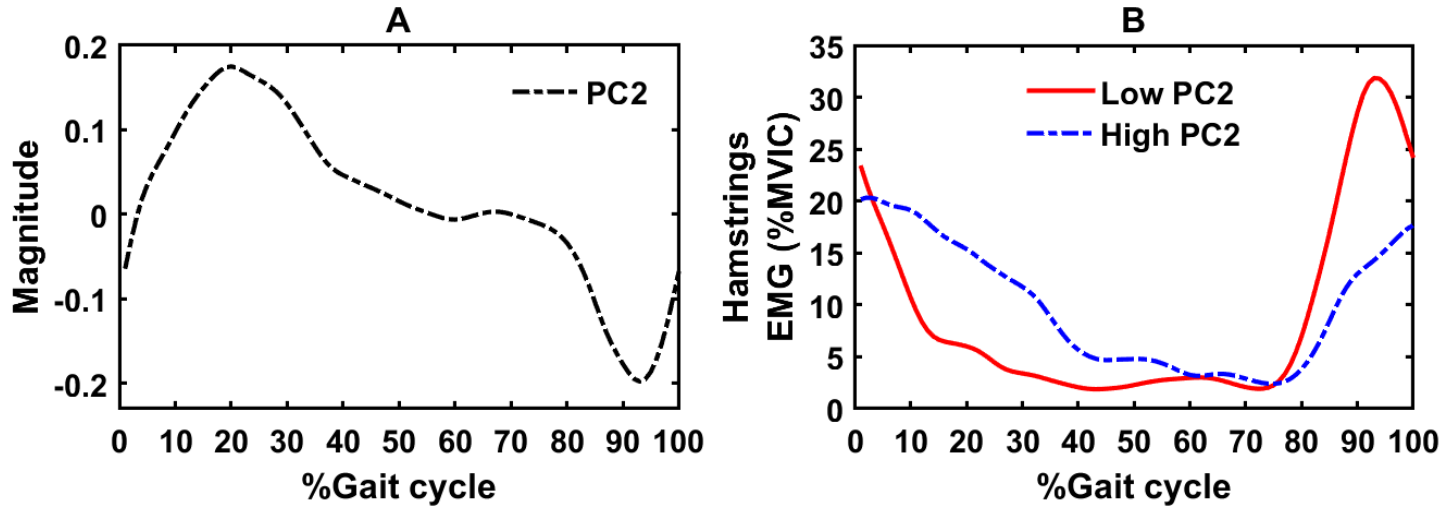

Figure 7: (A) Hamstrings principal component (PC) 2 (black dashed line) with (B) Mean hamstrings waveforms for a subset of participants that scored high (blue dashed line) and low (red solid line) on PC2. EMG was normalized to maximum voluntary isometric contraction (% MVIC).

4.3. JOINT ANGLES

Group ensemble average of gait angles of the hip, pelvis and trunk are presented in Figures 8 and 11. Description of the gait angle PCs and group statistics are presented in Table 7 and 8 respectively. Pairwise comparison of study groups for gait moment PCs are presented in Appendix 9. The first three PCs explained more than 95% of the variance in the joint angle excursion waveforms during gait.

Table 7: Percentage of explained variance and description of the principal components (PCs) for joint angles.

Angle	PC	Description	Variance explained (%)
Hip flexion angle	**1**	General shape and overall amplitude (higher scores = greater hip flexion angles)	90.27
	2	Difference in flexion at terminal swing/ initial contact compared to extension at pre/ initial swing (higher scores = greater difference)	6.10
	3	Timing of hip flexion during mid/ terminal stance (higher scores = delayed hip extension)	1.79
Hip adduction angle	**1**	General shape and overall amplitude (higher score = greater hip adduction angles)	67.16
	2	Difference in adduction at midstance to preswing compared to abduction angle during swing (higher score = greater differences)	18.26
	3	Difference in adduction angle at initial contact/ midstance compared to abduction angle at initial swing (higher scores = greater differences)	6.84
Hip medial rotation angle	**1**	General shape and overall amplitude (higher score = greater medial rotation)	85.34
	2	Difference in medial rotation at terminal stance/ preswing compared to lateral rotation at loading response/ terminal swing (higher score = greater differences)	6.02
	3	Difference in medial rotation at mid/ terminal stance compared lateral to rotation during midswing (higher score = less difference)	4.41
Pelvis obliquity angle	**1**	General shape and overall amplitude (higher score = greater ipsilateral pelvic drop)	71.06
	2	Difference in pelvic drop at pre/ initial swing compared to loading response/ midstance (higher score = greater difference)	13.71
	3	Difference in pelvic drop during swing compared to midstance to preswing (higher scores = greater difference)	10.45
Trunk lean angle	**1**	General shape and overall amplitude of ipsilateral trunk lean angles (higher score = greater ipsilateral trunk lean angles)	87.13
	2	Difference in ipsilateral trunk lean during mid/ terminal stance compared to swing (higher score = greater difference)	6.85
	3	Difference in ipsilateral trunk lean during initial contact/ terminal swing compared to terminal/ preswing (higher score = greater differences)	4.11

Table 8: Mean (standard deviation) values for gait joint angle principal components (PCs).

Angles (PC-scores)	PC	Healthy (n = 21)	Lateral THA (n = 19)	Posterior THA (n = 19)	Group effect p value*
Hip flexion angle	**1**	-14.71 (76.26)	-9.86 (63.63)	26.12 (77.05)	0.17
	2	11.91 (16.87)	-6.66 (15.96)	-6.50 (18.86)	0.00
	3	0.40 (11.66)	2.48 (10.98)	-2.92 (7.80)	0.28
Hip adduction angle	**1**	-0.12 (23.28)	2.73 (27.21)	-2.60 (23.25)	0.80
	2	4.87 (14.99)	0.38 (10.36)	-5.76 (9.81)	0.03
	3	3.13 (7.81)	-2.35 (7.17)	-1.12 (7.44)	0.06
Hip medial rotation angle	**1**	3.54 (68.60)	-6.75 (76.50)	2.84 (56.63)	0.87
	2	-8.95 (17.31)	4.60 (17.00)	5.29 (15.68)	0.01
	3	8.10 (12.89)	1.04 (12.40)	-10.00 (14.84)	0.00
Pelvis obliquity angle	**1**	2.65 (20.60)	-5.02 (16.04)	2.09 (14.76)	0.61
	2	3.68 (7.68)	-2.41 (8.16)	-1.66 (5.75)	0.05
	3	1.98 (6.63)	-0.12 (7.09)	-2.07 (6.06)	0.36
Trunk lean angle	**1**	-6.86 (16.35)	2.97 (17.58)	4.62 (18.45)	0.09
	2	-1.48 (5.93)	1.42 (4.56)	0.21 (4.07)	0.19
	3	-0.39 (3.71)	0.83 (3.88)	-0.40 (4.15)	0.53

n = number of participants in group, *p value for one-way analysis of variance, THA = total hip arthroplasty.

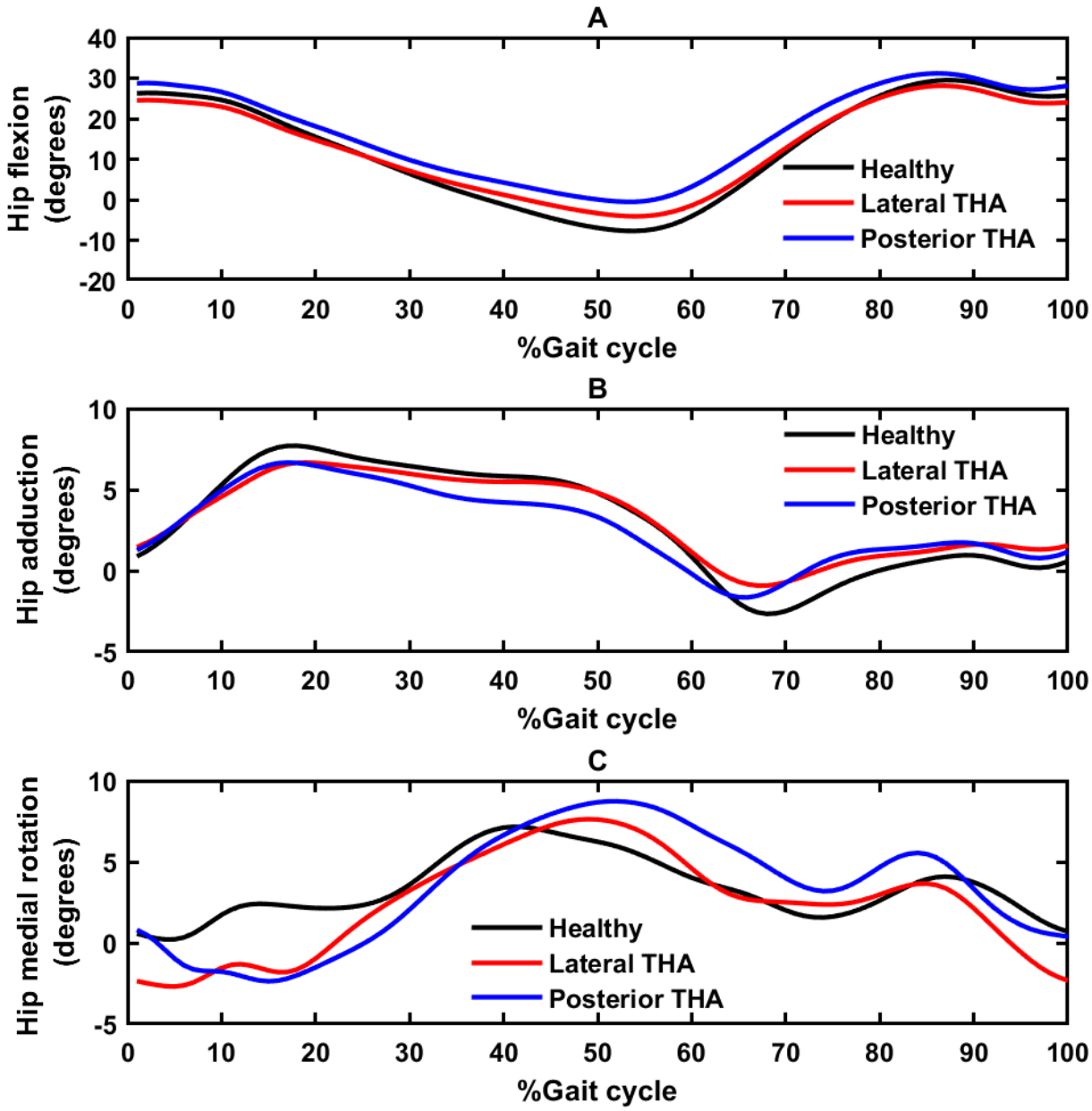

Figure 8: Group ensemble average hip joint (A) flexion angle (flexion = positive, extension = negative) (B) adduction angle (adduction = positive, abduction = negative) and (C) medial rotation angle (medial rotation = positive, lateral rotation = negative) during gait for lateral THA (red line), posterior THA (blue line) and healthy (black line) groups. Amplitude of joint angle, degrees is on the y-axis and percent of gait cycle on the x-axis (%Gait cycle).

4.3.1. Hip flexion angle

For hip flexion angles, there was a significant difference in PC2 between groups (Table 8). Hip flexion PC2 represents the difference in hip flexion excursion angles at terminal swing/ initial contact compared to extension at pre/ initial swing (Figure 9A, Table 7). Statistically significant lower PC-scores with large effect sizes were observed in the lateral (mean difference = 18.57, 95% CI = 5.08 to 32.06; $p < 0.001$; $d = 1.13$, Figure 9B) and posterior (mean difference = 18.41, 95% CI = 4.92 to 31.89; $p < 0.001$; $d = 1.04$, Figure 9B) THA groups compared to the healthy group. This indicates that THA groups had decreased hip flexion angle excursion at terminal swing/ initial contact versus extension at pre/ initial swing compared to the healthy group (Figure 8A). There were no remaining significant differences in hip flexion angles between groups (Table 8).

