

**Kinematics and Kinetics of Total Hip Arthroplasty  
Patients during Gait and Stair Climbing:  
A Comparison of the Anterior and Lateral Surgical Approaches**

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## Abstract

New surgical approaches for total hip arthroplasty (THA) are being developed to reduce muscle damage sustained during surgery, in the hope to allow better muscle functioning afterwards. The goal of this study was to compare the muscle sparing anterior (ANT) approach to a traditional lateral (LAT) approach with three-dimensional motion analysis. Kinematics and kinetics were obtained with an infrared camera system and force plates. It was hypothesized that (1) the ANT group would have closer to normal range of motion, moments and powers, compared to the LAT group, and that (2) the ANT group would have higher peak hip abduction moment than the LAT group. Forty patients undergoing unilateral THA for osteoarthritis between the ages of 50 and 75 (20 ANT, 20 LAT) were asked to perform three trials of walking, stair ascent and stair descent. Patients were assessed between six to twelve months postoperatively. Twenty age- and weight-matched control participants (CON) provided normative data. Results indicated that both THA groups had gait anomalies compared to the CON group. Both THA groups had reduced hip abduction moment during walking (CON vs. ANT:  $p < 0.001$ ; CON vs. LAT:  $p = 0.011$ ), and the ANT group had a significantly lower hip abduction moment compared to the LAT group ( $p = 0.008$ ). Similar results were observed during stair descent, where the ANT group had reduced peak hip abduction moment compared to the CON group ( $p < 0.001$ ) and the LAT group ( $p = 0.014$ ). This indicates that the anterior approach did not allow better gait and stair climbing ability after THA. It is therefore thought that other variables, such as preoperative gait adaptations, trauma from the surgery, or postoperative protection mechanisms to avoid loading the prosthetic hip, are factors that might be more important than surgical approach in determining the mechanics of THA patients after surgery.

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## Introduction

Hip replacement is a more and more common surgery. In the 2006-07 fiscal year, 24 253 hip replacements were performed in Canada, representing a 60.2% increase compared to 1996-97 and a 2.6% increase compared to 2005-06 (Canadian Institute for Health Information, 2009). The majority (89.4%) of those were primary procedures, and degenerative osteoarthritis (OA) was the main responsible diagnosis (81%) for those, followed by osteonecrosis (5.2%) and acute fracture (4.5%). Patients undergoing THA are getting younger, with a 140% ten-year increase for males in the 45-54 years age group, and a 94% ten-year increase for women in the 55-64 years age group. As patients get younger and are more physically active, the demands on the prosthesis increase (Crowninshield et al., 2006).

Many surgical approaches are used for THA, such as posterior, lateral, anterolateral, anterior and transtrochanteric. Many variables are to be taken into account when choosing surgical approach: preserving blood flow (Horwitz et al., 1993), having adequate exposure for good preparation and placement of the acetabular component (Nork et al., 2005), maintaining soft tissue integrity, reducing blood loss as well as hospital stay (Bennett et al., 2006). It has been stipulated that surgical approach could have an effect on hip function because of muscle sectioning or sparing (Masonis & Bourne, 2002). A few studies have compared surgical approaches with regards to hip function or strength (Downing et al., 2001; Horwitz, et al., 1993; Masonis & Bourne, 2002). However, in these studies, hip function is often simplified as isometric muscle strength. From a biomechanical point of view, this measure is insufficient in order to determine the actual joint functionality. Vaz and colleagues (1993) showed that hip abductor strength was very modestly correlated with

function measured as distance walked in six minutes. Hence, different definitions and measures of function exist and are not always correlated with each other. For this research, joint functionality is defined as the ability of a person to perform movements and activities of daily living with ranges of motion, moments of force and powers comparable to a healthy person.

The study of kinematics and kinetics of the lower limbs can provide important information on joint functionality and help customize rehabilitation after hip replacement (Bhave et al., 2007). Most of the studies on lower limb kinematics and kinetics after hip replacement are on gait (Andersson et al., 2001; Beaulieu et al.; Bennett, et al., 2006; Foucher et al., 2007; Madsen et al., 2004). However, patients who underwent hip replacement, like everybody else, are confronted to more demanding tasks in everyday life. For instance, they will often need to climb stairs. We believe that analyzing this more demanding task, in addition to gait, will provide a more accurate representation of the functionality of the patient after surgery. Hence, for this study, we will look at walking, stair ascent and stair descent.

### *Relevancy*

Although several studies have compared the outcome of THA, few have assessed the functionality of hip replacement patients with three-dimensional (3D) motion analysis. Also, there is a paucity of literature concerning the anterior surgical approach to the hip. Understanding how the surgical approach affects the joint functionality in daily tasks is important since the goal of this surgery is to allow the patient to regain their mobility and have a better quality of life. To our knowledge, only one study has investigated the kinematics and kinetics of patients operated by means of an anterior approach during gait

(Klausmeier et al., 2010). Another study has looked at the kinematics, but not the kinetics, of gait (Mayr et al., 2009). However, these studies focused on early gait recovery (6, 12 and 16 weeks post-surgery). No study has inquired in the long-term gait recovery of the anterior approach. Information gained in this study will provide valuable information that could be used in surgery and for the development of rehabilitation programs, which could reduce time to recovery and related healthcare costs.

### *Objectives*

The purpose of this study was to determine whether there were differences in walking and stair climbing 3D kinematics and kinetics of the lower limbs between a group of THA patients operated by means of an anterior approach (ANT) or a lateral approach (LAT), ten months after surgery. The two groups were also compared to an age- and weight-matched control group recruited from the general population. The objective of the study was to provide information to surgeons on the functional outcomes in order to help them choose the appropriate surgical approach for their patients.

### *Hypotheses*

One of the main advantages of the anterior approach is that it causes less overall damage to the abductor muscle group and external rotators (Meneghini et al., 2006), which stabilize the pelvis during single-legged stance. Hence, it is thought that the anterior approach would allow closer to normal kinematics and kinetics than the lateral approach, which splits the gluteus medius and minimus muscles. It was hypothesized that the ANT group would have closer to normal hip, knee and ankle range of motion (ROM), greater lower-limb peak moments of force and greater lower-limb peak powers than the LAT group

during gait, stair ascent and stair descent. More specifically, the hip should produce a closer to normal hip frontal plane peak angles and range of motion, and peak hip abduction moment in the ANT group compared to the LAT group. Differences at the knee and ankle will be analyzed in a more exploratory fashion.

## **Review of Literature**

Hip replacement is recognized as a viable solution for hip pain due to osteoarthritis, osteonecrosis, inflammation arthritis and acute fracture. The type of replacement and the surgical approach are recognized as two major factors affecting the outcome of the hip replacement. This review of literature will look at methods for evaluating the outcome of hip replacement as well as the differences between surgical approaches. From this review, gaps and methodological flaws will be identified, justifying the need for new research.

### *Surgical approach*

Another major factor for hip replacement is surgical approach. Several considerations can be taken into account when choosing a surgical approach. Adequate exposure is important in order to ensure good positioning of the prosthesis. Muscle sparing is also very important to have good stability and function after the hip replacement. Potential damage to the sciatic nerve, the lateral cutaneous nerve, the superior or inferior gluteal nerve, the femoral nerve or the obturator nerve is to be considered (Navarro et al., 1995; Schmalzried et al., 1991). Studies on the lateral and the anterior approach will here be discussed.

### *Lateral Approach*

The lateral approach is commonly used in Canada, representing 34% of all THAs (Canadian Institute for Health Information, 2009). This approach necessitates the detachment of the anterior portion of the gluteus medius in order to access the hip capsule. While it provides excellent exposure, some complications may occur, such as denervation of the abductors from damage to the superior gluteal nerve (Baker & Bitounis, 1989) or abductor avulsion (Weber & Berry, 1997).

Using fine wire electromyography (EMG), Baker and Bitounis (1989) found evidence of denervation of the tensor fascia lata in eight out of 29 hips operated through a direct lateral approach and five out of 28 in a modified lateral approach, where the gluteal flap was raised with a sliver of the greater trochanter. The lateral approach was therefore suspected to damage the inferior branch of the superior gluteal nerve. This damage is, according to the authors, the result of the detachment and reattachment of anterior gluteal flap to the greater trochanter. Also using fine wire EMG, Kenny et al. (1999) observed abnormal EMG signals as evidence of damage to the superior gluteal nerve in 13 out of 23 patients operated by means of a direct lateral approach. They assessed the gluteus medius and minimus, as well as the tensor fascia lata. These results, however, did not correlate with abductor weakness measured with the Trendelenburg test. They therefore concluded that other factors must contribute to abductor weakness. Franz and colleagues (2002) found delayed activation of the glutei and vasti muscles in THA patients at five months post-surgery. All surgeries were performed with a lateral approach, and the authors suggested that motor control training must be continued for longer than five months after surgery. Even if the abductors are not sectioned with a posterior approach, Vogt and colleagues (2004) observed delayed activation

of the gluteus medius at six weeks post-surgery for 14 THA patient operated through this approach. These studies suggest that neuromuscular impairments persist after hip replacement in both posterior and lateral surgical approaches.

Downing et al. (2001) report similar maximal isometric abductor strength measurements at three and twelve months postoperatively, measured with an isokinetic dynamometer (KINCOM), between the lateral and posterior surgical approach. Barber and colleagues (1996) reported similar Trendelenburg sign, limp, abductor strength, and passive range of motion between the posterior and the lateral approach. Horwitz et al. (1993) compared the direct lateral approach to the transtrochanteric and posterior approach, and found no significant differences between them in terms of presence of limp, passive range of motion and abductor strength (again measured with an isokinetic dynamometer) at six months and one year postoperatively. In a more recent study, Kiyama et al. (2010) also observed similar strength deficit in the lateral and posterior surgical approaches. Their results suggest that preoperative abductor strength and hip reconstruction parameters (such as femoral offset) are better predictors of abductor weakness after THA than surgical approach.

Müller et al. (2010) found more fatty atrophy in a group of THA patients operated by means of a modified (mini-incision) direct lateral approach, compared to a mini-incision anterolateral approach. They suggest that the detachment and repair of the anterior portion of the gluteus medius is responsible for this fat accumulation. Accordingly, only the anterior section of the gluteus medius had more fatty atrophy at three and twelve months postoperatively, whereas the middle and posterior section were not significantly different from the anterolateral approach. They also observed more gluteus medius tendon damage in the lateral group. The authors suggest that suturing does not necessarily guarantee proper postoperative tendon ingrowth.

Review articles therefore came to the conclusion that there is not enough evidence to suggest a significant difference between the lateral and posterior surgical approaches after hip replacement in terms of clinical outcome (Jolles & Bogoch, 2004; Masonis & Bourne, 2002).

Few studies have used gait analysis in order to compare the lateral surgical approach to others. Madsen and colleagues (2004) compared 3D gait kinematics of ten patients who had an anterolateral approach to ten who had a posterolateral approach, six to seven months after surgery. The anterolateral group showed reduced hip flexion and extension compared to the control group. They also had more trunk inclination over the operated side, a mechanism thought to reduce the demands on the abductor muscle group (Hurwitz et al., 1997). Recently, Meneghini and colleagues (2008) reported lower peak ground reaction force at mid-stance with a mini-incision anterolateral approach compared to a two-incision approach and a posterior approach, six weeks after surgery. They suggest this could be due to abductor weakness. However, all three groups had similar gait velocity increase, single-legged stance time, and abductor torque at mid-stance. While their measuring instruments were adequate (kinematics were measured with a four camera setup and a Helen Hayes marker set and kinetics with two force plates), they had very few participants: eight in both the mini-posterior and 2-incision approach groups, and seven in the mini-anterolateral approach group. Their results had therefore low statistical power.

Whatling and colleagues (2008) performed gait analysis on 14 patients with a lateral approach and 13 with a posterior approach. Both groups had reduced hip sagittal plane range of motion compared to the control participants, but only the lateral group had reduced pelvic frontal plane range of motion, peak abductor moment of force, and peak frontal plane power. The control group was, however, younger and lighter than both THA groups. The differences

observed could be partly due to this discrepancy between groups, but the authors did not include these variables as covariates in their statistical analysis.