4.3.2. Hip adduction angle

Hip adduction angles differed significantly for PC2 (Table 8). Hip adduction PC2 represents the difference in hip adduction at midstance to preswing compared to abduction angle during swing (Figure 9C, Table 7). Posterior THA group had significantly lower PC2 scores compared to the healthy group (mean difference = 10.63; 95% CI = 1.20 to 20.06; $p = 0.02$, Figure 9D) with large effect size ($d = 0.83$). This indicated that the posterior THA group had decreased hip adduction angle excursion between midstance to preswing compared to abduction angle during swing (Figure 8B). No remaining differences in hip adduction PCs were identified between groups (Table 8).

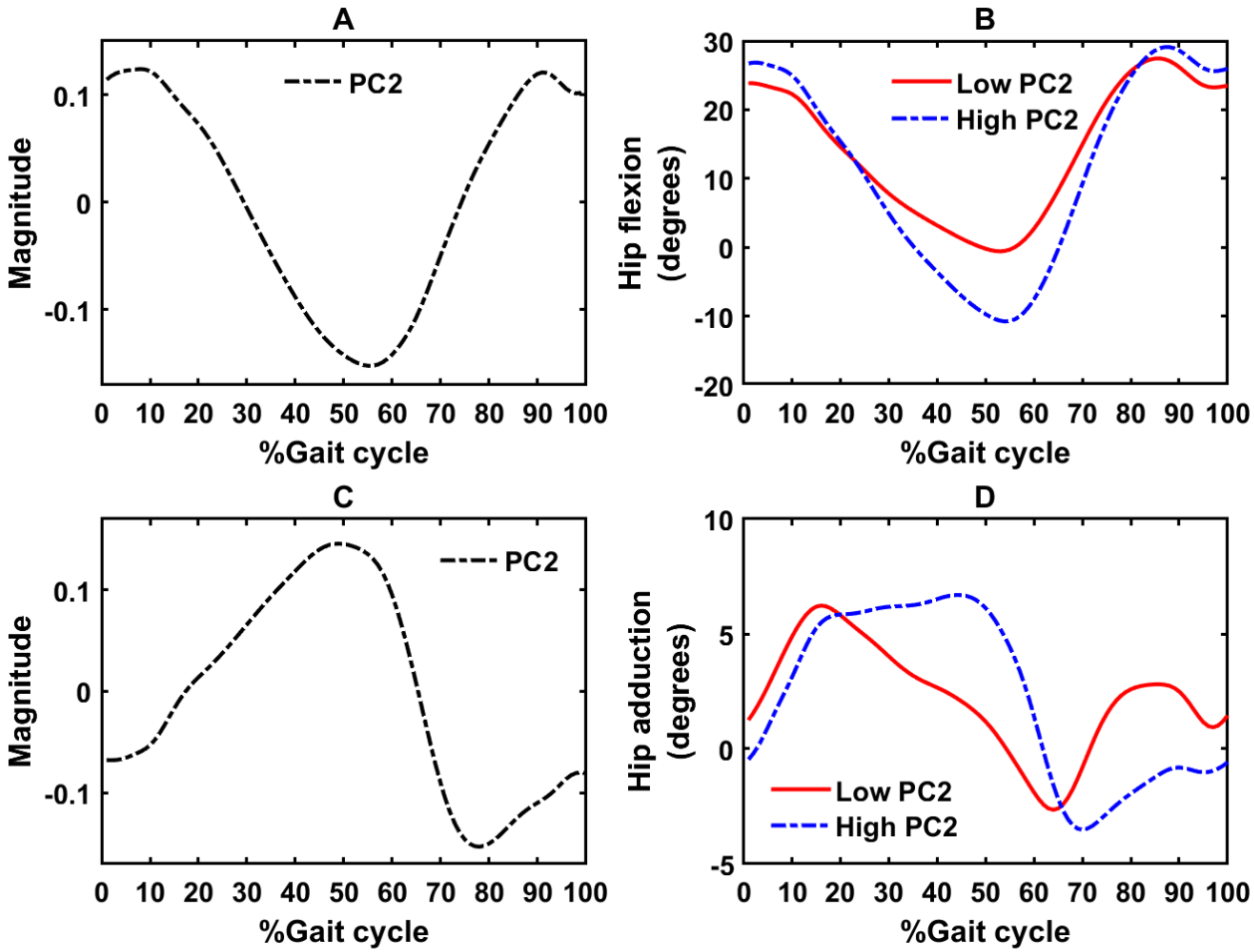

Figure 9: (A) Hip flexion angle principal component (PC) 2 (black dashed line) with (B) mean hip flexion angle (flexion = positive, extension = negative) waveforms for a subset of participants that scored high (blue dashed line) and low (red solid line) on PC2 (C) Hip adduction angle PC2 (black dashed line) with (D) mean hip adduction angle (adduction = positive, abduction = negative) waveforms for a subset of participants that scored high (blue dashed line) and low (red solid line) on PC2.

4.3.3. Hip medial rotation angle

Hip medial rotation angle differed significantly between THA groups for PC2 (Table 8). Hip medial rotation PC2 represents the differences in medial rotation at terminal stance/ preswing compared to lateral rotation at loading response/ terminal swing (Figure 10A, Table 7). Both lateral THA (mean difference = -13.5; 95% CI = -26.61 to -0.50; p = 0.04) and posterior THA groups (mean difference = -14.24; 95% CI = -27.30 to -1.19; p = 0.03) had significantly greater hip medial rotation PC2-scores compared to the healthy group, with medium (d = 0.79) and large (d = 0.86) effect sizes respectively. Thus, THA groups had greater medial rotation excursion angles between terminal stance/ preswing and loading response/ terminal swing (Figure 8C, Figure 10B). Significant group differences were also observed for hip medial rotation angle PC3 (Table 8). Medial rotation angle PC3 represents difference in medial rotation at mid/ terminal stance compared to lateral rotation during midswing (Figure 10C, Table 7). The posterior THA group had significantly lower PC3-scores compared to both healthy (mean difference = 18.1; 95% CI = 7.63 to 28.57; p < 0.001) and lateral THA groups (mean difference = 11.04; 95% CI = 0.31 to 21.76; p = 0.04) with large effect sizes (d = 1.31 and d = 0.81 respectively). This indicates that operated hip of participants in the posterior THA group was more laterally rotated during mid/ terminal stance with greater medial rotation during midswing (Figure 8C, Figure 10D).

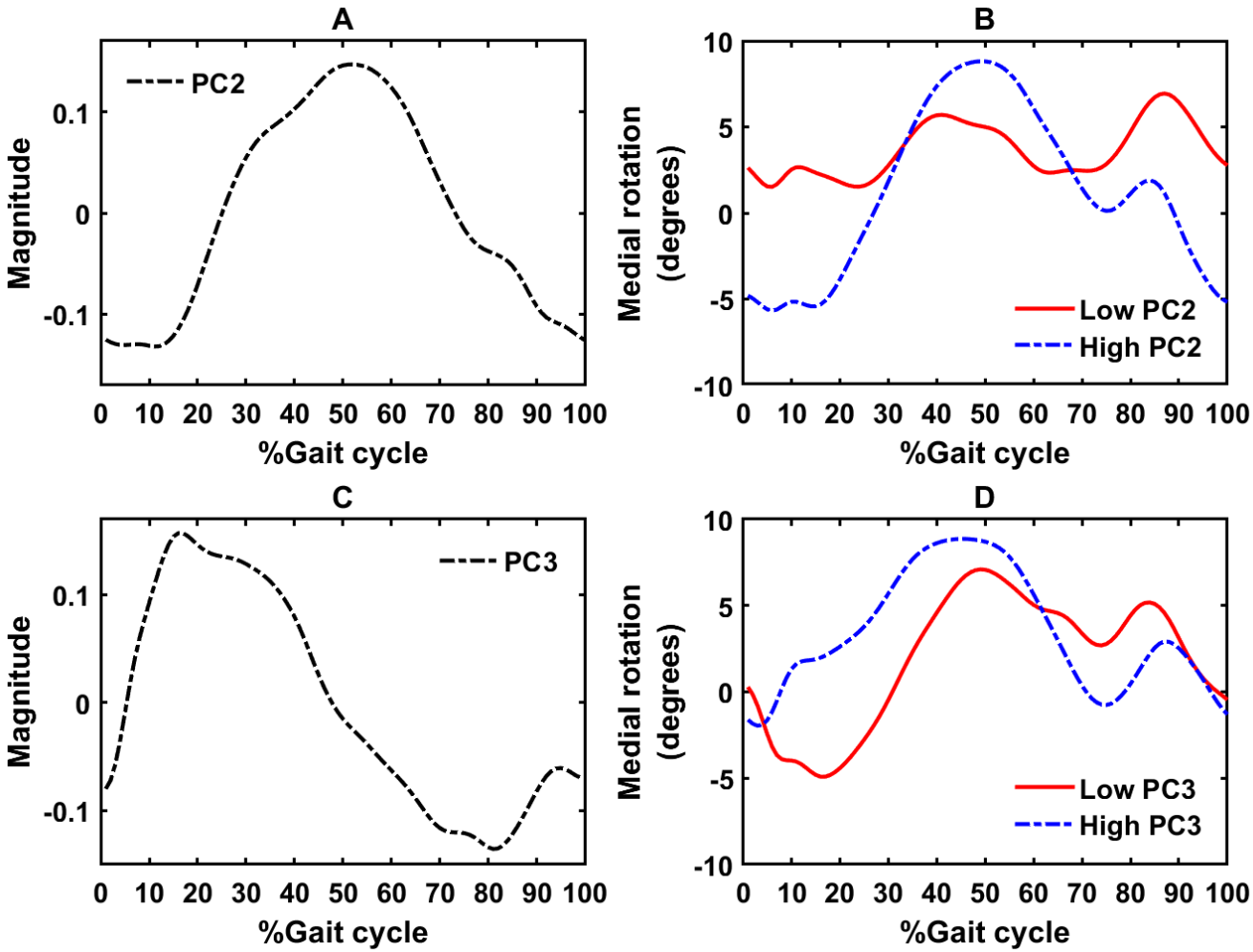

Figure 10: (A) Hip medial rotation angle principal component (PC) 2 (black dashed line) (B) mean hip medial rotation angle (medial rotation = positive, lateral rotation = negative) waveforms for a subset of participants that scored high (blue dashed line) and low (red solid line) on PC2 (C) Hip medial rotation angle PC3 (black dashed line) with (D) mean hip medial rotation angle waveforms for a subset of participants that scored high (blue dashed line) and low (red solid line) on PC3.

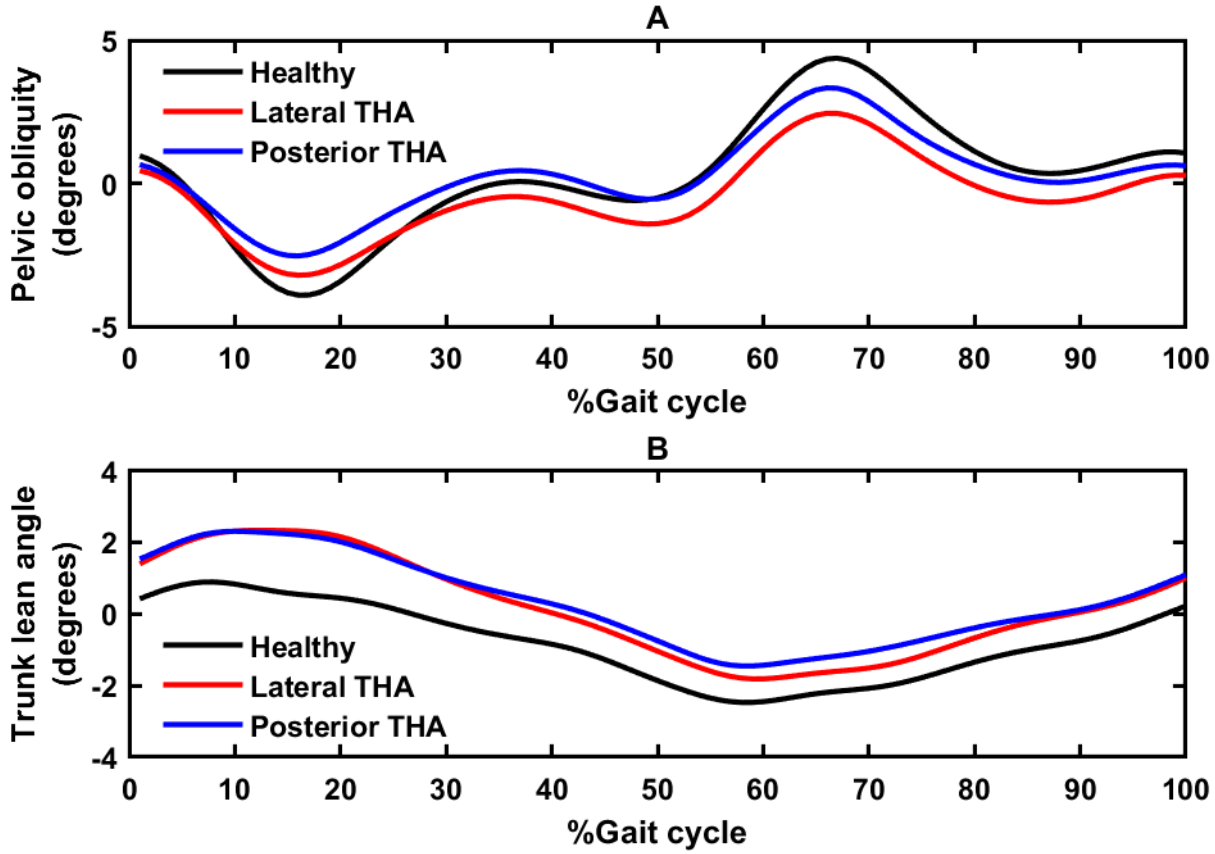

Figure 11: Group ensemble average (A) pelvic obliquity (ipsilateral pelvic drop = positive, contralateral pelvic drop = negative) and (B) trunk lean angles (ipsilateral trunk lean = positive, contralateral trunk lean = negative) during gait for lateral THA (red line), posterior THA (blue line) and healthy (black line) groups. Amplitude of joint angle, (degrees) is on the y-axis and percent of gait cycle on the x-axis (%Gait cycle).

4.3.4. Pelvic obliquity angle

Pelvic obliquity angle during gait differed significantly between groups for PC2 (Table 8). Pelvic obliquity PC2 represents the difference in pelvic drop at pre/ initial swing compared to loading response/ midstance (Figure 12A, Table 7). The lateral THA group demonstrated significantly lower PC2 scores compared to the healthy group (mean difference = 6.09; 95% CI = 0.40 to 11.79; $p = 0.03$) with medium effect size ($d = 0.77$), indicating they had decreased excursion (i.e. less ROM) in the pelvic obliquity angles during these times (Figure 11A, Figure 12B). There were no remaining significant between group differences in pelvic obliquity angles (Table 8).

4.3.5. Trunk lean angle

Trunk lean angle PCs during gait did not differ significantly between groups suggesting occurrence of similar trunk lean angles across study groups (Figure 11B, Table 8).

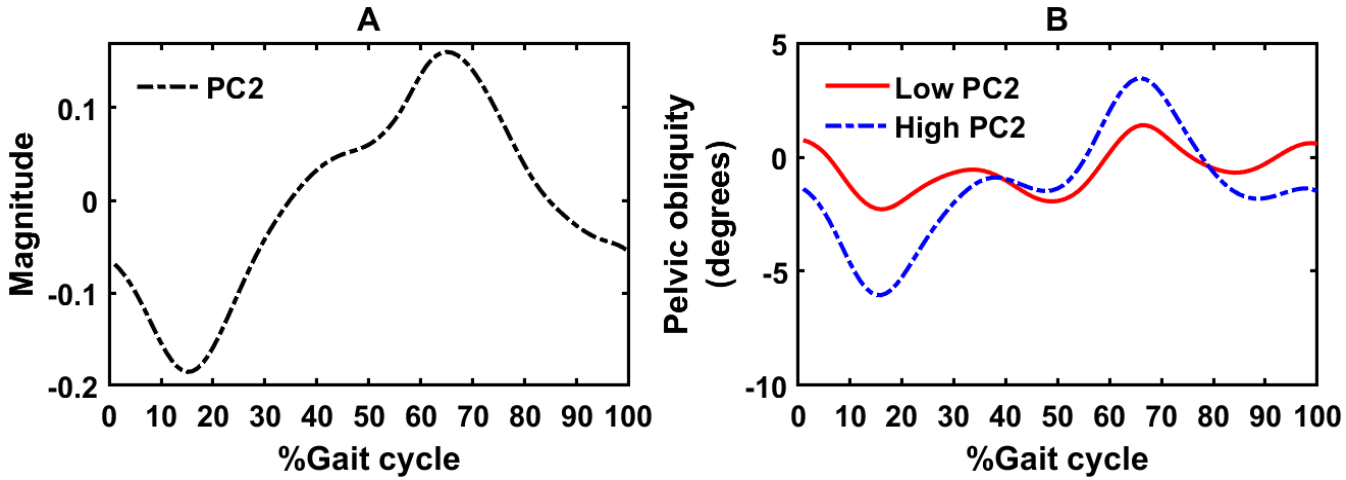

Figure 12: (A) Pelvic obliquity angle principal component 2 (PC2) (black dashed line) with (B) mean pelvic obliquity angle (ipsilateral pelvic drop = positive, contralateral pelvic drop = negative) waveforms for a subset of participants that scored high (blue dashed line) and low (red solid line) on PC2.

4.4. HIP MOMENTS

Group ensemble average of the external hip joint moments is presented in Figure 13. Description of gait moment PCs and group statistics are presented in Table 9 and 10 respectively. Pairwise comparison of study groups for gait moment PCs are presented in Appendix 10. The first three PCs collectively explained approximately 90% of the variance in the hip joint moment waveforms during gait.

Table 9: Percentage of explained variance and description of the principal components (PCs) for hip moments.

Hip moments	PC	Description	Variance explained %
Hip extension moment	**1**	General shape and overall amplitude (higher scores = greater hip extension moment)	57.83
	2	Difference in extension moment at initial contact/ midstance compared to terminal stance/ preswing (higher scores = greater difference)	22.28
	3	Difference in extension moment at initial swing compared to terminal swing (higher scores= greater difference)	5.34
Hip abduction moment	**1**	General shape and overall amplitude (higher score = smaller abduction moment)	54.26
	2	Difference in abduction moment at initial contact/ midstance compared to at preswing (higher score = greater differences)	18.18
	3	Difference in abduction moment at midstance versus at terminal stance (lower score = greater difference)	10.36
Hip lateral rotation moment	**1**	General shape and overall amplitude during stance (higher score = greater lateral rotation moments)	61.32
	2	Difference in lateral rotation moment at initial contact/ midstance versus medial rotation moments at terminal stance/ preswing (higher score = greater differences)	20.45
	3	Timing of lateral rotation moment during stance (higher score = delayed lateral rotation moment)	6.13

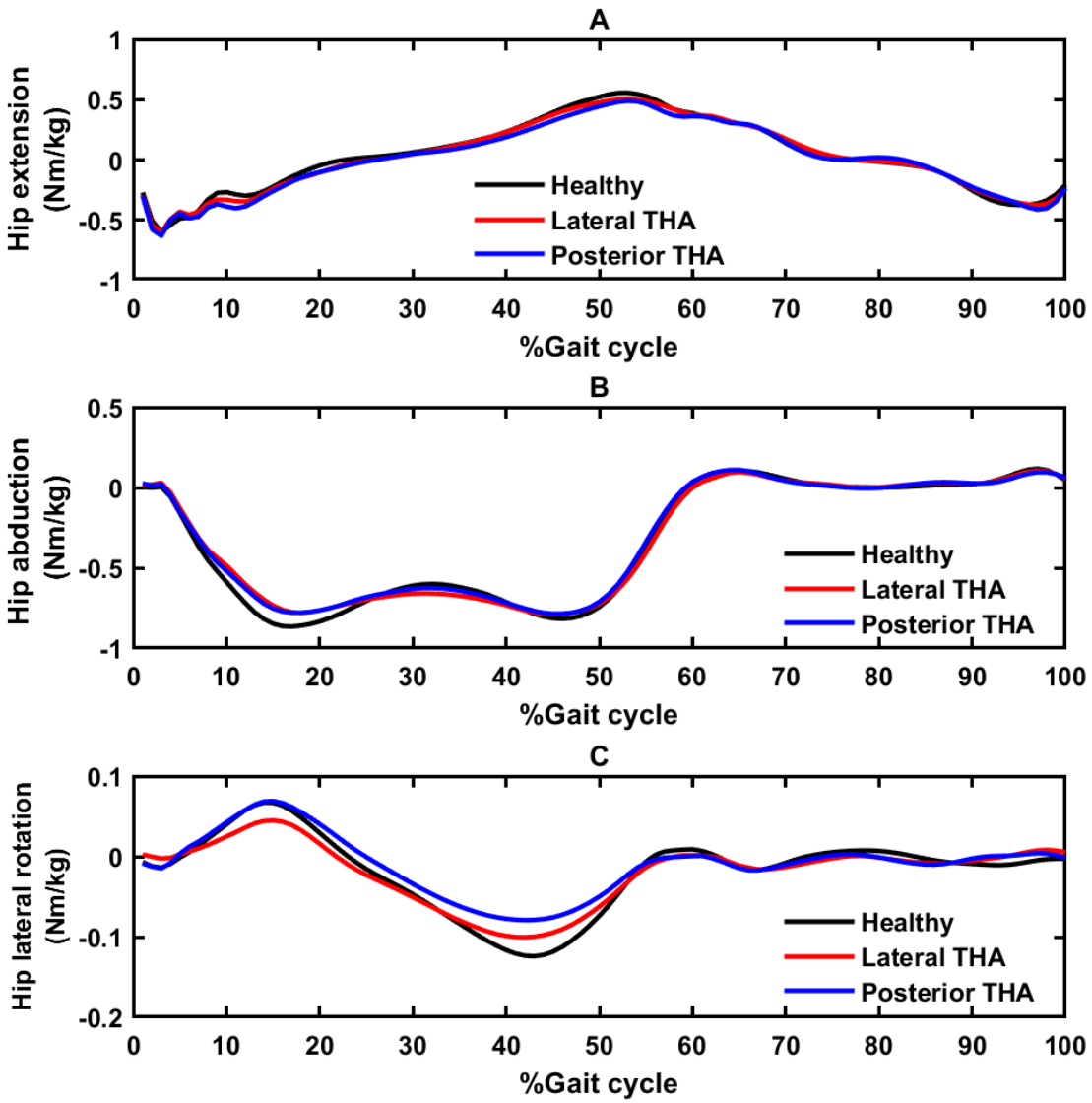

Figure 13: Group ensemble average of external hip joint moments (A) extension moments (extension = positive, flexion = negative) (B) abduction moments (abduction = positive, adduction = negative) and (C) lateral rotation moments (lateral rotation = positive, medial rotation = negative) during gait for lateral THA (red line), posterior THA (blue line) and healthy (black line) groups.