### *Anterior Approach*

The anterior surgical approach to the hip has not received as much attention in the literature as the posterior and the anterolateral approaches. Kennon and colleagues (2003) reported a low dislocation rate (1.3%) from a consecutive series of 2132 total hip replacements. Later, Sariali and colleagues (2008) reported a similar rate of dislocation of 1.5% for a consecutive series of 1764 THA. Recently, Restrepo et al. (2010) observed better early outcomes measured by questionnaires in a group of 50 THA patients operated through an anterior approach, compared to a group of 50 who had a direct lateral approach. Their anterior group had better scores in several physical and mental components of the Short-Form-36, the WOMAC and the quality-of-life component of the Linear Analog Scale Assessment questionnaires at six weeks and six months after surgery. The authors did not observe, however, any significant difference two years after surgery. They therefore suggested that the benefits of the anterior approach are mostly apparent shortly after the surgery.

In a cadaveric study, it was found that the anterior approach resulted in less abductor muscle damage compared to the posterior approach (Meneghini et al., 2006). There was, however, some damage to the gluteus medius muscle in two out of the six specimens and to the gluteus minimus muscle in four out of the six specimens operated through an anterior approach, as well as some damage to the rectus femoris and the tensor fascia lata. This study demonstrated that the anterior approach could cause damage to the abductor muscle group,

even though it does not necessitate muscle splitting. The authors suggested that gait analysis should be performed in order to ascertain the functional implications of their findings.

Migaud and colleagues (2007) compared the advantages and disadvantages of six different approaches. They reported the specificity (equipment- and prosthesis-wise), the ability to convert to a mini-incision and the potential complications of the approaches. They also measured the ability of the approaches to deal with several complications. Their results indicate that less invasive approaches (such as the anterior approach) required more specific instruments and prostheses and were not as adaptable as more invasive approaches (such as the posterolateral approach). They concluded that the ideal approach should be muscle sparing, give good access to both acetabulum and femoral head, allow easy training, allow the implantation of most prostheses models and be adaptable to potential complications. In their opinion, none of the current approaches meet these conditions.

Nakata and colleagues (2009) compared the anterior approach to the posterior approach for THA in regards to operative invasion (operation time and blood loss), prosthesis placement accuracy as well as functional recovery. The last aspect was measured with the following indices: time to walk more than 200 meters with a single cane, time to maintain a five-second single-legged stance, presence of Trendelenburg's sign at five days and at three weeks, time to walk 50 meters and use of a walking aid preoperatively and at three weeks postoperatively. Their results show better and earlier functional recovery for the anterior group. They stipulate that, since the anterior approach spares the gluteus maximus muscle, the hip's ability to adequately perform an extension enables the patients to perform activities of daily living (such as standing and stair climbing) earlier after surgery. They did not, however, evaluate this and such a statement has yet to be proven.

Ward and colleagues (2008) compared the mini-incision anterior approach to the mini-incision anterolateral, the standard posterior and the mini-incision posterior approaches in regards to gait parameters. They evaluated the patients before surgery and at six weeks and three months after surgery. Interestingly, they did not observe any significant difference between these four approaches. The measurement system they used (IDEEA, Minisun, Fresno, CA), however, has been shown to significantly underestimate several distance parameters such as speed, step length and stride length (Maffioletti et al., 2008), questioning the validity of the reported results. Also, this device uses biaxial accelerometers, and therefore movements in the frontal plane are not taken into account. In another study, this group also observed no significant difference in spatiotemporal gait parameters between the anterior and the posterior approach at self-selected and fast walking speed, using an instrumented mat (GAITRite, CIR Systems Inc. Clifton, USA) (Maffioletti et al., 2009). This instrument has been shown to provide reliable measurements of gait parameters (Bilney et al., 2003).

Recently, Mayr et al. (2009) compared gait kinematics of a group of THA patients operated by means of an anterior approach (n=16), to a group operated through the anterolateral approach (n=17) with three-dimensional motion analysis. This randomized prospective study had a preoperative and two postoperative assessments (six and twelve weeks). The anterior patients demonstrated significant improvements in sagittal and frontal plane hip range of motion six weeks after THA (compared to preoperative), as well as in peak hip flexion twelve weeks after THA. They did not, however, have a matched control group to provide normative data. Klausmeier et al. (2010) also explored the early gait recovery of the anterior and the anterolateral approach after THA. They measured hip abductors isometric strength, 3D kinematics and 3D kinetics of both groups before surgery,

as well as at six weeks and 16 weeks after surgery. They had twelve patients in the anterior group and eleven in the anterolateral group. Similarly to the study by Mayr et al. (2009), the anterior group demonstrated increased hip sagittal range of motion at six weeks compared to pre-surgery. At 16 weeks, both groups had similar ranges of motion, but they remained lower than the range of motion (ROM) of the control group. Both groups had no improvement in hip abduction moment of force compared to before surgery, and they remained lower than the control group after 16 weeks. Interestingly, the group operated through an anterolateral approach did not show a reduction in hip abduction moment six weeks after THA, even though their anterior part of gluteus medius and minimus have been detached and subsequently repaired during surgery.

There is currently no long-term data on the gait of patients operated by means of an anterior approach that could confirm that this approach is beneficial for the patient's mobility, from a biomechanical point of view. If THA patients operated through an anterior approach demonstrate favorable gait mechanics several months after their operation, this muscle sparing approach might gain in popularity and benefit the patients.

### *Measuring outcome*

The primary goal of hip replacement is to eliminate pain and restore function. However, there are many ways to assess the success of this type of surgery. This section will discuss the types of measurements of outcome for hip replacement and demonstrate the importance of the field of biomechanics in measuring outcome.

### *Qualitative Methods*

Questionnaires are a common method of assessing the outcome of hip replacement. Several validated questionnaires are available. One of the most recognized is the Harris hip score (Harris, 1969). The score is on 100 and includes function (47 points), pain (44 points), range of motion (5 points), and absence of deformity (4 points). It was developed to encompass all the important variables in one single measure that is reliable, reproducible and reasonably objective. The WOMAC questionnaire has been developed at McMaster University (Bellamy et al., 1988) and is specifically designed for osteoarthritis of the knee or hip. It has three dimensions: pain, stiffness and physical function, which are measured on a Likert scale. Scores are reported for each dimension or as a total score. Others will use the short form-36 (SF-36), a general health assessment questionnaire with eight dimensions: 1) limitations in physical activities because of health problems, 2) limitations in social activities because of physical or emotional problems, 3) limitations in usual role activities because of physical health problems, 4) bodily pain, 5) general mental health (psychological distress and well-being), 6) limitations in usual role activities because of emotional problems, 7) vitality (energy and fatigue), and 8) general health perceptions (Ware Jr & Sherbourne, 1992). The Merle d'Aubigné questionnaire measures pain, mobility and ability to walk (Merle d'Aubigné, 1954). The UCLA score (Amstutz et al., 1984) is a simple ten point score assessing activity level.

Scores between self-assessed questionnaires, however, can lack uniformity (Callaghan et al., 1990). Subjective methods of hip evaluation have been shown to lack validity assessing function of the hip in regards to walking performance. Boardman and colleagues (2000) analyzed the correlation between questionnaire scores and gait parameters.

They measured the functional and stiffness scores of the WOMAC and the physical component summary score (PCSS) of the SF-36 scores. For the gait analysis, they measured gait velocity, gait symmetry, and the distance walked in six minutes. They performed an assessment preoperatively and at 12 months postoperatively. Their data showed good correlations (Pearson's  $r$  between 0.5 and 0.81) between improvements as well as in absolute postoperative values. However, Lindemann and colleagues (2006) demonstrated that the improvement in the WOMAC functional score did not significantly correlated with walking performance ( $r = -0.21$  or less). They attributed this difference to the time interval between the surgery and the measurements. Their conclusion is that gait analysis is an important source of information for assessment of function after hip replacement that cannot be measured with a questionnaire. Also, they acknowledge that questionnaires are important because they reflect the level of satisfaction of the patient, an important factor not measurable with gait analysis. Qualitative and quantitative measurements are therefore complementary in assessing patient outcome after hip replacement surgery.

Another common measure is the Trendelenburg test. The patient is asked to stand on the operated leg for approximately 30 seconds (Hardcastle & Nade, 1985). The test is considered positive if the patient is unable to raise the non-operated side of his pelvis above the stance side. This test indicates abductor weakness. It has been used in several studies (Bach et al., 2002; Baker & Bitounis, 1989; Barber, et al., 1996; Downing, et al., 2001). However, it remains a qualitative measurement that is subject to the knowledge, experience and perception of the observer. This leads us to quantitative methods of assessing the outcome of hip replacement.

### *Quantitative Methods*

Success of the surgery is often measured with survival rates (Arthursson et al., 2007; Daniel et al., 2004; Treacy et al., 2005), which mostly take into account dislocation, infection, loosening and rate of revisions. Concerning the anterior approach, Siguier et al. (2004) reported ten dislocations, five septic complications, and three aseptic loosening cases out of 1037 hip replacements. Sariali et al. (2008) reported 27 dislocations and 21 femoral neck fractures out of a series of 1764 hips. Kennon et al. (2003) reported 28 dislocations, 87 fractures, and seven infections out of 2132 hips. The data from these studies results in a 3.8% complication rate. While these results are encouraging, today's patients want more out of their prosthesis than the absence of major complications. Hence, objective and more sensitive measurements of function are needed to assess the progression of the functionality of the hip joint after surgery.

Many authors measure isometric hip strength as a quantitative method to measure function (Barber, et al., 1996; Bhave, et al., 2007; Downing, et al., 2001; Gore et al., 1985; Gore et al., 1982; Horwitz, et al., 1993; Minns et al., 1993). Measuring isometric hip strength is easily done with a dynamometer and gives a good indication of muscle recovery and ability to produce adequate strength. Muscle deficiencies can cause alteration in gait. In walking, if the abductor muscle group (tensor fascia lata, gluteus medius, gluteus minimus and upper fibers of gluteus maximus) is unable to produce enough force, patients will lateralize their center of mass on top of the femur, hence causing a limp, also known as a Trendelenburg gait (Hardcastle & Nade, 1985). This can affect walking performance (LeVeau, 1992). Vaz and colleagues (1993), however, showed that hip abductor strength was very modestly correlated with function measured as distance walked in six minutes ( $r=0.48$ -

0.51). Their conclusion is that although hip strength is a good indicator of function, it should not be the sole predictor of function.

Measurement of kinematics can be an insightful method of assessing the functionality of a hip replacement. The study of kinematics includes gait temporal parameters such as velocity, cadence, stance phase duration, swing phase duration and stride length. It also includes range of motion, angular displacement, velocity and acceleration at the different articulations. The study of kinematics has been demonstrated to be repeatable (Kadaba et al., 1989) and a useful method of assessing hip function after hip replacement (Skinner, 1993). In order to measure the above-mentioned parameters, cameras are used to record the participant's movement and force plates or foot switches are used to identify events such as foot strike and foot off. Normal human gait is well documented (Rose & Gamble, 2006). By comparing the kinematics of normal people to people with hip replacement, we can observe the effects of the surgery on the patient's gait.

Aminian and colleagues (1999) measured the progress of twelve participants with osteoarthritis before and at three, six and nine months after THA. They measured the left and right stance time and double support time as well as the difference between left and right stance and double support time, which is a measure of symmetry. They concluded that the difference between left and right double support time is the temporal parameter that allows control of gait symmetry during rehabilitation. The goal of the study was to validate a new method of assessing progress in gait of patients with hip replacement using miniature accelerometers. Hence, the authors did not put much emphasis on the selection of the participants. The information regarding the kind of prosthesis used and surgical approach is not reported.

Bach and colleagues (2002) compared a robotic instrumentation system (Robodoc, Integrated Surgical Systems, CA) to a conventional procedure and a control group. They used an infrared 3D gait analysis system to measure certain gait kinematics variables: pelvic tilt (sagittal plane), pelvic obliquity (frontal plane), hip flexion and extension (sagittal plane), and hip abduction and adduction (frontal plane). The two procedures did not differ in those variables. They were both, however, similarly different from the control group, showing reduced pelvic obliquity range of motion, hip flexion and hip abduction. The authors attributed these deficiencies to the surgical approach used. They believed that the transgluteal approach affected the abductor muscles in both procedures.