.

Table 10: Mean (standard deviation) values for joint moment principal components (PCs).

Hip moments	PCs	Healthy (n = 21)	Lateral THA (n = 19)	Posterior THA (n = 19)	Group effect p value*
Hip extension moment	**1**	0.19 (0.9)	-0.01 (1.00)	-0.20 (1.37)	0.55
	2	-0.03 (0.51)	-0.01 (0.61)	0.04 (0.91)	0.95
	3	0.00 (0.35)	0.01 (0.36)	-0.01 (0.30)	0.98
Hip abduction moment	**1**	-0.10 (0.97)	0.01 (0.66)	0.10 (0.94)	0.76
	2	0.19 (0.44)	-0.18 (0.51)	-0.03 (0.50)	0.06
	3	0.01 (0.46)	-0.06 (0.29)	0.04 (0.35)	0.72
Hip lateral rotation moment	**1**	-0.06 (0.29)	-0.03 (0.27)	0.09 (0.19)	0.16
	2	0.04 (0.12)	-0.05 (0.14)	0.01 (0.17)	0.19
	3	-0.01 (0.09)	0.01 (0.07)	0.01 (0.08)	0.68

n = number of participants in group, *p value for one-way analysis of variance, THA = total hip arthroplasty.

No significant differences were identified in PCs of hip extension, abduction and lateral rotation external moment waveforms (Table 10). However, hip abduction external moment waveform was nearing significance for between group differences in PC2 (Table 10). PC2 of hip abduction represents difference in abduction moment at initial contact/ midstance compared to at preswing (Table 9). Lateral THA group had lower PC2-scores compared to the healthy group (mean difference = 0.36; CI = - 0.01 to 0.74; p = 0.06; d = 0.77). This indicates that lateral THA group had a lower difference between external hip adduction moment at initial contact/ midstance compared to at preswing.

4.5. MAXIMUM ISOMETRIC TORQUE

Descriptive statistics and pairwise comparisons of maximum isometric torques during the MVIC exercises are presented in Table 11 and Appendix 11 respectively.

Table 11: Mean (standard deviation) values for maximum isometric torque.

MVIC exercise	Healthy (n=20)	Lateral THA (n=19)	Posterior THA (n=19)	Group effect p value*
Hip abduction ‡	1.25 (0.36)	1.01 (0.32)	1.15 (0.21)	0.06
Hip extension‡	1.26 (0.38)	1.18 (0.31)	1.10 (0.24)	0.26
Knee extension‡	0.99 (0.27)	1.13 (0.28)	1.19 (0.23)	0.05
Knee flexion‡	0.71 (0.21)	0.61 (0.23)	0.76 (0.17)	0.09
Hip flexion‡	1.16 (0.26)	1.08 (0.21)	1.19 (0.25)	0.34

n = number of participants in group, *p value for one-way analysis of variance, THA = total hip arthroplasty, ‡ = Missing data: One healthy participant for all MVIC exercises, one lateral THA participant for hip abduction.

There were significant group effects in knee extension torque (Table 11). Group effects in maximum isometric hip abduction torque was approaching significance (p=0.06) with pairwise comparisons revealing that the healthy group had significantly higher torque values compared to the lateral THA group (mean difference = 0.24 Nm/kg; 95% CI = 0.00 to 0.48 Nm/kg; d = -0.70; p = 0.05). For knee extension torque, pairwise comparisons revealed the healthy group produced lower maximum isometric knee extension torque compared to the posterior THA group (mean difference = -0.20 Nm/kg; 95% CI = -0.41 to 0.00 Nm/kg; d = -0.80; p = 0.06). There were no remaining significant differences in maximum isometric muscle torque between groups.

4.6. SPATIO-TEMPORAL VARIABLES

Descriptive statistics of spatio-temporal variables of gait, including gait speed, step length, stride length and stance percent are presented in Table 12.

Table 12: Mean (standard deviation) values for spatio-temporal variables of gait.

Variable	Healthy (n=21)	Lateral THA (n=19)	Posterior THA (n=19)	Group effect p value*
Gait speed (m/s)	1.26 (0.15)	1.19 (0.18)	1.22 (0.19)	0.43
Step length (m/m)	0.39 (0.04)	0.37 (0.04)	0.36 (0.03)	0.13
Stride length (m/m)	0.77 (0.08)	0.74 (0.07)	0.73 (0.06)	0.20
Mean percent stance time (%gait cycle)	61.04 (1.57)	61.4 (2.49)	60.96 (1.42)	0.75

n = number of participants in group, *p value for one-way analysis of variance, THA = total hip arthroplasty.

No significant difference in spatio-temporal variables was observed across study groups (Table 12). However, one participant in the healthy groups had very short step and stride lengths, deviating approximately three standard deviations from the mean. Deletion of this participant from the analysis revealed significant group effects for step length ($p = 0.02$ versus $p = 0.13$) and stride length ($p = 0.03$ versus $p = 0.2$). The healthy group had significantly greater step ($p = 0.02$, $d = 1.00$) and stride length ($p= 0.04$, $d = 0.91$) compared to the posterior THA group.

4.7. CLINICAL MEASURES

Descriptive statistics of the HOOS and performance-based measures are presented in Tables 13 and 14 respectively. Pairwise comparisons of HOOS subscales are presented in Appendix 12.

Table 13: Median (minimum, maximum) scores on Hip Disability Osteoarthritis Outcome (HOOS) questionnaire.

HOOS Subscale	Healthy (n = 21)	Lateral THA (n = 19)	Posterior THA (n = 19)	Group effect p value*
HOOS-pain	100 (85,100)	96 (78,100)	98 (75,100)	0.03
HOOS-symptom	100 (75,100)	90 (65,100)	95 (70,100)	0.23
HOOS-activities of daily living	100 (87,100)	97 (79,100)	97 (82,100)	0.02
HOOS-sport/recreation	100 (63,100)	94 (69,100)	94 (63,100)	0.01
HOOS-quality of life	100 (75,100)	88 (44,100)	94 (50,100)	0.00

n = number of participants in group, *p value for the Kruskal-Wallis H test, THA = total hip arthroplasty.

Table 14: Mean (standard deviation) values for performance-based measure scores.

Performance-based measures	Healthy (n = 21)	Lateral THA (n = 19)	Posterior THA (n = 19)	Group effect p value*
Six-Minute Walk Test (m)	542.32 (90.71)	512.61 (66.18)	562.59 (59.25)	0.12
30 second Chair Stand Test (count)	16 (5)	15 (4)	17 (3)	0.31
11-Step stair ascend/descend test (s)	8.94 (3.64)	10.33 (2.93)	8.24 (2.13)	0.10

n = number of participants in group, *p value for one-way analysis of variance, THA = total hip arthroplasty.

4.7.1. HOOS

Except for HOOS-symptom, significant group effects were observed for HOOS subscales (Table 13). Pairwise comparisons identified both lateral and posterior THA groups had significantly lower scores for sport function ($p = 0.04$ and $p = 0.01$ respectively) and quality of life ($p = < 0.01$ and $p = 0.03$ respectively) subscales compared to the healthy group. For HOOS-pain and activities of daily living, pairwise comparison reported significantly lower scores in the lateral THA group compared to healthy group ($p = 0.03$ and $p = 0.02$ respectively).

4.7.2. Performance-based tests

There were no significant group effects on 6MWT, 30-CST, 11-step SCT (Table 14) indicating that that physical performance was similar across lateral THA, posterior THA and healthy groups.

CHAPTER 5: DISCUSSION

The current study examined, for the first time, the influence of lateral and posterior THA surgical approaches on lower extremity muscle activation patterns at one year following surgery. Given that the gluteus medius is mainly disrupted during the lateral THA approach and the gluteus maximus during the posterior THA approach, the main objective of the present study was to determine whether THA groups differed in gluteus medius and gluteus maximus muscle function, pelvic obliquity and compensatory lateral trunk lean angle during gait. Disproving our hypothesis, no differences in gluteus medius and gluteus maximus muscle function during gait were present between THA groups. Only a few differences were identified between THA groups including significantly higher activation of hamstrings and greater hip medial rotation angle excursions in the posterior THA group.

5.1. GAIT MUSCLE ACTIVATION

Although there were no differences in gluteus medius gait EMG waveforms between THA groups, the lateral THA group had higher gluteus medius muscle activation amplitudes at mid/ terminal stance phases of gait (PC3) compared to the healthy group. This finding is consistent with previous investigations, demonstrating prolonged and higher activation of gluteus medius following lateral THA approach up to six months following surgery (Horstmann et al., 2013; Pospischill et al., 2010). A potential reason for this increased or prolonged activation of the gluteus medius muscle in the lateral THA group could be due to pre-existing OA related weakness, detachment of the gluteus medius from the greater trochanter during surgery, or a combination of these factors (Petis et al., 2015). However, in contrast to our hypothesis, gluteus medius muscle activation waveforms did not differ between THA groups. This may suggest that at one year post-

THA, preoperative impairments in the muscle contributed to abnormalities seen in its activation pattern at this time.

Conversely, the posterior THA group exhibited increased gluteus maximus muscle activation amplitudes during the loading response phase of gait (PC2) compared to the healthy group. Supporting our results, a previous study has reported patients with posterior THA demonstrated increased activation of the gluteus maximus during gait at six to 18 months following surgery (Perron et al., 2000). Although gluteus maximus muscle activation gait patterns did not differ significantly between THA groups, the reported medium effect size ($d = 0.69$) could suggest that these differences could be clinically relevant. Impairments in gluteus maximus muscle function at this time could be due to preoperative OA related weakness in the gluteus maximus made more prominent by disruption of the muscle during THA.

Findings of this study also revealed, the posterior THA group had increased hamstring muscle activation, especially lateral hamstrings, during mid/ terminal stance (PC2) of gait compared to healthy and lateral THA groups. These results support a previous study that reported prolonged activation of the lateral hamstrings (biceps femoris) during gait in patients following posterior THA compared to healthy adults (Agostini et al., 2014). Abnormalities in hamstring muscle activation during gait could be a mechanism to compensate for weakness in the gluteus maximus due to disruption from the posterior THA approach or due to long-standing OA (Jonkers, Stewart, & Spaepen, 2003). Therefore, the reported increased recruitment of the hamstrings during gait in the posterior THA compared to the lateral THA group could suggest greater weakness persisting in the gluteus maximus at one year following posterior THA approach.

5.2. GAIT ANGLES

Multiple differences in joint angle waveforms during gait have been identified between THA and healthy groups in this study. Both lateral and posterior THA groups in the present study demonstrated large effect sizes for the reduction in hip flexion angle excursions (PC2) compared to the healthy group. Decreased hip flexion angle excursion has been previously reported up to 15 months following both lateral and posterior THA approaches compared to healthy adults (Beaulieu, Lamontagne, & Beaule, 2010; Queen et al., 2014). Decreased hip flexion angle excursions could be due to adaptive tightness in anterior hip joint structures due to hip OA or an adaptation developed following THA surgery. This would limit the ability of the hip to extend, resulting in long-term decreased hip flexion ROM (Colgan, Walsh, Bennett, Rice, & O'Brien, 2016; Holnapy, Illyes, & Kiss, 2013). However, we did not identify significant differences in hip flexion angle excursion between lateral and posterior THA groups, failing to confirm findings of a study that reported lower hip flexion ROM during gait following lateral THA approach compared to posterior THA approach (Whatling et al., 2008). Conflicting results could be due to the difference in the method to summarize hip angle waveforms. The present study analyzed changes in hip flexion angle excursions throughout gait, whereas the previous study computed average hip flexion angle during gait which could have been influenced by peak angles. Thus, hip flexion angle at one year post-THA was not influenced by the surgical approach with both groups having a similar reduction in hip flexion angle ROM during gait.

The posterior THA group in this study also demonstrated reduced hip adduction angle excursion during gait compared to the healthy group. Existing literature reports reduced hip adduction angle excursion during gait following both lateral and posterior THA approaches compared to healthy adults (Beaulieu et al., 2010; Bennett et al., 2008; Rutherford, Moreside, &

Wong, 2015). This reduction in hip adduction angles in the posterior THA group could be indicative of an adaptation to reduce the demand on hip muscles. Additionally, tightness in hip joint capsule could also explain this reduction in hip adduction angle excursion during gait. Despite differences between the lateral THA and healthy groups not being statistically significant, the identified medium effect size (d = 0.73) could suggest the presence of clinically relevant, reduced hip adduction angle excursion in the lateral THA group as well. Finally, at one year post-THA, there were no differences in hip adduction angles during gait between lateral and posterior THA groups, indicating that the surgical approach did not influence hip adduction angles.

The present study identified greater hip lateral rotation angles during loading response and medial rotation angles during terminal stance/ preswing (PC2) in THA groups compared to healthy groups, which was a large effect. Posterior THA group also had increased lateral rotation at midstance and medial rotation angle at midswing (PC3) compared to the lateral THA and healthy groups. This is different from a previous study by Petis et al. which reported similar hip angles in both lateral and posterior THA groups at 12 weeks post-THA and could be credited to the difference in follow-up period or methods used to analyze gait waveforms (e.g. PCA) (Beaulieu et al., 2010; Rathod, Orishimo, Kremenic, Deshmukh, & Rodriguez, 2014; Varin, Lamontagne, & Beaule, 2013). The increased medial and lateral rotation angles during gait seen in the posterior THA group in this study could be because of the altered muscle activation patterns, including the deep rotators that were not measured in this study, affecting control of hip rotation during gait.

Contrary to our hypothesis, the current study reported decreased pelvic obliquity excursion (PC2) during gait in the lateral THA group compared to the healthy group. These results fail to +support conclusions of previous studies that disruption of the gluteus medius during lateral THA

approach caused increased pelvic obliquity angles, indicated by Trendelenburg gait patterns. However, one study did report lower pelvic obliquity ROM following lateral THA approach compared to posterior THA approach (Whatling et al., 2008). A possible rationale for this finding could be reduced elasticity of lateral hip tissues and increased gluteus medius activation in the lateral THA group masking possible weakness persisting in the gluteus medius at one year after surgery. There was no evidence of pelvis drop (more negative pelvic obliquity angles during stance) indicating that gluteus medius was able to control the pelvis position during gait in both THA groups. Finally, lateral trunk lean angle during gait did not differ between groups in the present study, contradicting previous evidence suggesting increased ipsilateral trunk lean in patients after THA compared to healthy adults (Perron et al., 2000; Vogt, Brettmann, Pfeifer, & Banzer, 2003). Contradictory evidence could be due to the time of follow-up. We can therefore conclude that despite possible weakness persisting in the gluteus medius muscle in the lateral THA group, the increased activation of the gluteal muscle was sufficient to stabilize the pelvis during gait without the use of compensatory mechanisms like lateral trunk lean.

5.3. GAIT MOMENTS

This study did not identify differences in external hip moments between study groups. These results agree with those of a study by Petis et al., which reported similar hip moments between patients in lateral and posterior THA groups at six and 12 weeks post-THA (Petis et al., 2017). Although some previous studies found patients with THA demonstrated significantly different moments on the operated leg compared to healthy adults (external adduction and medial rotation moments, $p < 0.003$) and unoperated leg (decreased external adduction moment, $p < 0.05$), these results could be influenced by the difference in the follow-up period (Foucher et al., 2007; Queen

et al., 2014). Also, this study identified hip adductor moment was nearing significant levels ($p = 0.06$), with moderately ($d = 0.77$) reduced external hip adduction moment during gait in lateral THA group compared to the healthy group. These results in the presence of reduced isometric hip abduction torque and reduced pelvic obliquity excursion during gait could suggest the presence of adaptative mechanisms that reduce the load on the hip abductors.

5.4. ISOMETRIC HIP TORQUES

The lateral THA group demonstrated borderline significant ($p = 0.06$) reduction in isometric hip abduction torque compared to the healthy group with a large effect size ($d = 0.80$). These results suggest that some weakness in the abductor muscle group is present at one year following lateral THA approach, although results were not significant. Regardless, following lateral THA approach, participants were able to effectively stabilize the pelvis during gait without adopting compensatory patterns like ipsilateral lateral trunk lean. Additionally, results of this study reinforce inferences made previously in this discussion that abductor muscle function did not differ between THA groups at one year following THA. Opposing our hypothesis, there were no differences between THA groups. Previous studies have demonstrated greater hip abductor muscle weakness following the lateral THA approach compared to the posterior THA approach, attributed to the disruption of the gluteus medius during this approach (Rasch, Dalen, & Berg, 2010; Rosenlund et al., 2016; Winther et al., 2016). Conflicting results of this study could be due to differences in time of follow-up and method of assessment of participants. Although isometric hip extension torque did not differ between study groups, care needs to be taken when interpreting these findings as high activation in the hamstrings muscle during the prone hip extension MVIC exercise could mask weakness in the gluteus maximus (Kwon & Lee, 2013; Sakamoto, Teixeira-

Salmela, Rodrigues, Guimarães, & Faria, 2009). Finally, posterior THA group had significantly higher isometric knee extension torque compared to the healthy group, indicating return of strength in this muscle group at one year follow-up. However, these results were different from those of previous studies that identified significantly lower knee extensor strength on the involved side, in patients with THA compared to healthy adults ($p < 0.05$) or unoperated leg ($p < 0.001$) (Fukumoto et al., 2013; Winther et al., 2016). Fukumoto et al. reported significantly lower maximal isometric knee extensor strength assessed using hand-held dynamometer on the involved THA compared to healthy adults ($p < 0.05$) at six months after THA. Winther et al. also identified 18% less muscular strength in knee extensors, during one repetition maximum leg press, at three months post-THA, with no differences between lateral and posterior THA surgical approach groups. Thus disagreements in findings could be credited to the longer follow-up time in the current study and different testing methods used.

5.5. SPATIO-TEMPORAL PARAMETERS

No differences in spatio-temporal gait parameters including percent stance time, step length, stride length, and gait speed were reported between lateral THA, posterior THA, and healthy groups. This is consistent with previous studies that concluded similar spatio-temporal parameters between THA approaches at one year; however, it conflicts with studies that reported reduced step and stride length after THA compared to healthy adults or unoperated leg (Bahl et al., 2018; Queen et al., 2014). Contrasting results were driven by an outlier in our healthy group, removal of which revealed a significantly shorter step and stride length in the posterior THA group compared to healthy adults. Reduced step and stride lengths may be due to the reduced hip flexion ROM and adduction angles during gait seen among the participants in the posterior THA group.

5.6. CLINICAL OUTCOMES

In regard to self-report outcomes, lateral THA group had increased pain and decreased activities of daily living than the healthy group as measured by the HOOS. Additionally, both THA groups had reduced sports participation and quality of life than the healthy group. There were no significant differences in the HOOS between THA groups in the present study. This was consistent with previous studies that found no difference in pain or risk of experiencing pain at up to 12 months after lateral or posterior THA (Rosenlund et al., 2017; Witzleb et al., 2009). However, one study found significantly lower HOOS-pain scores, among patients with lateral compared to posterolateral THA approaches with small between group differences (up to three years after THA) (Amlie et al., 2014). Conflicting results could be due to differences in self-report measurement tools, time from THA, sample sizes, and sample characteristics. In regard to performance-based measures (6MWT, 30CS, 11-stepSCT), there were no differences between groups, which is supported by a previous study (Queen et al., 2014). Thus, results from self-report (HOOS) and performance-based tests (6MWT, 30-CST, 11-step SCT) of physical function used in this study conflict. The discrepancy in scores on these measures could be attributed to participant's perception of pain, psychological status, age, and perhaps muscle strength following THA (Blom et al., 2016). It is therefore important to include both these measures while assessing patient function following THA.

5.7. LIMITATIONS

The main limitation of this study is that preoperative data for the participants were not available. This is important since preoperative function is strongly associated with long-term functional outcome following THA (Hofstede, Gademan, Vlieland, Nelissen, & Marang-van de

Mheen, 2016). Second, surgeons were not randomized to surgical approach. Hence surgeon skill/ expertise, training or preferences could have influenced the outcome of surgery and choice of THA approach used (Ohmori et al., 2017). Third, although participants were not randomized to surgical approach, there were no set criteria adopted to decide which surgical approach would benefit the participant more. Hence this could not have impacted the postoperative muscle or joint function recovery. Fourth, study groups were inconsistent with regard to the distribution of men and women. This could influence results as sex specific differences in hip angles and gluteus medius and maximums muscle activation during gait have been previously reported (Hart, Garrison, Kerrigan, Palmieri-Smith, & Ingersoll, 2007; Ko, Tolea, Hausdorff, & Ferrucci, 2011). Fifth, the femoral offset and prosthesis placement can influence abductor muscle function, as well as gait mechanics which we were unable to account for in this study (Asayama, Chamnongkich, Simpson, Kinsey, & Mahoney, 2005; Asayama, Kinsey, & Mahoney, 2006; Sariali, Klouche, Mouttet, & Pascal-Moussellard, 2014). Sixth, soft tissue artifact caused by skin-maker movement over underlying bone produces errors in the estimation of the skeletal segment, especially that of the thigh and thus could impact joint angle and moment measures (Barré, Jolles, Theumann, & Aminian, 2015). Seventh, it is difficult to completely isolate muscle contraction during MVIC exercises and hence estimation of isometric torques may be affected by contributions from secondary muscles (e.g. hamstrings for hip extension) (Kwon & Lee, 2013; Sakamoto et al., 2009). Eighth, we were unable to collect data on our complete sample due to time constraints.

CHAPTER 6: CONCLUSION

6.1. CONCLUSION AND SUMMARY

This study contributes to understanding the influence of THA surgical approach on the recovery of gait function including muscle and joint function, and clinical outcomes at one year following THA surgery. Overall, we can conclude that participants with THA continued to demonstrate impairments in gait function at one year post-THA surgery. However, between posterior and lateral THA groups, there were only a few differences in gait function with no differences in maximum isometric torques and clinical outcomes at one year post-THA.

It was hypothesized that greater pelvic drop would be present in the lateral THA group due to disruption of gluteus medius during surgery. The opposite in fact did occur with decreased pelvic obliquity angles. Although gluteus medius had a higher activation level during gait and borderline isometric abduction weakness, this muscle was able to effectively control pelvis position during walking in the lateral THA group as evidenced by the lack of pelvis drop.

Posterior THA group had significantly higher gluteus maximus, hamstring activation EMG, decreased hip adduction and increased hip medial rotation angle excursions during gait compared to the healthy group. These finding could suggest a delayed recovery in the gluteus maximus muscle function at one year post-THA, impairing its ability to effectively control hip rotation and producing a compensatory increased activation in the hamstring muscle during gait. However, preoperative weakness from OA cannot be discounted.

Since there were only a few differences between THA groups, most deficits were likely due to preoperative long-standing OA, rather than the THA surgery. Alterations seen in the gluteus medius and gluteus maximus muscle function during gait were to accommodate residual weakness

persisting due to long-standing hip OA one year following THA. It is therefore important for rehabilitation professionals to include a variety of functional exercises at different stages in the rehabilitation process in addition to those that emphasize improving strength of hip abductors, extensors, and joint ROM. Emphasis should also be given to effectively re-train gait immediately after THA to prevent the development of persistent or adaptative gait patterns including diminished joint angle excursions and increased muscle activation. Additionally, the post-THA physical function may be influenced by preoperative functional status and severity of OA. Hence it could be beneficial to include a preoperative assessment and exercise regime.