Bennett and colleagues (2006) measured similar variables to compare a minimally invasive approach to a traditional approach for a total hip arthroplasty. They measured the range of pelvic tilt, hip flexion/extension, knee flexion/extension, ankle dorsiflexion/plantarflexion, and foot progression. Interestingly, they looked at the other lower limb articulation, as gait alterations can be observed at different articulations since the segments are linked and influence each other. For instance, greater ankle dorsiflexion is believed to be a shock absorbing mechanism to relieve pain in higher articulations (Mont et al., 2007). The interaction between the articulations is too often put aside. Hence, in our research, we will include the knee and ankle kinematics and kinetics in our analysis.

The study of forces at the hip joint is another subject of interest, as these could determine the demands on the prosthesis, and also the wear that will eventually occur. Some of the first studies on the subject include the work of Elson and Charnley (1968), who estimated the resultant force with the wear of 37 polytetrafluoroethylene (PTFE) acetabular cups retrieved from patients. The stainless steel femoral heads caused premature wear of the cups and this wear was used to estimate the direction of force at the hip. Others have

measure hip contact force with instrumented stems (Bergmann et al., 2001; Heller et al., 2001; Hodge et al., 1989; Hodge et al., 1986; Rydell, 1966). This gives more precise measure of the forces at the hip, but is invasive and not applicable for studying joint forces in unaffected people. However, these data allowed the validation of models of the hip that estimate the forces acting on the articulation surface (Heller, et al., 2001).

The study of kinetics also provides valuable information on the outcome of hip replacements. Usually, an inverse dynamics approach combines force plate and kinematic data in order to obtain information on the distribution of force in the articulations, moments of force and powers produced by the different muscle groups. McCrory and colleagues (2001) found significantly lower ground reaction force and impulse in patients with THA compared to a control group. The authors did not, however, control for gender, type of prosthesis, or surgical approach. Also, the control group was approximately 32 years younger than the THA group. The authors justify this by wanting to compare the THA group with near ideal gait pattern. To this we could argue that differences observed could be the effect of the age difference, and not the hip replacement surgery. It is interesting to have a large group of patients with several different characteristics, thus allowing better generalization, but we believe it is important to control, or at least to consider such characteristics as confounding variables, for age, gender, type of replacement and surgical approach. In doing so, we can identify the probable cause of such variation in the patient's gait. Perron and colleagues (2000) compared the gait of a group of 18 patients with THA to a healthy group using 3D kinematics, kinetics and muscle activation. They found several impairments in the THA group such as a lower peak hip extension moment of force, lower hip extension moment at early push-off, lower hip angular velocity and absorption in the mid-stance phase, lower hip power generation at the late-stance phase, lower peak abduction moment of force in the

weight acceptance phase, and lower peak hip external rotation. They also showed that the knee and ankle were involved in gait adaptations 47 weeks after hip replacement. These observations have been used to identify specific variables in the current research. In this study, the participants were all women and the surgical approaches used were half posterior and half anterolateral. Again, this allowed good generalization, but potential significant differences can be overseen when combining two surgical approaches.

### *Stair Climbing*

While the majority of the research mentioned above concerns gait, walking is not the only activity THA patients encounter in their daily lives. Indeed, these patients could be confronted with staircases every day, and the ability to climb up and down stairs without pain could be desirable. Stair ascent and descent are demanding tasks for the hip joint. During stair descent, peak hip flexion moments of force can be up to one and a half times greater than during walking (Andriacchi et al., 1980). In a more recent study using 3D kinematics and kinetics, it has been shown that stair ascent produces greater hip sagittal moments than stair descent, while both tasks produced greater moments than level walking (Protopapadaki et al., 2007). THA participants with instrumented prostheses have been used to validate hip contact force algorithms including separate contributing muscle forces (Heller, et al., 2001).

Bergmann and colleagues (2001) also used instrumented prostheses to measure hip contact forces and moments of force. Their data showed that stair ascent and descent caused greater torsional moment at the hip than sitting, standing, and walking, whether it being at a slow, normal or fast pace. They speculated that this is caused by the fact that stair climbing does not occur as often as walking, and therefore is performed in a less optimized way. The

patients had an average of 238% of their bodyweight (BW) peak resultant contact force when walking at a normal pace, whereas stair ascent had a peak of 251% BW, and stair descent 260% BW.

Foucher and colleagues (2008) measured 3D kinematics and kinetics of a group of patients who had THA through a lateral and a posterior approach. They report reduced hip flexion, abduction, and internal rotation moments compared to normal participants. They also used their 3D kinematic and kinetic data as input in a musculoskeletal modeling program (SIMM, Santa Rosa, CA, USA) in order to estimate the hip contact force in bodyweights (BW). Peak hip contact forces neared statistical significance ( $p=0.055$ ) between their THA group ( $3 \pm 0.4$  BW) and controls ( $3.5 \pm 0.6$  BW). This peak contact force was significantly negatively correlated with the peak abduction moment in THA patients, suggesting that weak abductors could increase the load applied on the prosthesis. Mechanical testing has also shown that stair climbing results in an increase micro-movement, potentially influencing the stability of the prosthesis (Kassi et al., 2005).

As mentioned by Wells and colleagues (2007), stair climbing has the ability to highlight differences that might go unnoticed with gait analysis. It is therefore important to study stair climbing, as the prostheses undergo more stress for this movement. Nadeau and colleagues (2003) compared level walking to stair climbing in a group of healthy men over 40 years old, and they observed increased knee extension moment as well as power and hip extension power in stair climbing. As the body needs to rise against gravity when ascending stairs, these differences in the sagittal plane were expected. The authors also describe a concentric contraction of the abductors that raises the pelvis on the contralateral side, in order to clear the next step. They suggest that patients with weak abductors, for instance from hip replacement surgery, might have difficulty producing this movement.

Gluteus medius dysfunction, and consequently reduced hip abduction moment of force, has been associated with other impairments, such as the progression of ipsilateral medial knee osteoarthritis (Chang et al., 2005) and anterior knee pain (Brindle et al., 2003) during stair climbing. Sparing the gluteus medius muscle during hip replacement surgery might reduce the onset of such impairments and therefore increase the quality of life of patients.

## Methodology

### *Study design*

This study compares three groups: the first group consists of patients having undergone THA through an anterior approach (ANT), the second, patients having undergone THA through a lateral approach (LAT), and the third is an age- and weight-matched control group (CON). The THA participants were tested approximately 10 months post-surgery. The control group provides normative data for joint mechanics of this age group.

### *Participants*

Forty participants between 50 to 75 years old were recruited through the Ottawa Hospital, division of orthopedic surgery, on a voluntary basis through convenient sampling. All patients meeting the inclusion criteria in the previous year were contacted by telephone and, if they were willing to participate, were then screened for exclusion criteria. Recruitment stopped after twenty patients that had an anterior approach and twenty that had a lateral approach were recruited. Inclusion criteria were having undergone primary unilateral total hip arthroplasty for non-inflammatory degenerative osteoarthritis within the last year either through a lateral or anterior surgical approach and being able to walk and climb stairs. Exclusion criteria included bilateral hip replacement, hip replacement due to infection, fracture or failure of a previous prosthesis, concomitant surgical procedure during the surgery as well as any past or present condition that could alter gait (e.g stroke). A healthy age- and weight-matched control group was recruited from the general population of the Ottawa region. Before entering the study, the participants were screened by a research assistant, and subsequently recruited if eligible. The consent form was sent to them by mail

or e-mail. At the time of data collection, the researcher re-explained the procedure, and informed written consent was obtained. The surgeons did not participate in the recruitment and did not have knowledge of who accepted or refused participation in the study. The study has been approved by the Ottawa Hospital and the University of Ottawa research ethics boards and informed consent was obtained for all participants prior to the motion analysis.

### *Surgical Approach*

#### *Anterior Approach*

In the anterior approach, while the patient is lying supine, the surgeon performs a single straight incision starting slightly lateral and distal to their anterior superior iliac spine and ending slightly anterior to their greater trochanter (Matta et al., 2005). This access route uses the nervous interval between the superior and inferior gluteal nerves and the femoral nerve. The fascia is incised over the tensor in line with the incision. The interval between the tensor fascia lata and the sartorius is developed with blunt dissection, and the lateral hip capsule is exposed. The rectus femoris and sartorius are retracted medially. The lateral femoral circumflex vessels are clamped, cauterized, and transected. An L-shaped capsulectomy is performed and the hip is then dislocated anteriorly. The anterior and lateral flaps are tagged for subsequent repair. The hip is then dislocated anteriorly. After implantation of the prosthesis, the capsule tags are sutured and the fascia lata is closed with a running suture. In our group of twenty patients, seventeen surgeries were performed by the same surgeon and three by another surgeon.

### *Lateral Approach*

In the lateral approach, a straight incision is made directly over the greater trochanter, with equal cephalad and caudal distance from the tip of the greater trochanter, while the patient is lying in lateral decubitus (Mulliken et al., 1998). The fascia is then incised in between the bellies of the gluteus maximus and tensor fascia lata muscles. Blunt retractors are used to separate the anterior part of the gluteus medius. The combined tendon of the gluteus medius and vastus lateralis is then detached using electrocautery. The gluteus minimus is then divided in line with its fibers in order to access the capsule. An anterior capsulectomy is performed, and the hip is dislocated anteriorly by external rotation, flexion and adduction. After the implantation of the prosthesis, the gluteus minimus is reapproximated with heavy absorbable suture. The same type of suture is used to reapproximate the combined gluteus medius and vastus lateralis insertion to the posterior tendinous cuff. Three surgeons performed the twenty surgeries for the lateral group. Nine were done by the same surgeon that performed the 17 anterior approach surgeries; 6 were done by the same surgeon that performed the other three anterior approach surgeries, at the last five were done by another surgeon.

### *Materials and Equipment*

#### *Motion Recording*

The movements of the participants were captured with an infrared nine-camera motion analysis system (Vicon MX-13, Oxford Metrics, Oxford, UK) recording at 200 Hz (Figure 1). The calibration was done in two parts: first, a dynamic calibration was done with a three marker T-shaped wand (240 mm). It was waved in a continuous motion inside the

desired recording volume. Each camera must have captured at least 3000 frames with the three markers visible. This allowed establishing the position of each camera relative to the others. Second, a static calibration with an L-shaped frame (ErgoCal 14 mm) positioned the origin of the global coordinate system (shown in Figures 1 and 2). Forty-five reflective markers (14 mm diameter) were strategically placed on specific anatomical landmarks on the participants (Appendix B). These markers were used for joint angle calculation.

### *Ground Reaction Forces*

Up to four force plates (models OR6-7-1000 and OR6-6-2000, AMTI, Watertown, MA; model 9286B, Kistler Instruments Corp, Winterhur, Swtz) recorded ground reaction forces at 1000 Hz. The AMTI force plates were embedded in a walkway flush with the flooring. The Kistler force plates were mounted on the first and second stairs of a custom-made three stairs setup with side ramps (Figure 3). Each step had a 17.8 cm height and a 28 cm depth, following current construction norms (Government of Ontario, 2010).