6.2. FUTURE DIRECTION

To better understand the impact of long-standing OA on gait, future research should compare muscle function during gait at multiple time points, assessing patients preoperatively, at six months and one year post-THA. Additionally, studies should account for the severity of OA and THA surgical approach adopted. Also, the activity of hamstrings during MVICs could mask impairment in gluteus maximus muscle function following posterior THA. Thus, future THA research could incorporate both eccentric and isometric muscle contraction exercises in multiple positions to try to isolate the contribution of the gluteus maximus muscle and hamstring torque generation. Further investigations incorporating different functional activities (e.g. stair climbing) to assess pelvic obliquity ROM following THA could help better understand mechanisms adopted by these patients to control the pelvis during single leg stance. Finally, PCA analysis used in this study has proved to be a novel method to identify deviations in gait patterns missed in previous studies and should be used more frequently to compare gait or other functional tasks following THA.

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Appendix 1: Ethics approval certificate.

Centre intégré universitaire de santé et de services sociaux du Centre-Ouest-de-l'Île-de-Montréal
Québec
Hôpital général juif

CENTRE GÉRIATRIQUE DONALD BERMAN MAIMONIDES GERIATRIC CENTRE
CENTRE D'HÉBERGEMENT FATHER-DOWD RESIDENTIAL CENTRE
CENTRE D'HÉBERGEMENT HENRI-BRADET RESIDENTIAL CENTRE
CENTRE D'HÉBERGEMENT ST-ANDREW RESIDENTIAL CENTRE
CENTRE D'HÉBERGEMENT ST-MARGARET RESIDENTIAL CENTRE
CENTRE MIRIAM HOME AND SERVICES
CENTRE DE RÉADAPTATION CONSTANCE-LETHBRIDGE REHABILITATION CENTRE
CENTRE DE RÉADAPTATION MAB-MACKAY REHABILITATION CENTRE
CHSLD JUIF DE MONTRÉAL JEWISH ELDERCARE CENTRE
CLSC DE BENNY FARM
CLSC DE CÔTE-DES-NEIGES
CLSC MÉTRO
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CLSC RENÉ-CASSIN
HÔPITAL CATHERINE BOOTH HOSPITAL
HÔPITAL GÉNÉRAL JUIF JEWISH GENERAL HOSPITAL
HÔPITAL MOUNT SINAI HOSPITAL
HÔPITAL RICHARDSON HOSPITAL

Integrated Health and Social Services University Network for West-Central Montreal

BUREAU DE L'EXAMEN DE RECHERCHE
RESEARCH REVIEW OFFICE

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July 11, 2016

Dr. Shawn Robbins
Orthopaedics
Constance Lethbridge Rehabilitation Centre

SUBJECT: **Protocol #MM- CODIM-MBM-16-075 entitled** "Does total hip arthroplasty surgical approach affect muscle activation and joint mechanics during gait"

Dear Dr. Robbins,

Thank you for submitting the following documents pertaining to the above-mentioned protocol to Research Review Office for review:

- Protocol
- Science Approval from the JGH Science Committee (July 4, 2016)
  - Appendix A: Consent Form
    - French Main Consent Form (Version Date: 6 juillet 2016)
    - English Main Consent Form (Version: July 6, 2016)
  - Appendix B: Screening Form
  - Appendix C: Advertisement for Healthy Group
    - English and French Poster
  - Appendix D: Demographic Form
  - Appendix E: Chart Review – Surgical Information
  - Appendix F: Hip Disability and Osteoarthritis Outcome Score
    - English HOOS Hip Survey (Version LK 2.0)
    - French Questionnaire de Hanche HOOS (Version LK 1.0)
  - Appendix G: Physical Function Performance Measures
  - Appendix H: Personal Information

The Research Ethics Committees of the West-Central Montreal Health (Federalwide Assurance Number: 0796) are designated by the province (MSSS) and follows the published guidelines of the TCPS 2 - Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (2010), in compliance with the "Plan d'action ministériel en éthique de la recherche et en intégrité scientifique" (MSSS, 1998), the membership requirements for Research Ethics Boards defined in Part C Division 5 of the Food and Drugs Regulations; acts in conformity with standards set forth in the United States Code of Federal Regulations governing human subjects research, and functions in a manner consistent with internationally accepted principles of good clinical practice.

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Québec

Hôpital général juif

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As this study involves no more than minimal risk in accordance with TCPS 2 article 6.12, this protocol received a delegated research ethics review. We are pleased to inform you that the above-mentioned documents are granted Delegated Approval for the period of one year. For quality assurance purposes, you must use the "Research Ethics Approval" stamped consent form when obtaining consent by making copies of the enclosed one.

Please be advised the English and French Poster (stamped 11 JUIL.2016) are granted approval. For quality assurance purposes, you must use the "Research Ethics Approval" stamped posters by making copies of the enclosed ones. In addition, in order to post your advertisement in our institution, you must contact the Public Relations Department (Room A-811) for stamping. They may be reached at 514-340-8222 extension 5818.

For your information, the above-mentioned protocol will be presented for corroborative approval at the next meeting of the MBM Research Ethics Committee to be held on **August 26, 2016**.

Delegated Approval Date:	**July 11, 2016**
Expiration date of Delegated Approval:	**July 10, 2017**

In addition to the Constance Lethbridge Rehabilitation Centre, it is expected that the ethical approval of this project granted by our Committee will be applied to the following establishments:

- Jewish General Hospital

Your "Continuing Review Application", available on our website at www.jgh.ca/rec, must be received by the Research Review Office one month prior to the expiration date mentioned above in order to ensure timely review. Please remind the researcher(s) conducting this research at another establishment where this research is taking place that they must also submit a "Continuing Review Application" for their site by the same deadline. Failure by any site to do so will require that the JGH Reviewing REC informs the person mandated to review and authorize the research of the site(s) in question that their researcher did not submit the required form, and that the authorization for the study at that site must be suspended.

Respectfully,

Dr. Vasiliki Bessy Bitzas, N, PhD, CHPCN(C)
Chair, Medical/Biomedical Research Ethics Committee
VBB/mm
MM-CODIM-MBM-16-075Approval.doc
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Appendix 2: Medical screening form.

Medical screening form

Initials of Potential Subject:_____Age:_____Sex (M/F):_____

Script (read to participant prior to medical questions): We are asking you to participate in a research project involving participants who have had a hip replacement and healthy adults. The purpose of the study is to examine differences in walking patterns in patients who underwent hip replacement one year ago and determine if the surgical approach affects walking patterns. Before agreeing to participate in this project, we need to ensure you are eligible. I would like to ask you a few questions to ensure that you are eligible to complete this study.

Have you ever had a hip replaced? Yes No

When? _____ Which one? _____

Are you between the ages of 50 to 80 years? Yes No

Are you able to walk a city block? Yes No

Have you had any pain in your legs in the last 3 months? Yes No

Do you use a gait aid (e.g. cane or walker) when you walk?	Yes	No
Have you had recent trauma or surgery to your leg over the last year?	Yes	No
Have you ever had leg alignment surgery (HTO)?	Yes	No
Have you had any hip injections over the last 3 months?	Yes	No
Have you ever had a knee or ankle replaced?	Yes	No
Do you have any arthritis in your legs?	Yes	No
Do you have inflammatory arthritis (e.g. rheumatoid arthritis)	Yes	No
Have you ever had a stroke or TIA?	Yes	No
Do you have any severe breathing problems, or do you require an oxygen tank to assist with breathing?	Yes	No
Do you have any serious heart problems (e.g. angina, previous severe heart attack)?	Yes	No
Do you have any allergies to adhesives (e.g. tape or Band-Aid)?	Yes	No
Do you have any neurological conditions (e.g. Multiple Sclerosis, Parkinson's Disease, Alzheimer's Disease)?	Yes	No

Do you have any other medical conditions that you think we should know about?

_____

_____

_____

Have you had any previous hip injuries or hip surgeries?

_____

_____

_____

Is this person eligible to participate: Yes No

If no:
Thank you for taking the time to answer my questions. Unfortunately, you cannot be enrolled in the study due to your previous medical history. Thank you again for your time.

If yes:

Thank you for your time. You are eligible to participant in the study. Here is a copy of the consent form for you to review (hand over consent form). Please read it over before your study appointment and we can answer any questions at that time. We would like your phone number and email so we can arrange a time to begin the study.

Person Name (if eligible):_____

Phone Number (if eligible):_____

Email (if eligible):_____

Appendix 3: HOOS hip survey.

Hip Dysfunction and Osteoarthritis Outcome Score (HOOS) Hip Survey

Today's date: **Date of birth:**

Name:

INSTRUCTIONS: This survey asks for your view about your hip. This information will help us keep track of how you feel about your hip and how well you are able to do your usual activities
Answer every question by ticking the appropriate box, only one box for each question. If you are uncertain about how to answer a question, please give the best answer you can.

Symptoms
These questions should be answered thinking of your hip symptoms and difficulties during the last week.

S1. Do you feel grinding, hear clicking or any other type of noise from your hip?

Never	Rarely	Sometimes	Often	Always
□	□	□	□	□

S2. Difficulties spreading legs wide apart

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

S3. Difficulties to stride out when walking

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

Stiffness
The following questions concern the amount of joint stiffness you have experienced during the last week in your hip. Stiffness is a sensation of restriction or slowness in the ease with which you move your hip joint.

S4. How severe is your hip joint stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

S5. How severe is your hip stiffness after sitting, lying or resting later in the day?

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

Pain

P1. How often is your hip painful?

Never	Monthly	Weekly	Daily	Always
□	□	□	□	□

What amount of hip pain have you experienced the last week during the following activities?

P2. Straightening your hip fully

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

What amount of hip pain have you experienced the **last week** during the following activities?

P3. Bending your hip fully

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P4. Walking on a flat surface

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P5. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P6. At night while in bed

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

P7. Sitting or lying

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

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
□	□	□	□	□

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your hip.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A4. Standing

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your hip

A5. Bending to the floor/pick up an object

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A6. Walking on a flat surface

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A12. Lying in bed (turning over, maintaining hip position)

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A14. Sitting

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

Function, sports and recreational activities

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your hip

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

SP2. Running

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

SP3. Twisting/pivoting on loaded leg

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

SP4. Walking on uneven surface

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

Quality of Life

Q1. How often are you aware of your hip problem?

Never	Monthly	Weekly	Daily	Constantly
□	□	□	□	□

Q2. Have you modified your life style to avoid activities potentially damaging to your hip?

Not at all	Mildly	Moderately	Severely	Totally
□	□	□	□	□

Q3. How much are you troubled with lack of confidence

Not at all	Mildly	Moderately	Severely	Extremely
□	□	□	□	□

Q4. In general, how much difficulty do you have with your hip?

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

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

Appendix 4: Performance-based test form.

Subject #_____ Date: _____

Physical Function Performance Measures

30s Chair Test (30s-CST) - the maximum number of sit-to-stand repetitions completed from a chair in 30 seconds.	
Instructions: "For this test, do the best you can by going as fast as you can but do not push yourself to a point of overexertion or beyond what you think is safe for you. 1. Place your hands on the opposite shoulder so that your arms are crossed at the wrists and held close across your chest. Keep your arms in this position for the test. 2. Keep your feet flat on the floor and at shoulder width apart. 3. On the signal to begin, stand up to a full stand position and then sit back down again so as your bottom fully touches the seat. 4. Keep going for 30 seconds and until I say stop. 5. Get ready and START".	Total number of chair stands (up and down = 1): Did they require use of their arms to stand (Yes or No)

Stair Climb Test (11-step SCT) - the total time taken to ascend and descend one flight of stairs (flight of 11 stairs).	
Instructions: "For this test, do the best you can by going as fast as you can but do not push yourself to a point of overexertion or beyond what you think is safe for you. 1. Start with both feet on the bottom landing. 2. On start, go to the top of the stairs as fast but as safe as you can, turn around and return back down and stop with both feet back on the ground landing. 3. Use the rail only if needed. 4. Get ready and START".	Time(s): Did they use the railing (Yes or No)

6 Minute Walk Test (6MWT) - the total distance walked in six minutes time.	
Instructions: "For this test, do the best you can by going as fast as you can, but do not push yourself to a point of overexertion or beyond what you think is safe for you. 1. Start with both feet on the start line. 2. On start, walk as quickly but as safely as possible around the course / up and down the hallway. 3. Continue the course / walkway to cover as much ground as possible over 6 minutes. 4. Walk continuously if possible, but do not be concerned if you need to slow down or stop to rest. The goal is to feel at the end of the test that no more ground could have been covered in the 6 minutes. 5. You can sit down to rest if you require. 6. Get ready and START".	Distance(m):

Appendix 5: Participant consent form (English).

Hôpital général juif
Jewish General Hospital

McGill

constance-lethbridge
CENTRE DE RÉADAPTATION - REHABILITATION CENTRE

Consent Form

Does Total Hip Arthroplasty Surgical Approach Affect Muscle Activation and Joint Mechanics during Gait

Co-principal Investigator
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Email: shawn.robbins@mcgill.ca

Introduction

We are asking you to take part in a research project that will examine the walking pattern of patients one year following hip replacement, and to compare these patterns to those adults with no hip problems. You are being asked to participate because you had a hip replacement at the Jewish General Hospital or you have had no hip problems. Before agreeing to participate in this project, please take the time to read and carefully consider the following information. This consent form explains the aims of the study, procedures, advantages, risks and inconvenience as well as the persons to contact, if necessary. We invite you to ask any questions you have about the study. The researcher and the staff assisting with the project will answer your questions. Ask them to explain any word or information which is not clear to you. You do not have to take part in this study if you do not want to.

Purpose

Different types of surgery techniques are used to perform a hip replacement. Two of the most common techniques are the posterior and the lateral approaches. The posterior approach temporarily removes the muscles at the back of the hip. The lateral approach cuts the muscles at the side of the hip. It is important to compare surgical techniques to determine the most effective surgery and to help design strengthening programs.

This study aims to determine if the surgical approach affects walking patterns in patients who underwent hip replacement one year ago and to compare these patients to adults with no hip problems. Also, comparisons will be made between these groups on measures of pain, mobility, and strength. Patients will be recruited from the Jewish General Hospital. The study will include

Does Total Hip Arthroplasty Surgical Approaches Affect Muscle Activation and Joint Mechanics during Gait

21 participants who had a hip replacement by the lateral approach, and 21 participants who had a hip replacement by the posterior approach one year ago. Twenty-one adults with no hip problems will be recruited from the local community.

Study Procedures

The study will not involve treatment and all study procedures are non-therapeutic. The study will last for eight months. If you agree to participate, you will go the Constance Lethbridge Rehabilitation Centre in Montreal for data collection. You will responsible for providing your own transportation. Firstly, you will complete one survey that will ask you how you feel about your hip as well as how it affects you in your daily activities. Next you will change into shorts and a t-shirt. You will perform three mobility tests. The first one will be a sit to stand action repeated over 30 seconds; the second is an 11-stair climbing and descending test; and the third is a test requiring you to walk for 6 minutes. After that, small devices will be placed on your skin over your leg muscle using stickers. We will shave the area and clean it with alcohol prior to attaching the devices. These devices will measure when your muscles are being used. You will be required to do some exercises to ensure the devices are working properly. Next, reflective markers will be applied to your skin with adhesive tape. Cameras around the room are capable of measuring the position of the markers. This information will be used to analyze your walking pattern. You will then be asked to walk along an 8 metre platform at your usual walking speed. This will be repeated 7 to 10 times. Finally, you will be required to complete a series of five exercises requiring you to use your maximum strength. Each exercise will be held for 5 seconds and repeated three times. This is the only visit for the study and it should take 2.5 hours.

Access to Your Medical Chart

If you had a hip replacement, we will require access to your medical charts for surgical information including type of prosthesis, surgical approach, operating surgeon, and recent X-rays. Only information pertaining to the study will be examined.

Risks and Discomforts

This study does not include treatments, since you have already undergone the hip replacement. Thus, your standard of care will not be affected. You will have had an X-ray as part of your one year follow-up visit. We will gather data from these images. However, you will not undergo additional X-rays for this study. Thus, potential risks for this study are minimal. A few small areas of skin will be shaved before positioning electrodes and markers. As such, strict hygiene measures (razor, hypoallergenic adhesive tapes, cleaning skin with alcohol) will be respected. Skin reaction where electrodes or markers are fixed is an uncommon risk but could occur. You might feel some discomfort when removing the electrodes or markers. There is a small risk of injury, pain, or discomfort during the walking and strength tests. You will be asked for feedback during testing to make sure you are not uncomfortable.

Benefits

You will not personally benefit from taking part in this study. This study does not involve any treatments. However, you will be making a contribution to the advancement of science in the field of hip replacement.

Voluntary participation/withdrawal

Your participation in the research study described above is completely voluntary. It is understood that you can refuse to participate or withdraw at any time without this affecting the health care and services you are receiving or will receive. In case of withdrawal on your part, the study documents concerning you will be destroyed if that is your decision.

Confidentiality

All personal information gathered about you during the study will be coded in order to ensure its confidentiality. A master list will match participant identification numbers with names and this will be kept separate from the data in a locked file cabinet. Paper collection sheets will be stored in a locked filing cabinet in a locked office. Data will also be kept on a password protected computer. Only the members of the research team will have access to it. This data will be kept under lock and key at Constance Lethbridge Rehabilitation Centre by Dr. Shawn Robbins for a period of five years following the end of the study, after which it will be destroyed. In the event that the results of this study are presented or published, no information identifying the participant will be included. Some data will be transferred between study locations. For instance, surgical information (e.g. implant type) will be transferred from Jewish General Hospital to the Constance Lethbridge Rehabilitation Centres. Forms will be coded with participant ID numbers and no personal information will appear on the files.

For the purpose of monitoring this research, your research study file as well as your medical records identifying you could be checked by a person authorized by the Research Ethics Committee of the Jewish General Hospital.

Costs and compensation

You will not be paid for your participation in this study. There will be no costs to you for participating in this study. There will be no compensation for any travel costs. Parking is free at the Constance Lethbridge Rehabilitation Centre.

Compensation in Case of Injury

If you suffer an injury as a result of participating in the study, necessary medical treatment will be available at no additional cost to you. Unless required by law, compensation for such things as lost wages, disability or discomfort due to such an injury will not be offered. However, by signing this consent form you do not give up any of your legal rights (including the right to seek

compensation for an injury resulting from your participation in the study) nor relieve the sponsor, institution and investigator from their professional and legal responsibilities.

Investigator Compensation

The researcher in charge of this study is receiving funding (money) from a Granting Agency, Fonds de Recherche du Quebec – Sante (FRQS), to carry out this research. The funds are being deposited into a research and development account.

Contact Persons

If you have any questions regarding the study, need to report a side effect, or withdraw from the study, please contact Shawn Robbins at any time at 514-487-1891 extension 194 or by email shawn.robbins@mcgill.ca OR Dr. John Antoniou at 514-340-8222 extension 22948.

For any questions concerning your rights as a person taking part in this study or if you have comments or wish to file a complaint you can communicate with the Jewish General Hospital's Local Commissioner of Complaints & Quality of Services, Rosemary Steinberg, at (514) 340-8222 ext. 25833.

Does Total Hip Arthroplasty Surgical Approaches Affect Muscle Activation and Joint Mechanics during Gait

Statement of Consent

I have read this consent form, and had the study explained to me. I am aware of the study's aims, the study procedures, and the risks and benefits to taking part. My participation in this study is voluntary and I can withdraw from the study at any time. I do not give up any of my legal rights by signing this consent form.
A signed copy of this consent form will be given to me. I agree to participate in this study.

_____
NAME OF PARTICIPANT (print)

_____ _____
SIGNATURE OF PARTICIPANT DATE

_____
NAME OF PERSON WHO
OBTAINTED CONSENT (print)

_____ _____
SIGNATURE OF PERSON WHO DATE
OBTAINTED CONSENT

Responsibility of the Principal Investigator

I certify that I have explained to the above individual the terms of this form. I have answered all the questions he/she has asked. I have indicated that he/she remains free, at any time, to end his/her participation in the above described research study. A signed and dated copy of this form will be given to the above individual.

_____
NAME OF THE PRINCIPAL INVESTIGATOR
OR REPRESENTATIVE (print)

_____ _____
SIGNATURE OF THE PRINCIPAL INVESTIGATOR DATE
OR REPRESENTATIVE

Appendix 6: Pairwise comparison of study groups for gait EMG principal components (PCs).

Muscle	PC	*Healthy-Lateral THA*			*Healthy-Posterior THA*			*Lateral THA-Posterior THA*		
		Mean diff (95% CI)	**Adjusted p value***	**Effect size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect size**
Gluteus medius ‡	**1**	-67.55 (-195.95, 60.84)	0.60	-0.36	-19.10 (-147.5, 109.29)	1.00	-0.11	48.45 (-81.58, 178.48)	1.00	0.44
	2	-15.56 (-55.36, 24.23)	1.00	-0.27	-5.41 (-45.21, 34.38)	1.00	-0.11	10.15 (-30.16, 50.45)	1.00	0.25
	3	-36.38 (-63.96, -8.80)	0.01	-1.04	-20.37 (-47.95, 7.2)	0.22	-0.61	16.01 (-11.92, 43.94)	0.49	0.44
Gluteus maximus ‡	**1**	-46.89 (-126.87, 33.08)	0.46	-0.55	-74.96 (-154.93, 5.02)	0.07	-0.69	-28.06 (-109.06, 52.93)	1.00	-0.26
	2	6.99 (-23.04, 37.03)	1.00	0.17	33.58 (3.55, 63.62)	0.02	0.98	26.59 (-3.83, 57.01)	0.11	0.69
	3	7.81 (-13.49, 29.12)	1.00	0.32	12.78 (-8.53, 34.09)	0.43	0.5	4.97 (-16.61, 26.54)	1.00	0.16
Tensor fascia latae	**1**	-31.69 (-80.88, 17.49)	0.35	-0.5	-6.96 (-56.14, 42.23)	1.00	-0.12	24.74 (-25.66, 75.14)	0.69	0.37
	2	-7.73 (-30.47, 15.01)	1.00	-0.24	3.95 (-18.79, 26.69)	1.00	0.16	11.68 (-11.62, 34.98)	0.66	0.39
	3	-11.46 (-24.21, 1.30)	0.09	-0.62	-2.42 (-15.18, 10.33)	1.00	-0.19	9.03 (-4.04, 22.1)	0.28	0.53

Note: CI, confidence interval, *adjusted p value for Bonferroni correction for the pairwise comparison, ‡ = missing data on one participant in healthy group for all PCs of gluteus medius and gluteus maximus, THA = total hip arthroplasty.

Appendix 7: Pairwise comparison of study groups for gait EMG principal components (PCs) of quadriceps-group interaction effects.