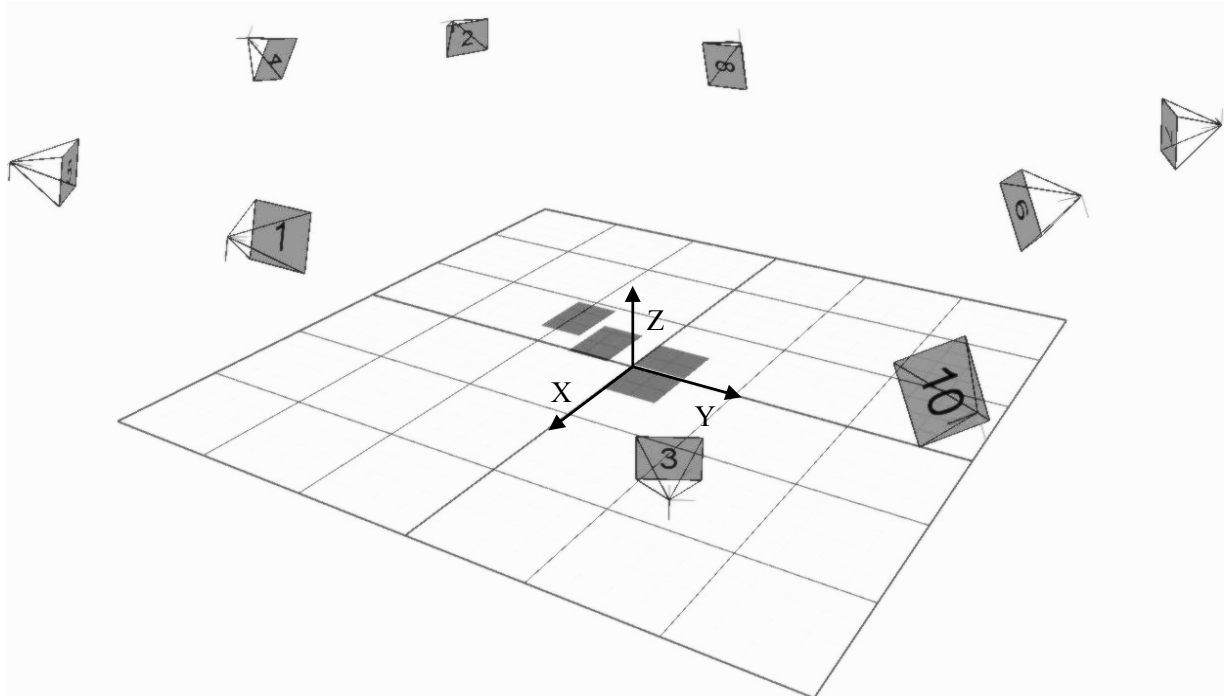


Figure 1. 3D camera setup with force plate position and system of axis.

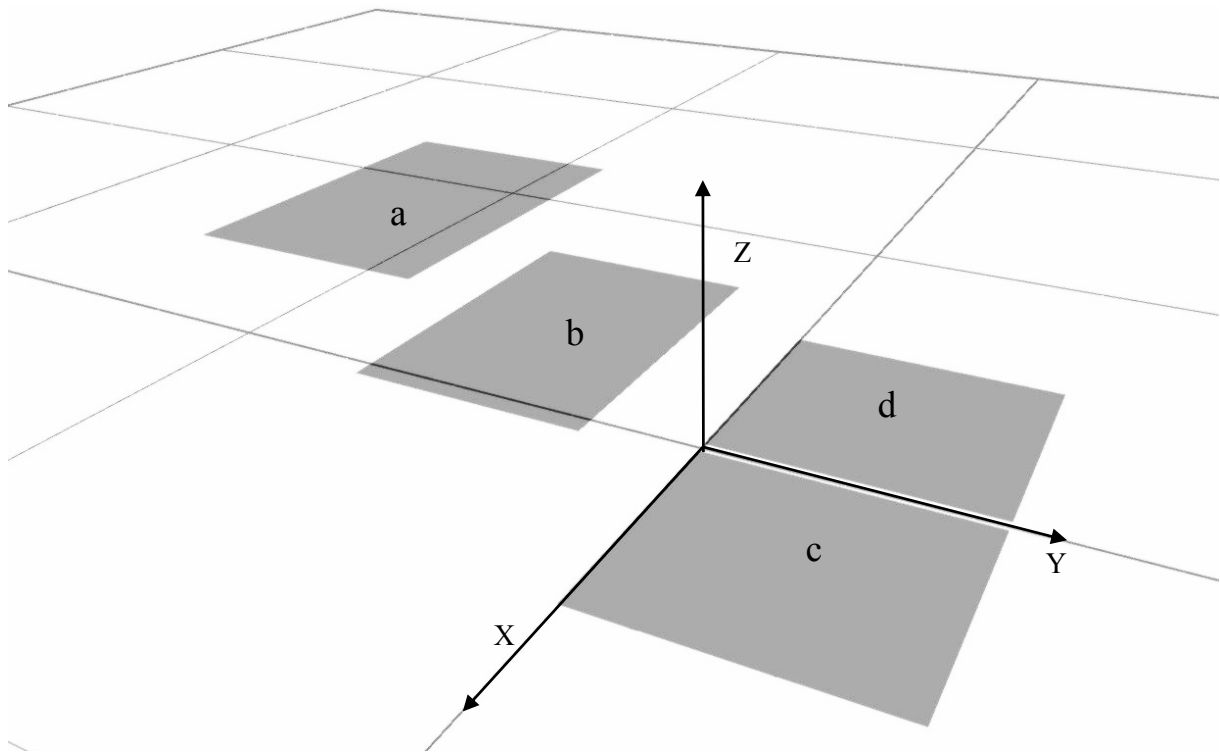


Figure 2. Force plates set-up. (a) & (b) Kistler 9286B; (c) AMTI OR6-7-1000; (d) AMTI OR6-6-2000. c is used for walking; c & d are used for sitting and standing; a, b & c are used for stair ascent and descent.

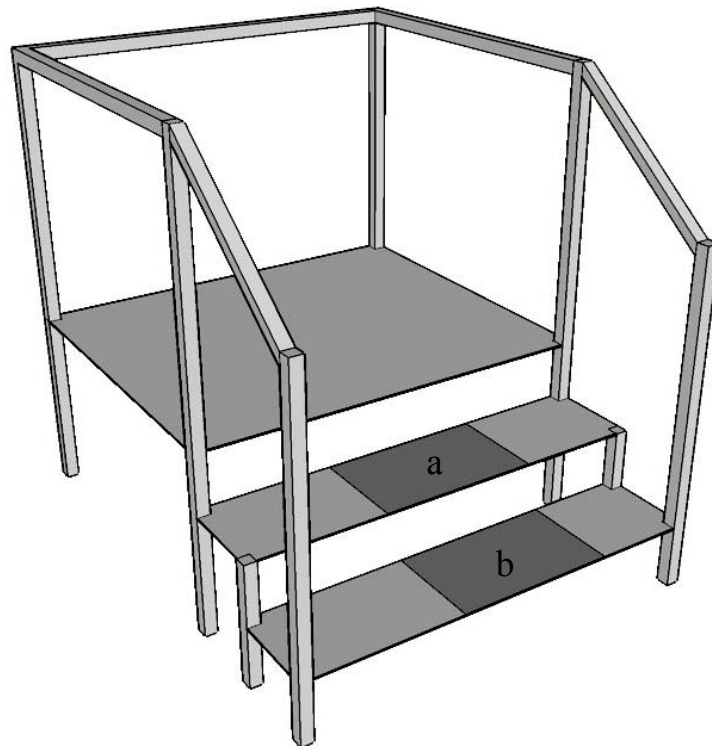


Figure 3. Stair apparatus. Kistler force plates (a & b) are on the second and first step.

## *Protocol*

Upon acceptance in the study, participants were sent a letter explaining, in common language, the experiment several days before coming to the laboratory. On the testing day, they were met in the parking lot and escorted to the laboratory. The research protocol was re-explained and any questions or concerns were answered before signing the consent form and commencing the testing. They filled out three questionnaires: the Western Ontario McMaster Osteoarthritic Index (WOMAC), the Short-Form 12 and the UCLA activity score. Participants then traded their clothes for special black tight clothes (shorts and t-shirt) that limit marker movement on the body and kept their own shoes. Anthropometric measurements of the participant were noted for subsequent use in the model (Table 1).

Table 1. Anthropometric measurements of the participants.

Measurement (units)	Measurement Description
Mass (Kg)	Weight of the participant
Height (cm)	Height of the participant
Leg length (cm)	Distance between anterior superior iliac spine and medial malleolus (leg fully extended)
Knee width (cm)	Medio-lateral width of the knee across the line of the knee axis when standing
Ankle width (cm)	Medio-lateral distance across the malleoli

The forty-five reflective markers were placed on specific bony landmarks with Velcro or double-sided tape, following a modified Helen Hayes marker set. The participants first performed a static trial in which they were asked to stand feet at shoulder width, arms in front parallel to the ground, and stay motionless. They then were asked to perform three tasks: walking, stair ascending and stair descending. At any time, the participant could rest. For each task, participants were allowed to practice until they were accustomed to the task. They were asked to perform at least six trials each of walking, stair ascent and descent.

### *Walking*

Participants were asked to walk at their normal pace and step on a force plate imbedded in the walkway without modifying their stride length. If it was noticed that they changed their gait to target the force plate or did not land in the middle of the force plate, the trial was discarded. In all, six successful trials were recorded: three with the operated leg landing on the force plate and three with the non-operated leg.

### *Stair Ascent and Descent*

Participants were asked to ascend the stairs at their own pace without using the handrail (for safety purpose only). Six trials were recorded, three of which the participant started climbing the staircase with the left foot and three with the right foot. For stair descent, participants were asked to descend the staircase at their own pace, again without using the handrail. Six trials were recorded, three starting with the left foot and three starting with the right foot.

### *Data Analysis*

#### *Kinematics*

Prior to calculation of the kinematics, the marker trajectories for each trial were filtered using a Woltring filtering routine, set at a mean square error of  $15 \text{ mm}^2$  (Woltring, 1986). Kinematics measures (displacement, velocity and acceleration, both linear and angular) were obtained by combining the 3D image of the movement and time. The kinematics were obtained using Vicon's Nexus software (v1.3) and a modified version of the Helen Hayes model, named University of Ottawa Motion Analysis Model (UOMAM), as illustrated in appendix A. This model was used to calculate joint centers of rotation and segment length based on the position of the skin markers. The linear and angular displacements, velocities

and accelerations of each segment, joint of the lower limbs and pelvis were calculated. The UOMAM has been developed for this study because the markers on the left and right anterior superior iliac spines (ASIS) often disappeared in peak hip flexion for participants with considerable abdominal fat, especially in the stair ascent task. The UOMAM uses two extra markers placed on the lateral aspect of the iliac crests: right iliac crest (RIC) and left iliac crest (LIC). If an ASIS marker disappears, the UOMAM automatically creates a virtual ASIS marker based on the position of the iliac crest marker and continues to calculate the hip joint center with this virtual marker.

The lower limbs are modeled as a rigid linked system with three degrees of freedom articulations. The hip joint center is calculated using regression equation following the method proposed by Davis III (1991). The knee and ankle centers of rotation were located in the middle of their respective lateral and medial markers. The pelvis angle was reported according to the global coordinate system, whereas the hip, knee, and ankle angle were reported relative to their local coordinate system, in relation to the segment above. A static trial was used in order to define the neutral angle of each articulation.

Gait events were identified within each trial in order to normalize the data by time. This allows averaging within and between participants. The variables were therefore reported in function of the percentage of the gait cycle. The events of interest were first ipsilateral foot-strike, contralateral foot-off, contralateral foot-strike, ipsilateral foot-off, and second ipsilateral foot-strike.

### *Kinetics*

The kinetic data were obtained with an inverse dynamics approach, and consist of the moments of force and powers. Three dimensional ground reaction forces obtained from the

force plates were filtered using a second order Butterworth low-pass filter set at 6 Hz and were combined to the kinematic data obtained from the camera system in order to calculate the internal moments and powers at each joint. These kinetic data were normalized by body mass to allow between subjects comparison. Each trial was cut and time-normalized to a 100% cycle and then averaged for the three trials. Trials were averaged for control group and each surgical approach groups.

### *Statistical Tests*

Multiple analyses of covariance (MANCOVA) were used to compare the variables between the three groups (ANT, LAT and CON). Age was a covariate as it was found to significantly differ between groups ( $p=0.013$ ). For each kinematic variable, a Bonferroni correction was used and the alpha level set at 0.0167 since three variables were extracted from each joint-plane combination (maximum, minimum, and range of motion). For kinetics, the alpha level was set at 0.025 since only the maximum and minimum value of each joint-plane combination was extracted. If a significant difference was found, post-hoc between groups pairwise comparisons were performed. The variables of interest are shown in Table 2.

Table 2. Description of variables of interest for walking, stairs ascent and descent.