Muscle	PC	*Healthy-Lateral THA*			*Healthy-Posterior THA*			*Lateral THA-Posterior THA*		
		Mean diff (95% CI)	**Adjusted value***	**Effect size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect size**
Vastus lateralis ‡	**1**	-7.72 (-65.92, 50.48)	0.79	-0.08	34.51 (-24.54, 93.55)	0.25	0.38	42.23 (-18.23, 102.69)	0.17	0.51
	2	5.89 (-11.51, 23.29)	0.50	0.21	-6.98 (-24.62, 10.67)	0.43	-0.24	-12.87 (-30.94, 5.21)	0.16	-0.50
	3	6.81 (-4.55, 18.16)	0.23	0.36	-2.39 (-13.91, 9.14)	0.68	-0.15	-9.19 (-20.99, 2.61)	0.12	-0.49
Vastus medialis ‡	**1**	9.13 (-57.97, 76.22)	0.79	0.08	40.18 (-27.89, 108.24)	0.24	0.34	31.05 (-38.65, 100.75)	0.38	0.38
	2	9.45 (-21.78, 40.68)	0.55	0.17	9.40 (-22.29, 41.08)	0.55	0.18	-0.05 (-32.49, 32.39)	1.00	0.00
	3	4.85 (-24.67, 34.38)	0.74	0.09	-10.72 (-40.67, 19.24)	0.48	-0.20	-15.57 (-46.25, 15.1)	0.31	-0.58
Rectus femoris‡	**1**	16.04 (-18.60, 50.69)	0.36	0.27	37.86 (2.71, 73.01)	0.04	0.69	21.82 (-14.17, 57.81)	0.23	0.45
	2	-6.43 (-18.36, 5.51)	0.29	-0.38	-7.07 (-19.18, 5.04)	0.25	-0.36	-0.64 (-13.04, 11.76)	0.92	-0.03
	3	6.80 (-1.78, 15.38)	0.12	0.49	6.41 (-2.29, 15.12)	0.15	0.57	-0.38 (-9.3, 8.53)	0.93	-0.03

Note: CI, confidence interval, *adjusted p value for Bonferroni correction for the pairwise comparison, THA = total hip arthroplasty, ‡ = missing data on one participant in healthy group for all PCs of vastus lateralis, vastus medialis and rectus femoris.

Appendix 8: Pairwise comparison of study groups for gait EMG principal components (PCs) of hamstrings-group interaction effects.

Muscles	PC	*Healthy-Lateral THA*			*Healthy-Posterior THA*			*Lateral THA-Posterior THA*		
		Mean diff (95% CI)	**Adjusted p value***	**Effect Size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect Size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect Size**
Lateral hamstrings	**1**	-29.51 (-66.01, 6.99)	0.11	-0.51	-23.05 (-59.55, 13.46)	0.21	-0.44	6.47 (-30.94, 43.87)	0.73	0.10
	2	-9.06 (-26.45, 8.33)	0.30	-0.35	-31.22 (-48.61, -13.83)	0.00	-1.34	-22.16 (-39.98, -4.34)	0.02	-0.68
	3	-1.60 (-14.62, 11.42)	0.81	-0.08	-1.49 (-14.51, 11.53)	0.82	-0.07	0.11 (-13.23, 13.45)	0.99	0.01
Medial hamstrings	**1**	-17.85 (-47.68, 11.98)	0.24	-0.36	-1.57 (-31.40, 28.26)	0.92	-0.04	16.28 (-14.29, 46.85)	0.29	0.33
	2	3.55 (-14.28, 21.39)	0.69	0.12	-10.60 (-28.44, 7.23)	0.24	-0.42	-14.16 (-32.43, 4.12)	0.13	-0.47
	3	-11.38 (-23.57, 0.82)	0.07	-0.59	-5.31 (-17.50, 6.89)	0.39	-0.28	6.07 (-6.43, 18.56)	0.33	0.31

Note: CI, confidence interval, *adjusted p value for Bonferroni correction for the pairwise comparison, THA = total hip arthroplasty.

Appendix 9: Pairwise comparison of study groups for gait angle principal components (PCs).

Angle	PC	*Healthy-Lateral THA*			*Healthy-Posterior THA*			*Lateral THA-Posterior THA*		
		Mean diff (95% CI)	**Adjusted p value***	**Effect size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect size**
Hip Flexion	**1**	-4.85 (-61.67, 51.97)	1.00	-0.07	-40.83 (-97.65, 15.98)	0.24	-0.53	-35.99 (-94.21, 22.23)	0.40	-0.51
	2	18.57 (5.08, 32.06)	0.00	1.13	18.41 (4.92, 31.89)	0.00	1.04	-0.16 (-13.98, 13.66)	1.00	-0.01
	3	-2.08 (-10.16, 6.00)	1.00	-0.18	3.32 (-4.76, 11.40)	0.94	0.33	5.40 (-2.88, 13.68)	0.34	0.57
Hip adduction	**1**	-2.86 (-22.08, 16.37)	1.00	-0.11	2.47 (-16.75, 21.70)	1.00	0.11	5.33 (-14.37, 25.03)	1.00	0.21
	2	4.49 (-4.94, 13.93)	0.73	0.35	10.63 (1.20, 20.06)	0.02	0.83	6.14 (-3.53, 15.80)	0.37	0.61
	3	5.48 (-0.37, 11.34)	0.07	0.73	4.25 (-1.60, 10.11)	0.24	0.56	-1.23 (-7.23, 4.77)	1.00	-0.17
Hip medial rotation	**1**	10.29 (-42.67, 63.24)	1.00	0.14	0.70 (-52.26, 53.66)	1.00	0.01	-9.59 (-63.85, 44.68)	1.00	-0.14
	2	-13.55 (-26.61, -0.50)	0.04	-0.79	-14.24 (-27.30, -1.19)	0.03	-0.86	-0.69 (-14.06, 12.68)	1.00	-0.04
	3	7.06 (-3.40, 17.53)	0.30	0.56	18.10 (7.63, 28.57)	0.00	1.31	11.04 (0.31, 21.76)	0.04	0.81
Pelvic obliquity	**1**	7.67 (-5.96, 21.30)	0.51	0.41	0.56 (-13.07, 14.19)	1.00	0.03	-7.11 (-21.08, 6.86)	0.64	-0.46
	2	6.09 (0.40, 11.79)	0.03	0.77	5.35 (-0.35, 11.04)	0.07	0.78	-0.75 (-6.59, 5.09)	1.00	-0.11
	3	2.10 (-3.06, 7.26)	0.96	0.31	4.05 (-1.11, 9.22)	0.17	0.64	1.95 (-3.34, 7.25)	1.00	0.30
Trunk lean	**1**	-9.83 (-23.46, 3.80)	0.24	-0.58	-11.47 (-25.10, 2.15)	0.13	-0.66	-1.65 (-15.61, 12.32)	1.00	-0.09
	2	-2.90 (-6.78, 0.97)	0.21	-0.55	-1.69 (-5.56, 2.18)	0.86	-0.33	1.21 (-2.75, 5.18)	1.00	0.28
	3	-1.22 (-4.28, 1.83)	0.98	-0.32	0.01 (-3.05, 3.070)	1.00	0.00	1.23 (-1.90, 4.37)	1.00	0.31

Note: CI, confidence interval, *adjusted p value for Bonferroni correction for the pairwise comparison, THA = total hip arthroplasty.

Appendix 10: Pairwise comparison of study groups for joint moment principal components (PCs) during gait.

Moments	PC	*Healthy-Lateral THA*			*Healthy-Posterior THA*			*Lateral THA-Posterior THA*		
		Mean diff (95% CI)	**Adjusted p value***	**Effect size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect Size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect Size**
Hip extension	**1**	0.2 (-0.66, 1.06)	1.00	0.21	0.38 (-0.48, 1.24)	0.82	0.34	0.18 (-0.7, 1.06)	1.00	0.15
	2	-0.03 (-0.56, 0.51)	1.00	-0.05	-0.07 (-0.61, 0.47)	1.00	-0.1	-0.05 (-0.6, 0.51)	1.00	-0.06
	3	-0.01 (-0.28, 0.25)	1.00	-0.04	0.01 (-0.25, 0.27)	1.00	0.03	0.02 (-0.25, 0.29)	1.00	0.07
Hip abduction	**1**	-0.1 (-0.78, 0.57)	1.00	-0.13	-0.2 (-0.88, 0.48)	1.00	-0.21	-0.10 (-0.8, 0.6)	1.00	-0.12
	2	0.36 (-0.01, 0.74)	0.06	0.77	0.21 (-0.17, 0.59)	0.52	0.45	-0.15 (-0.54, 0.23)	1.00	-0.30
	3	0.07 (-0.23, 0.36)	1.00	0.17	-0.03 (-0.33, 0.27)	1.00	-0.08	-0.10 (-0.4, 0.21)	1.00	-0.30
Hip medial rotation	**1**	-0.03 (-0.23, 0.17)	1.00	-0.11	-0.15 (-0.35, 0.05)	0.21	-0.6	-0.12 (-0.32, 0.08)	0.45	-0.52
	2	0.09 (-0.03, 0.2)	0.21	0.64	0.03 (-0.08, 0.15)	1.00	0.2	-0.06 (-0.17, 0.06)	0.74	-0.35
	3	-0.02 (-0.08, 0.04)	1.00	-0.24	-0.02 (-0.08, 0.05)	1.00	-0.22	0.00 (-0.06, 0.07)	1.00	0.02

Note: CI, confidence interval, *adjusted p value for Bonferroni correction for the pairwise comparison, THA = total hip arthroplasty.

Appendix 11: Pairwise group comparisons for maximum isometric muscle torques during maximum voluntary isometric contraction exercises (MVIC).

MVIC exercise	*Healthy-Lateral THA*			*Healthy-Posterior THA*			*Lateral THA-Posterior THA*		
	Mean diff (95% CI)	**Adjusted p value***	**Effect Size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect Size**	**Mean diff (95% CI)**	**Adjusted p value***	**Effect Size**
Hip abduction‡	0.24 (0.00, 0.48)	0.05	0.70	0.10 (-0.14, 0.34)	0.93	0.34	-0.14 (-0.39, 0.11)	0.49	-0.52
Hip extension‡	0.09 (-0.16, 0.34)	1.00	0.23	0.17 (-0.08, 0.42)	0.31	0.50	0.08 (-0.17, 0.33)	1.00	0.29
Knee extension‡	-0.14 (-0.35, 0.07)	0.29	-0.51	-0.20 (-0.41, 0.00)	0.06	-0.80	-0.06 (-0.27, 0.15)	1.00	-0.23
Knee flexion‡	0.10 (-0.06, 0.26)	0.42	0.45	-0.05 (-0.21, 0.11)	1.00	-0.26	-0.15 (-0.32, 0.02)	0.09	-0.74
Hip flexion‡	0.09 (-0.11, 0.28)	0.81	0.34	-0.02 (-0.22, 0.17)	1.00	-0.12	-0.11 (-0.31, 0.08)	0.49	-0.48

Note: CI, confidence interval, *adjusted p value for Bonferroni correction for the pairwise comparison, THA = total hip arthroplasty**,** ‡ = Missing data: One healthy participant for all MVIC exercises, one lateral THA.

Appendix 12: Pairwise group comparisons scores of the Hip Disability Osteoarthritis Outcome (HOOS) questionnaire subscales.

HOOS subscales	**Adjusted p value***		
	Healthy-Lateral THA	***Healthy-Posterior THA***	***Lateral THA-Posterior THA***
HOOS-pain	0.03	0.58	0.39
HOOS-symptom	0.47	0.37	1.00
HOOS-activities of daily living	0.02	0.25	0.91
HOOS-sport/recreation	0.04	0.01	1.00
HOOS-quality of life	0.00	0.03	0.26

*adjusted p value for Bonferroni correction for the pairwise comparison, THA = total hip arthroplasty.