Category	Joint	Description (unit)
Kinematics	Hip	Maximum angle (°)
		Minimum angle (°)
		Range of motion (°)
	Knee	Maximum angle (°)
		Minimum angle (°)
		Range of motion (°)
	Ankle	Maximum angle (°)
		Minimum angle (°)
		Range of motion (°)
Kinetics	Hip	Maximum moment (Nm/kg)
		Minimum moment (Nm/kg)
	Knee	Maximum moment (Nm/kg)
		Minimum moment (Nm/kg)
	Ankle	Maximum moment (Nm/kg)
		Minimum moment (Nm/kg)
	Hip	Maximum power (W/kg)
		Minimum power (W/kg)
	Knee	Maximum power (W/kg)
		Minimum power (W/kg)
	Ankle	Maximum power (W/kg)
		Minimum power (W/kg)

## Article

### *The Effect of Anterior or Lateral Surgical Approach in THA Patients on Gait Kinematics and Kinetics.*

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## Introduction

There are ongoing efforts to develop minimally invasive surgery for total hip arthroplasty (THA) (Bertin & Röttinger, 2004). However, some authors did not find any advantage in such approaches in terms of function when measured with standardized questionnaires (Harris hip score, WOMAC and SF-12), as well as operative time, blood loss, complication rate and length of hospital stay (Bennett, et al., 2006; de Beer et al., 2004; Ogonda et al., 2005). These results could be explained by the fact that these studies have solely looked at a mini-incision version of a traditional approach (a direct lateral or a posterior approach). Others have focused on developing a truly muscle sparing approach through the anterior aspect of the thigh (Keggi et al., 1994; Kennon, et al., 2003; Matta, et al., 2005). The anterior approach already has low reported dislocation rates (Sariali, et al., 2008; Siguier, et al., 2004), and could result in faster postoperative mobilization and function (Nakata, et al., 2009; Ward, et al., 2008).

Few studies have inquired in the biomechanics of patients after THA through an anterior approach. Maffiuletti et al. (2009) compared the anterior approach to the posterior approach in terms of spatiotemporal gait parameters, which include gait velocity, cadence, step and stride time, single and double support duration, support distance, and toeing out. At six months post-surgery, they found no difference between both THA groups during normal walking. Both groups, however, walked slower and took shorter steps compared to the control group when asked to walk at a faster pace. Mayr et al. (2009) went a step further and performed a prospective randomized study comparing gait parameters and kinematics of patients operated through either an anterior or anterolateral approach. They focused on early functional recovery, as patients performed the testing preoperatively, at six weeks and at

twelve weeks postoperatively. The anterior group revealed significant improvements in gait velocity, cadence and stride time. The anterior group had improvements in hip kinematics earlier (at six weeks) than the anterolateral group. They did not, however, have a matched control group, and did not actually compare both groups (such as with a mixed between-within analysis of variance). Klausmeier et al. (2010) also compared the anterior approach to the anterolateral approach. They measured gait parameters and kinematics as well as gait kinetics through inverse dynamics (moments, powers and forces) and isometric strength using an isokinetic dynamometer. They assessed the patient before, at six weeks and at 16 weeks after surgery. The results were slightly in favor of the anterior approach, with an absence of decrease hip maximum isometric abductor strength at six weeks and closer to normal peak external rotation moment at six and 16 weeks post-surgery.

The above-mentioned study had a relatively small sample size, reducing the statistical power and relative short-term follow-up after surgery. Our study compared the three-dimensional (3D) kinematics and kinetics of the lower-limbs of 40 THA patients operated on through an anterior approach (20) and a lateral approach (20), to an age-, height- and weight-matched control group during gait after ten months of the surgery. It is hypothesized that the anterior approach patients, because of the sparing of the gluteus medius and minimus, will have closer to normal hip kinematics and kinetics. As impairments at a certain articulation can affect other joints, we will look at the kinematics and kinetics of the knee and ankle as well. Again, the anterior group is expected to perform closer to normal knee and ankle kinematics and kinetics.

## Materials and Methods

### *Participants*

Sixty participants aged between 50 and 75 years old were recruited for this study. Forty of them were recruited retrospectively from the Ottawa Hospital after undergoing elective total hip arthroplasty by convenient sampling. Twenty of them had a lateral approach (LAT). Three different surgeons performed these surgeries (9/6/5). Twenty had an anterior approach (ANT). Two different surgeons performed these (17/3). A group of twenty healthy participants was recruited from the general population (CON). In order to be eligible for the study, THA patients must have had a unilateral THA due to osteoarthritis. Exclusion criteria for both THA groups were hip replacement due to a fracture, infection, or the failure of a previous implant. Patients were also excluded if they had a concomitant surgical procedure, previous surgery on any other lower limb joint or any other condition that could alter gait (i.e. stroke). Any potential participant with a Body Mass Index (BMI) of over 35 was also excluded. Institutional review board approval was obtained, and all participants provided informed consent. Patient's demographics are presented in Table 3.

Table 3. Participants' gender ratio, average age, weight, height, body mass index (BMI), and time of testing after surgery. Mean (SD).

Group	Female/Male (n)	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m <sup>2</sup> )	Time after THA (days)
LAT	10/10	66.2 (6.7)	77.2 (19.4)	168 (11)	27.2 (5.0)	323 (79)
ANT	14/6	60.5 (6.0)	77.3 (13.3)	165 (6)	28.5 (4.9)	291 (114)
CON	10/10	63.5 (4.4)	70.7 (14.2)	168 (9)	24.9 (3.5)	-

### *Surgical Approach*

Patients in the ANT group had, while lying supine, a single straight incision starting slightly lateral and distal to their anterior superior iliac spine and ending slightly anterior to

the greater trochanter (Matta, et al., 2005). This access route uses the nervous interval between the superior and inferior gluteal nerves and the femoral nerve. The lateral hip capsule is accessed between the sartorius and tensor fascia lata. An L-shaped capsulectomy is performed and the hip is dislocated anteriorly. Of the 20 patients, five patients were implanted a Stryker Accolade stem with Trident acetabular component. The remaining 15 had a Wright Medical Profemur stem with either a Lineage (n=8), Conserve Plus (n=6) or Dynasty (n=1) acetabular component.

Patients in the LAT group had a straight incision directly over the greater trochanter while lying in lateral decubitus position (Mulliken, et al., 1998). The fascia was incised between the gluteus maximus and tensor fascia lata muscle bellies. The anterior one third of the gluteus medius and the gluteus minimus were detached. The hip was accessed with an anterior capsulectomy and dislocation was done anteriorly. Of the 20 patients, 13 were implanted a Stryker Accolade stem with a Trident acetabular component. The remaining seven had a Wright Medical Profemur stem with a Conserve Plus acetabular component.

### *Motion Analysis Procedure*

Each participant underwent a two-hour motion analysis session at the University of Ottawa Human Movement Biomechanics Laboratory. Wearing a tight fitting suit, a total of 45 reflective markers were fixed to their body with either Velcro or double-sided tape, following a modified Helen Hayes model. Specific landmarks for measuring lower limb kinematics were: anterior and posterior superior iliac spines, thigh (approximately midway between the greater trochanter to knee center line), lateral and medial femoral condyles, shank (midway between knee center and lateral malleolus), lateral and medial malleoli, posterior aspect of calcaneus, and head of second metatarsal. A nine-camera infrared motion

analysis system (Vicon MX-13, Oxford Metrics, Oxford, UK) was used to track the markers during gait at a 200 Hz sampling frequency. The resulting 3D trajectories were filtered using a Woltring filtering routine set at a mean square error of 15 mm<sup>2</sup> (Woltring, 1986). A force plate (model OR-6-6-2000, AMTI, Watertown, MA, USA) imbedded in the floor recorded 3D ground reaction forces, which were subsequently filtered using a Butterworth 2<sup>nd</sup> order 6 Hz low-pass filter. The participants were asked to walk a distance of approximately ten meters at their preferred pace. Although they knew they had to hit the force plate in order to have a successful trial, they were instructed to ignore it and several practice trials were performed in order to avoid gait modifications. A total of three successful trials were collected for each leg. This paper, however, focuses on the data for the operated leg.

The lower limbs were modeled as a rigid linked system with three degrees of freedom articulations. Anthropometric measurements (height, weight, and leg length) were used to measure the hip joint center location (Davis III, et al., 1991). The knee joint center was located at the midline of the lateral and medial femoral condyle markers. The ankle was located similarly, at the midline of the lateral and medial malleoli. The pelvis 3D angles were reported in relation to the global coordinate system, whereas the hip, knee, and ankle 3D angles were reported according to the relative position of their proximal and distal segment. A static standing trial was used as a reference for the neutral angle. The resulting data were normalized by time, from the foot strike on the force plate to the ipsilateral foot strike (100% gait cycle). An inverse dynamics approach was used in order to obtain lower limb 3D kinetics (moments of force and powers). Kinetic data were normalized by time and bodyweight in order to allow inter-participant comparison. The variables analyzed included peak angles and range of motion (ROM) for kinematics, as well as peak moments of force

and powers for kinetics. These variables were extracted within each trial and averaged for the three trial of each participant.

### *Statistical Analysis*

It was found that the groups did not differ and therefore were well matched for height ( $p=0.452$ ) and weight ( $p=0.326$ ). However, age was found to be significantly different between groups ( $p=0.013$ ). Hence, we included age as a covariate in the statistical analysis. A total of 12 multiple analyses of variance (MANCOVA) were run on the data, which was grouped by type of variable (angle, moment of force and power) and articulation of interest (hip, knee, and ankle). A Bonferroni correction was used in order to reduce the chances of a type I error. For kinematic data, the alpha level was adjusted at 0.017, since three variables were extracted from each joint-plane combination (maximum angle, minimum angle and ROM). For kinetics, the alpha level was adjusted at 0.025, since two variables were extracted from each joint-plane combination (maximum and minimum moment and power). If the main effect for the MANCOVA was significant, pairwise post-hoc comparison between groups were looked at.

## **Results**

Both THA groups had anomalies in their gait as compared to the control group (Table 4). The LAT group showed reduced hip flexion at foot strike ( $p=0.001$ ), as well as a reduced peak hip extension ( $p<0.001$ ) during mid-stance. The ANT group also had reduced peak hip extension ( $p=0.007$ ) at mid-stance. Consequently, both THA groups showed reduced hip ROM in the sagittal plane ( $p<0.001$  for both groups vs. CON). In the frontal plane, both groups had reduced peak hip adduction angle, but only the ANT group was significantly

reduced compared to the control group (ANT:  $p=0.007$ ; LAT:  $p=0.088$ ). Both groups had reduced peak hip abduction moment compared to the control group (ANT:  $p<0.001$ ; LAT:  $p=0.011$ ), and the ANT group's peak moment was even lower than the LAT group's ( $p=0.008$ ). The LAT group had a higher peak internal rotation ( $p=0.002$ ) near ipsilateral foot-off (I-FO). Both groups showed a reduced peak hip external moment (ANT:  $p<0.001$ ; LAT:  $p=0.014$ ).

At the knee joint, the LAT group had lesser extension during mid-stance compared to the control group ( $p=0.003$ ). Both the ANT ( $p<0.001$ ) and LAT ( $p=0.001$ ) groups had reduced peak flexion moment of force in late stance (30-60% gait cycle) in comparison to the control group. However, the ANT group had a higher peak knee extension moment at contralateral foot-off (C-FO, which occurs on average at 15% of the gait cycle, compared to the LAT group ( $p=0.009$ ), and the control group (not significantly,  $p=0.336$ ). At the ankle, the ANT group had a reduced peak plantar flexion moment versus the control group ( $p=0.006$ ).

The ANT group showed a reduced pelvis peak obliquity at C-FO ( $p=0.009$ ). However, this group also had a greater peak obliquity at I-FO, occurring around 65% of the gait cycle ( $p=0.004$  vs. LAT). Consequently, the ANT group had a closer to normal pelvis obliquity ROM ( $8.3 \pm 2.2^\circ$ ) compared to the CON group ( $9.4 \pm 3.3^\circ$ ). The LAT group had a pelvis angle ROM of  $7.5 \pm 2.1^\circ$ , which was, however, not significantly different from the CON group ( $p=0.179$ ). The difference between positive and negative peak pelvis obliquity angle was  $0.34 \pm 2^\circ$  for the CON group,  $0.91 \pm 2^\circ$  for the LAT group and  $1.89 \pm 2.4^\circ$  for the ANT group. The ANT group was significantly different from both the CON ( $p=0.005$ ) and LAT ( $p=0.001$ ) groups. The peak anterior tilt was  $3.7 \pm 0.6^\circ$  for the ANT group, although not significantly different ( $p=0.189$ ) from the CON group ( $2.2 \pm 0.6^\circ$ ). The LAT group had a

peak anterior tilt of  $2.9 \pm 0.6^\circ$ . The sagittal plane kinematics of the hip, knee and ankle are shown in Figure 4a, 4c and 4d.

Table 4. Kinematics, kinetics, and gait parameters during walking. Mean (SD).

Variable	CON	LAT	ANT
<b>Angles (<math>^\circ</math>)</b>			
Pelvic obliquity at contralateral foot-off †	4.9 (2.0)	3.9 (1.9)	3.2 (1.7)
Pelvic obliquity at ipsilateral foot-off ‡	-4.5 (1.9)	-3.0 (1.4)	-5.1 (1.5)
Hip flexion at ipsilateral foot-strike *	33.4 (4.3)	28.0 (4.4)	30.6 (4)
Hip peak extension *†	-15.2 (3.2)	-10.1 (3.4)	-12.0 (3)
Hip flexion/extension range of motion *†	51.0 (4.3)	41.1 (4.7)	44.8 (5.1)
Hip peak adduction †	9.5 (2.8)	7.6 (2.5)	7.0 (2.4)
Hip int/external rotation at ipsilateral foot-off *	-3.6 (4.3)	0.7 (3.5)	-0.1 (4.0)
Knee peak extension at mid-stance *	0.8 (4.4)	5.6 (4.8)	2.8 (4.2)
Ankle peak dorsiflexion *†	10.0 (3.6)	14.3 (3.1)	13.9 (3.9)
<b>Moments (Nm/kg)</b>			
Hip peak abduction *†‡	-0.90 (0.14)	-0.75 (0.17)	-0.58 (0.14)
Hip peak external rotation *†	-0.16 (0.05)	-0.11 (0.06)	-0.09 (0.04)
Knee peak extension ‡	-0.43 (0.19)	-0.30 (0.19)	-0.55 (0.19)
Knee peak flexion at mid-stance*†	0.35 (0.16)	0.16 (0.18)	0.11 (0.14)
Ankle peak plantar flexion †	-1.40 (0.13)	-1.35 (0.10)	-1.29 (0.09)
<b>Power (W/kg)</b>			
Hip peak generation	1.57 (0.32)	1.14 (0.43)	1.31 (0.36)
Hip peak absorption ‡	-0.61 (0.23)	-0.43 (0.22)	-0.70 (0.21)
<b>Gait parameters</b>			
Velocity (m/s)	1.29 (0.15)	1.14 (0.21)	1.31 (0.15)
Cadence (steps/min) ‡	105.1 (9.5)	102.1 (11.5)	112.1 (8.3)

\* Significant difference between the CON and the LAT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers,  $p \leq 0.05$  for gait parameters).

† Significant difference between the CON and the ANT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers,  $p \leq 0.05$  for gait parameters).

‡ Significant difference between the LAT and the ANT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers,  $p \leq 0.05$  for gait parameters).

The LAT group absorbed less hip power in mid-stance ( $p=0.011$  vs. ANT) and generated less power at the hip during the push-off phase, although the difference was not significant ( $p=0.04$  vs. CON). The hip frontal plane kinematics and kinetics are shown in Figure 4b.

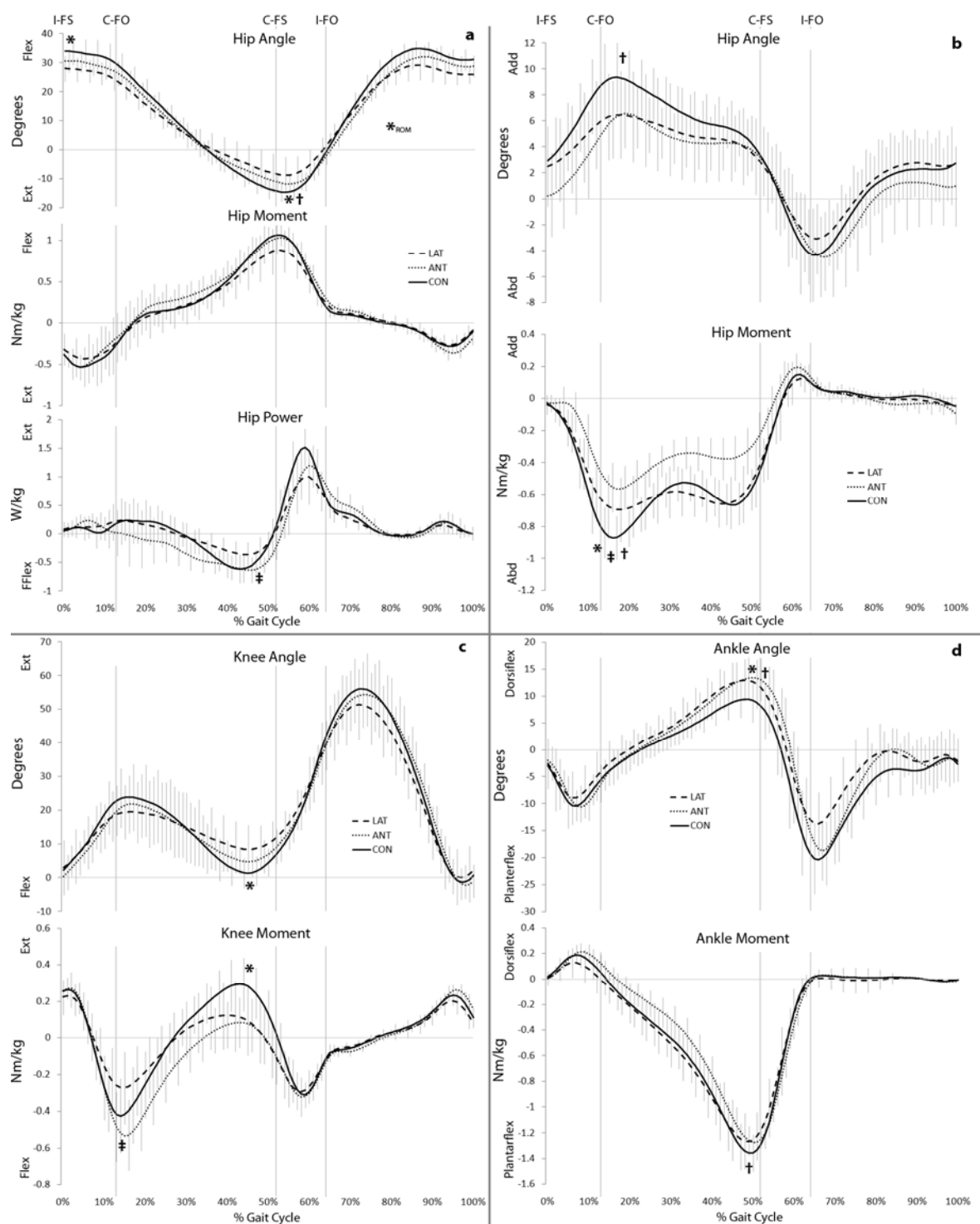


Figure 4. a: Hip sagittal plane angle, moment and resultant power. b: Hip frontal plane angle and moment. c: Knee sagittal plane angle and moment. d: Ankle sagittal plane angle and moment. All during a gait cycle (foot-strike to foot-strike). I-FS: initial foot-strike; C-FO: contralateral foot-off; C-FS: contralateral foot-strike; I-FO: ipsilateral foot-off. \*Significant difference between the LAT and CON groups. †Significant difference between ANT and CON groups. ‡ Significant difference between ANT and LAT groups. ( $p=0.017$ )

Regarding spatiotemporal gait parameters, the ANT group had a walking speed of  $1.31 \pm 0.14$  m/s, slightly more than the CON group ( $1.29 \pm 0.15$  m/s), whereas the LAT group walked with a speed of  $1.14 \pm 0.21$  m/s, which was almost significantly different from the CON group ( $p=0.079$ ). This rather elevated gait speed for the ANT group was the result of an increased cadence, which was significantly ( $p=0.049$ ) higher than the LAT group.

## Discussion

It was hypothesized that patients undergoing THA through a muscle sparing anterior approach would show closer to normal gait kinematics and kinetics than other operated through a lateral approach. To verify this, hip, knee and ankle kinematics and kinetics were obtained with 3D motion analysis for 20 patients for each approach and compared to an age- and weight-matched control group. The results obtained from this gait analysis revealed several gait abnormalities between both THA groups and the control group. Some of the results are in opposition to what we had anticipated. Most importantly, the ANT group not only showed a reduced hip abduction moment of force compared to the control group, but also compared to the LAT group. This finding raises several questions, as hip abduction during single-legged stance in gait is mainly created by the gluteus medius and minimus muscles (Clark & Haynor, 1987), and their anterior third is partly detached when using a lateral approach, whereas the anterior approach does not affect these muscles. These results contradict those of a recently published study where a group of 12 individuals having undergone THA through an anterior approach had a peak hip abductor moment of  $0.81 \pm 0.22$  Nm/kg at only 16 weeks after surgery (Klausmeier, et al., 2010). The authors also had a group of 11 patients having undergone THA through an anterolateral approach, and they

showed a peak hip abduction moment of  $0.77 \pm 0.12$  Nm/kg, which is very similar to the LAT group in the current study.

According to a cadaveric study by Meneghini et al. (2006), the anterior approach does cause some muscle damage. The gluteus medius was damaged in two of the six specimens with an average of 2.62% of its musculature area. The gluteus minimus also sustained damage in four of the specimens with an average of 8.48% of its musculature area. Finally, there was muscle damage to the tensor fascia lata (TFL) in all six of their specimens. The amount of damage was on average 31.32% of its musculature area.

Although the gluteus medius and gluteus minimus are recognized as the main hip abductors, respectively accounting for 59 and 20% of the hip abductor muscle cross-sectional area (Clark & Haynor, 1987), the TFL also contributes to hip abduction (Neumann, 2010). Some even suggest that it is the main abductor (Gottschalk et al., 1989). It is possible that the potential damage sustained caused the observed hip abduction moment reduction in the ANT group. As mentioned by Neumann et al. (2010), muscle action in the anatomic position is now well understood, but not when the body is moving. Our results suggest that the TFL might play a more important role in abduction when the hip is slightly flexed. The gluteus medius has three sections (posterior, middle and anterior) and contracts in a phasic manner (Soderberg & Dostal, 1978). The damage sustained to the anterior part of the gluteus medius through the lateral approach could explain the reduced hip abduction moment. Unfortunately, we did not measure electromyographic activity of the muscles surrounding the hip. We therefore cannot assess muscle function and associate surgical approaches to specific altered muscle activity.

The abductor sparing anterior approach did not allow the patients to regain normal frontal plane hip kinematics and kinetics, as expected. Klausmeier et al. (2010) observed

smaller frontal plane hip range of motion in their anterior ( $9.7 \pm 2.8^\circ$ ) and anterolateral ( $8.5 \pm 2.5^\circ$ ) groups compared to their control group ( $13.6 \pm 5.6^\circ$ ), but they did not provide peak angles. These results are most likely due to their short assessment time after surgery (16 weeks) compared to ours (10 months).

The ANT group displayed significantly reduced pelvis obliquity at contralateral foot-off compared to the control group. This difference was, however, small ( $1.7^\circ$ ) and might not be clinically significant. At ipsilateral foot-off, the same variable was significantly different between the ANT and the LAT group ( $1.9^\circ$ ). Again, a difference of two degrees might not be clinically significant. Neither group had pelvis kinematics concur with a Trendelenburg gait, where the pelvis drops on the non-operated side (Hardcastle & Nade, 1985), nor a Duchenne gait, where the pelvis rises on the non-operated side and the trunk leans over to the operated side (Schröter et al., 1999).

The ANT group did achieve closer to normal sagittal plane kinematics at the hip than the LAT group. Their hip was slightly more extended at foot strike than the LAT group, though it did not reach the extension of the control group. Again, this is surprising, as we would have expected that the surgery, being on the anterior aspect of the hip joint, would have limited hip extension for the ANT group. It therefore appears that the anterior approach does not increase hip contracture in the sagittal plane compared to the lateral approach. The range of motion in that plane did not return to normal for either THA groups. Both groups, however, have greater sagittal plane ranges of motion than earlier assessments from other studies (Klausmeier, et al., 2010; Mayr, et al., 2009). This demonstrates that patients are still improving their gait 10 months after surgery, regardless of the surgical approach.

The differences found at the knee and ankle joints are indicators of gait adaptations from the surgery. Similar studies (Klausmeier, et al., 2010; Mayr, et al., 2009) have only

looked at the hip and could have missed important information on how the patients adapt their gait after surgery. The LAT group had a more flexed knee and the ankle had increased dorsiflexion during mid-stance. These results are similar to what Perron et al. (2000) observed in a group of 18 women having undergone THA with either a posterior or anterolateral approach (equally represented). Their analysis indicated that the reduced hip extension at early push-off was significantly correlated with an increased knee flexion and ankle dorsiflexion. Although both our THA groups had significantly increased ankle dorsiflexion, only the LAT group had significantly less knee extension during mid-stance. Our results are also similar to those of this study in regards to the knee moments. Indeed, both our THA groups exhibited a reduced peak knee flexion moment during mid-stance. However, our ANT group had a higher peak knee extension moment during the loading phase, suggesting adequate functioning of the quadriceps muscles.

As for spatiotemporal parameters, the ANT group walked slightly faster than the control group, whereas the LAT group was slightly slower, and had a higher cadence. The values for gait velocity of our groups are similar to those of healthy population (Bendall et al., 1989; Hageman & Blanke, 1986; Prince et al., 1997; Waters et al., 1988). A recent study comparing gait parameters of the anterior and the posterior surgical approaches for THA reported higher values for both gait velocity (anterior: 1.35 m/s; posterior: 1.39 m/s; controls: 1.44 m/s) and cadence (anterior: 114.7 steps/min; posterior: 116.7 steps/min; controls: 116.2 steps/min) at self-selected speed (Maffiuletti, et al., 2009). They had 17 participants in each group, who were of similar height and weight. The only considerable difference was age, as their participants were older and assessed earlier postoperatively (6 months). This difference could be due to the methodology, as Maffiuletti et al. (2009) used an instrumented mat, whereas we used motion capture with skin markers. Our patients might have been affected

by the more invasive procedure: wearing special clothing, having markers on their body and having to land on the force plate. Regardless, they did not find any significant difference between surgical approaches using these variables. This is not surprising, as gait parameters only represent the final outcome of gait, and do not provide information on joint coordination nor force production and distribution (Lamontagne et al., 2009).

There are some limitations to this study. For example, the gender ratio is unequal: the increased number of females in the ANT group could have skewed the results. Also, the ANT group was assessed earlier than the lateral group, but the difference was not significant, and both groups were approaching full recovery from the procedure at that time. The ANT group was younger, but we have controlled this by including age as a covariate in our statistical analysis. Finally, we did not perform preoperative motion analysis. It is possible that preoperative function could be one of the main factors influencing postoperative function (Foucher, et al., 2007; Ward, et al., 2008). This study's strengths include a rather large sample size for this type of study, as well as a thorough gait analysis, including the knee and ankle articulations. It also benefits from an age-, weight- and height-matched control group. The results raise questions concerning how muscles produce an adequate abductor moment during gait, as the anterior group had lower values than both the lateral and control group. The tensor fascia lata is the only abductor that could be damaged with an anterior approach (Meneghini et al., 2006), and it could contribute to a larger amount of hip abduction moment than we think. Future work should include electromyography of the abductor muscles, ideally with fine wire EMG, allowing the differentiation of the three sections of gluteus medius. In conclusion, 10 months after THA, neither groups achieved similar gait kinematics and kinetics of the control group. This study did not demonstrate superior kinematic and kinetic data for either surgical approach.

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## Article

### *Does the Anterior Approach for Total Hip Arthroplasty Better Restore Stair Climbing Gait Mechanics?*

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## Introduction

The number of hip replacements is constantly increasing in Canada, and patients are getting younger. According to the Canadian Joint Replacement Registry (2009), the highest 10-year increase in males was in the 45-54 years old age group (140%). In females, the highest increase was in the 85+ age group (105%), but the second highest was the 55-64 years old age group (94%). As the male patients' age decreases, the expectations of functional outcome of the prostheses are increasing. Patients now expect to be able to efficiently perform activities of daily living (ADL) (Crowninshield, et al., 2006). However, it has been shown that gait anomalies persist, even ten years after surgery (Bennett et al., 2008). Some ADL, such as stair climbing, are more demanding than walking (Protopapadaki, et al., 2007), and can therefore give valuable insight in the performance of a hip prosthesis. Recently, it has been shown that THA patients had lower hip adduction and external rotation moments of force one year after the surgery when walking (Foucher, et al., 2008). Another recent study (Shrader et al., 2009) reported lower hip extension in stair ascent, as well as lower hip peak abduction moment of force for stair descent three months after THA.

As surgical approach can influence the functional outcome of this procedure, efforts have been made in order to develop less invasive approaches, such as the anterior approach (Keggi, et al., 1994; Kennon, et al., 2003; Matta, et al., 2005). This approach allows implantation without any sectioning of the muscle and tendons surrounding the hip, increasing postoperative hip stability (Nakata, et al., 2009) and lowering complication rates (Kennon, et al., 2003). The above-mentioned studies by Shrader et al. (2009) and Foucher et al. (2008) had patients operated through a lateral and a posterior approach. Concerning the anterior approach, a recent study (Maffiuletti, et al., 2009) measured gait parameters, which

can only give limited information (Lamontagne, et al., 2009). Only the study by Mayr et al. (2009) measured gait kinematics from a group of patients operated through an anterior approach. However, they did not measure kinetics, did not have a properly matched control group and only analyzed gait.

The purpose of this study is to determine the effect of surgical approach on lower-limb joint mechanics during stair ascent and descent by comparing three-dimensional (3D) kinematics and kinetics (moment of force and power) of the hip, knee and ankle of two groups of THA patients (lateral and anterior approach) to those of a healthy control group. Since the anterior approach spares the hip abductors, it is hypothesized that the patients operated through an anterior approach will have closer to normal hip abductor and internal rotation angles and moments, as well as other adaptations at the other articulations.

## **Material and Methods**

### *Participants*

A total of 60 participants between the age of 50 and 75 were recruited for this study. Twenty had a THA by means of a lateral approach (LAT), 20 had a THA by means of an anterior approach (ANT), and 20 were control participants. For the LAT group, three surgeons performed the surgeries (9/6/5). For the ANT group, two surgeons performed the surgeries (17/2). All THA patients were recruited in a retrospective convenient sampling method. Patients who had hip replacement due to an infection, a fracture, or the failure of a previous implant were excluded from the study. Patients were also excluded if they had a concomitant surgical procedure, previous surgery on any other lower limb joint or any other condition that could alter gait (i.e. stroke). Patients with a Body Mass Index (BMI) of over

35 were also excluded. The demographics of the three groups are shown in table 5. The institution's research ethics board approved the protocol, and informed consent was obtained for all participants.

Table 5. Participants' gender ratio, average age, weight, height, body mass index (BMI), and time of testing after surgery. Mean (SD).

Group	Female/Male (n)	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m <sup>2</sup> )	Time after THA (days)
LAT	10/10	66.2 (6.7)	77.2 (19.4)	168 (11)	27.2 (5.0)	323 (79)
ANT	14/6	60.5 (6.0)	77.3 (13.3)	165 (6)	28.5 (4.9)	291 (114)
CON	10/10	63.5 (4.4)	70.7 (14.2)	168 (9)	24.9 (3.5)	-

### *Surgical Approach*

For the LAT group, a direct lateral approach was used (Mulliken, et al., 1998). While lying in the lateral decubitus position, a straight incision was made directly over the greater trochanter. The fascia was incised between the tensor fascia lata and gluteus maximus bellies. The anterior third of the gluteus medius and gluteus minimus was detached. The hip joint was then accessed through an anterior capsulectomy. The hip was dislocated anteriorly. Thirteen patients had a Stryker Accolade stem with a Trident cup implanted. The remaining seven had a Wright Medical Profemur stem with a Conserve Plus cup. The gluteus medius and gluteus minimus were repaired using heavy absorbable suture.

For the ANT group, a single straight incision started slightly lateral and distal to the anterior superior iliac spine and ended slightly anterior to the greater trochanter (Matta, et al., 2005). This internervous approach is located medially from the superior and inferior gluteal nerves and laterally from the femoral nerve. The lateral hip capsule was accessed through the interval between the tensor fascia lata and the sartorius. The sartorius and rectus femoris were reflected medially. An L-shaped capsulectomy was performed. The hip was dislocated anteriorly, usually prior to the neck osteotomy. Five patients had a Stryker Accolade stem

with Trident cup implanted. The remaining 15 had a Wright Medical Profemur stem with either a Lineage (n=8), Conserve Plus (n=6) or Dynasty (n=1) acetabular component.

### *Motion Analysis Procedure*

Three-dimensional kinematics were obtained using a nine-camera infrared motion analysis system (Vicon MX-13, Oxford Metrics, Oxford, UK) sampling at 200 Hz. Trajectories were filtered using a Woltring filtering routine with a mean square error of 15 mm<sup>2</sup> (Woltring, 1986). The cameras were positioned around a three-step staircase on which two force plates (Model 9286BA, Kistler Instruments Corp, Winterhur, Swtz) were placed on the first and second step. Two additional force plates (Model OR6-6-2000, AMTI, Watertown, MA, USA) were set flush to the floor at the bottom at the staircase. The ground reaction forces were filtered using a Butterworth 2<sup>nd</sup> order 6 Hz low-pass filter. The staircase was build accordingly to the governing Building Code Act (Government of Ontario, 2010), with a height of 17.8 cm, a depth of 28.0 cm and a width of 91.5 cm.

A modified Helen Hayes marker set with 45 markers was used to calculate 3D joint kinematics of the lower limbs and pelvis. Markers used for the lower limbs include: anterior and posterior superior iliac spines, thigh (approximately midway between the greater trochanter to knee center line), lateral and medial femoral condyles, shank (midway between knee center and lateral malleolus), lateral and medial malleoli, posterior aspect of calcaneus, and head of second metatarsal. The angles are reported according to their local joint coordinate system, relative to a static standing trial. Anthropometric measurements (height, weight, and leg length) were used to measure the hip joint center location (Davis III, et al., 1991). The lower body was modeled as a rigid linked body. Knee and ankle joint centers were located at half the distance between the corresponding medial and lateral markers.

Angles are reported in relation to their respective proximal and distal segment's local coordinate systems, with a static trial serving as reference for neutral angle (i.e. 0°).

Three-dimensional hip, knee and ankle moments of force and powers were obtained with an inverse dynamics approach and normalized by weight. Kinematics and kinetics were normalized by time for a complete gait cycle (100%) from foot strike on the first step to the next ipsilateral foot strike (third step) for stair ascent and from foot strike on the second step to the ipsilateral foot strike on the ground for stair descent. Each patient performed at least three trials of stair ascent and descent, starting with each leg, for a total of six trials. They were instructed to ascent and descent in a step-over-step manner and to use the pace they would normally use, without using the handrail (only present for safety purposes). Several practice trials were performed to ensure that the participants were comfortable with the task. All specific variables were extracted for each trial, and then averaged for the three trials of each participant. A grand ensemble average was then calculated for each group.

### *Statistical Analysis*

A series of ANOVA on demographic data indicated that the groups did not differ and were indeed matched for height ( $p=0.452$ ) and weight ( $p=0.326$ ), but not age ( $p=0.013$ ). Therefore, we included age as a covariate in the analysis of the kinematics and kinetics variables. Variables were grouped by type (angle, moment of force and power) and articulation (hip, knee, and ankle) for a total of 12 multivariate analyses of covariance (MANCOVA). The alpha level for the MANCOVAs and subsequent post-hoc analyses were adjusted with a Bonferroni correction: kinematics variables was adjusted to  $\alpha=0.017$ , as three variables were extracted for each joint and plane combination (maximum angle, minimum angle and range of motion). Similarly, the alpha level of kinetic data was adjusted to

$\alpha=0.025$ , as the maximum and minimum value of each joint and plane combination were extracted. If the MANCOVA was found to be significant, pairwise comparisons between groups were observed.

## Results

As shown in Table 6, the LAT group scored lower on the WOMAC than the CON group for pain ( $p=0.025$ ), stiffness ( $p=0.004$ ) and function ( $p=0.002$ ), whereas the ANT group only scored lower on function ( $p=0.037$ ). The MANCOVAs revealed several differences in 3D joint kinematics and kinetics for both THA groups. (Table 7 – Stair ascent; Table 8 – Stair descent).

Table 6. WOMAC scores.

Category	CON	LAT		ANT	
		Mean (SD)	p-value vs. CON	Mean (SD)	p-value vs. CON
Pain	97 (6.8)	88 (13.4)	0.025*	91.2 (10)	0.351
Stiffness	91.3 (15.2)	73.8 (17.2)	0.004*	78.9 (16.7)	0.060
Function	96.9 (6.2)	87.1 (9.9)	0.002*	89.8 (9.8)	0.037*

\* Indicates a significant difference with the control group ( $p \leq 0.05$ ).

### *Stair Ascent*

Both the ANT and the LAT groups showed gait patterns different from the control participants. The ANT group had greater hip extension angle than the control group accompanied by a greater hip flexion moment of force. The LAT group showed a more abducted hip angle during the stance phase, a reduced frontal plane range of motion (Figure 5), as well as altered transverse plane kinematics at the knee (more external rotation at toe-off and less range of motion) and the ankle (more internal rotation during stance). The LAT group also had lower peak hip internal rotation moment of force compared to the control group.

Finally, both the ANT ( $p=0.023$ ) and LAT ( $p=0.015$ ) group had reduced power generated at the hip compared to the control group. At the knee, the ANT group surprisingly had a higher generated power than the LAT group ( $p=0.002$ ).

Table 7. Kinematics and kinetics during stair ascent. Mean (SD).

Variables	CON	LAT	ANT
<b>Angles (°)</b>			
Hip peak flexion	69.3 (5.3)	64.3 (6.3)	64.1 (6.8)
Hip peak extension *	5.9 (5.3)	3.1 (3.5)	1.4 (5.1)
Hip peak adduction in stance †	10.5 (4.1)	6.5 (3.9)	7.1 (3.9)
Hip add/abduction range of motion †	16.2 (4.6)	11.4 (3.1)	12.9 (4.1)
Ankle peak external rotation in stance †	-23.16 (3.9)	-17.9 (5.6)	-21.4 (6.3)
<b>Moments (Nm/kg)</b>			
Hip peak flexion *	0.36 (0.2)	0.41 (0.1)	0.53 (0.2)
Hip peak internal rotation †	0.22 (0.1)	0.13 (0.1)	0.16 (0.1)
<b>Power (W/kg)</b>			
Hip peak generation *†	1.35 (0.3)	1.04 (0.3)	1.07 (0.4)
Knee peak generation ‡	1.63 (0.5)	1.21 (0.4)	1.86 (0.5)

\* Indicates a significant difference between the control and the ANT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers).

† Indicates a significant difference between the control and the LAT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers).

‡ Indicates a significant difference between the LAT and the ANT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers).

### *Stair Descent*

Both THA groups had reduced peak hip flexion. The ANT group had a lower peak hip abduction moment during the transition from single- to double-legged support (Figure 6), compared to both control ( $p < 0.001$ ) and LAT group ( $p = 0.014$ ). The LAT group showed reduced peak knee extension moment at that same time ( $p = 0.007$  vs. CON). Both ANT ( $p = 0.022$ ) and LAT ( $p = 0.015$ ) groups had reduced peak hip power compared to the control participants. Only the LAT group had reduced peak absorption power ( $p = 0.002$  vs. CON;  $p = 0.013$  vs. ANT).

Table 8. Kinematics and kinetics during stair descent. Mean (SD).

Variable	CON	LAT	ANT
<b>Angles (°)</b>			
Hip peak flexion *†	43.2 (5.6)	37.8 (5.3)	37.9 (5.2)
Hip peak extension	12.1 (4.6)	8.7 (4.4)	8.3 (4.2)
Hip external rotation in stance	-9.2 (5.1)	-5.3 (4.8)	-5.2 (4.9)
<b>Moments (Nm/kg)</b>			
Hip peak abduction *‡	-0.90 (0.26)	-0.80 (0.32)	-0.55 (0.18)
Hip peak internal rotation *	0.11 (0.05)	0.07 (0.06)	0.05 (0.04)
Knee peak extension †	-0.78 (0.29)	-0.48 (0.22)	-0.65 (0.28)
<b>Power (W/kg)</b>			
Hip peak generation *†	0.77 (0.27)	0.52 (0.18)	0.61 (0.25)
Knee peak absorption †‡	-3.35 (0.70)	-2.50 (0.70)	-3.32 (0.69)

\* Indicates a significant difference between the control and the ANT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers).

† Indicates a significant difference between the control and the LAT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers).

‡ Indicates a significant difference between the LAT and the ANT group ( $p \leq 0.017$  for angles;  $p \leq 0.025$  for moments and powers).

## Discussion

It was hypothesized that patients undergoing THA through a muscle sparing anterior approach would show closer to normal stair ascent and descent kinematics and kinetics than other operated through a lateral approach. To verify this, hip, knee and ankle kinematics and kinetics were obtained with 3D motion analysis for 20 patients for each approach while performing these tasks and compared to an age- and weight-matched control group.

### *Stair Ascent*

The ANT group showed 4.8 degrees more hip extension than the control group ( $p=0.008$ ), whereas the LAT group had 2.7 degrees more, although this difference was not statistically significant ( $p=0.262$ ). This is surprising considering that the soft tissue damage from the surgery is on the anterior aspect of the hip, and could therefore limit extension of the hip. Sagittal plane range of motion was very similar for all groups. Our results differ from

those of Shrader et al. (2009), where their THA patients exhibited reduced hip extension angle. This could be attributable to the fact that their participants were operated through a posterolateral approach, which necessitates the sectioning of the gluteus maximus, the release of the external rotators and a posterior capsulectomy. Their range of motion was smaller for all their groups, compared to our data. This could be due to a smaller step height, but they do not provide the dimensions of their stair apparatus. The hip extension moments of force are slightly reduced for both ANT (-0.53 Nm/kg) and LAT (-0.55 Nm/kg) groups compared to the control group, but these differences were not significant ( $p=0.26$  vs. ANT;  $p=0.231$  vs. LAT). As the hip extensors are not sectioned or exposed in both surgical approaches, these results were expected.

Both ANT and LAT groups showed reduced hip flexion near the end of the gait cycle (ANT: 5.4 degrees less than CON, LAT: 4.8 degrees less than CON). Although the pairwise comparisons were not significant ( $p=0.027$  ANT vs. CON and  $p=0.06$  LAT vs. CON), the main effect of the MANCOVA was significant ( $p=0.015$ ). This trend could indicate that the THA patients might have difficulty raising their leg when going up stairs. Damage to the rectus femoris and tensor fascia lata can sometimes occur with the anterior approach (Meneghini et al., 2006), as well as for the lateral approach, and these muscles contribute to hip flexion. Another explanation could be an increased forward lean by the THA participants. Proposed by Foucher et al. (2008), this positioning of the body could be used by THA patients to increase their feeling of stability by reducing the demands on their ipsilateral knee. This could be the case with the LAT group: they exhibited reduced knee flexion, extension moments, as well as power generated at the knee.

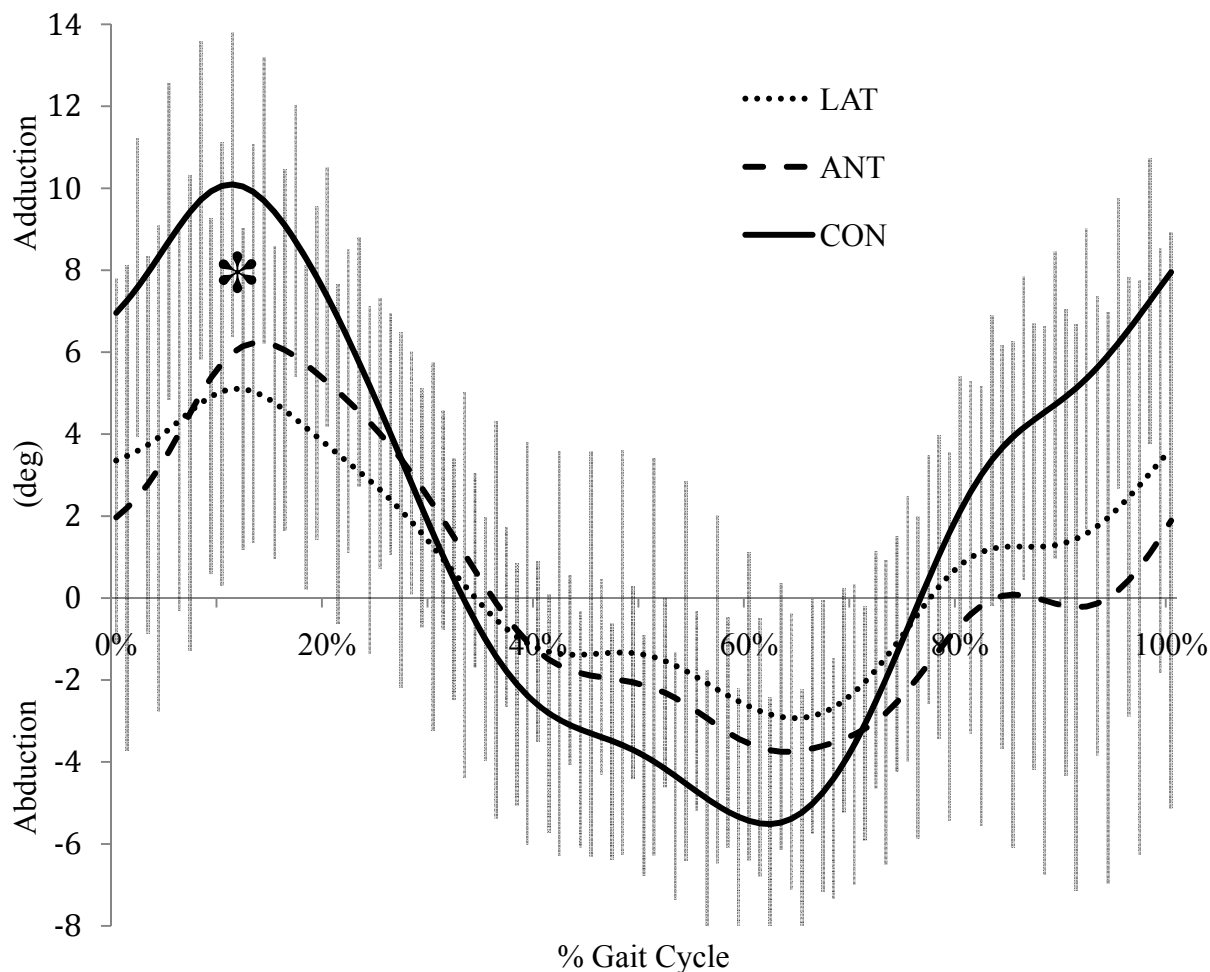


Figure 5. Hip abduction/adduction angle of THA patients operated through an anterior (ANT) or a lateral (LAT) surgical approach, as well as a control (CON) group, during stair ascent. \*Indicates a significant difference in peak adduction angle ( $p < 0.001$ ) and frontal plane range of motion ( $p = 0.001$ ) between the LAT and the control group. Note that the peak adduction angle ( $p = 0.024$ ) and frontal plane range of motion ( $p = 0.036$ ) of the ANT group were close to being significantly different from the control group.

In the frontal plane, both groups had a more abducted hip during the stance phase (3.9 degrees more for the LAT group and 3.6 degrees more for the ANT group). However, only the LAT group was significantly different from the control group ( $p = 0.01$  LAT vs. CON and  $p = 0.024$  ANT vs. CON). This could be due to other factors than the release of the gluteus medius, such as protective mechanisms to reduce the load on the prosthesis. We did not observe any difference between groups when comparing peak hip abduction moments.

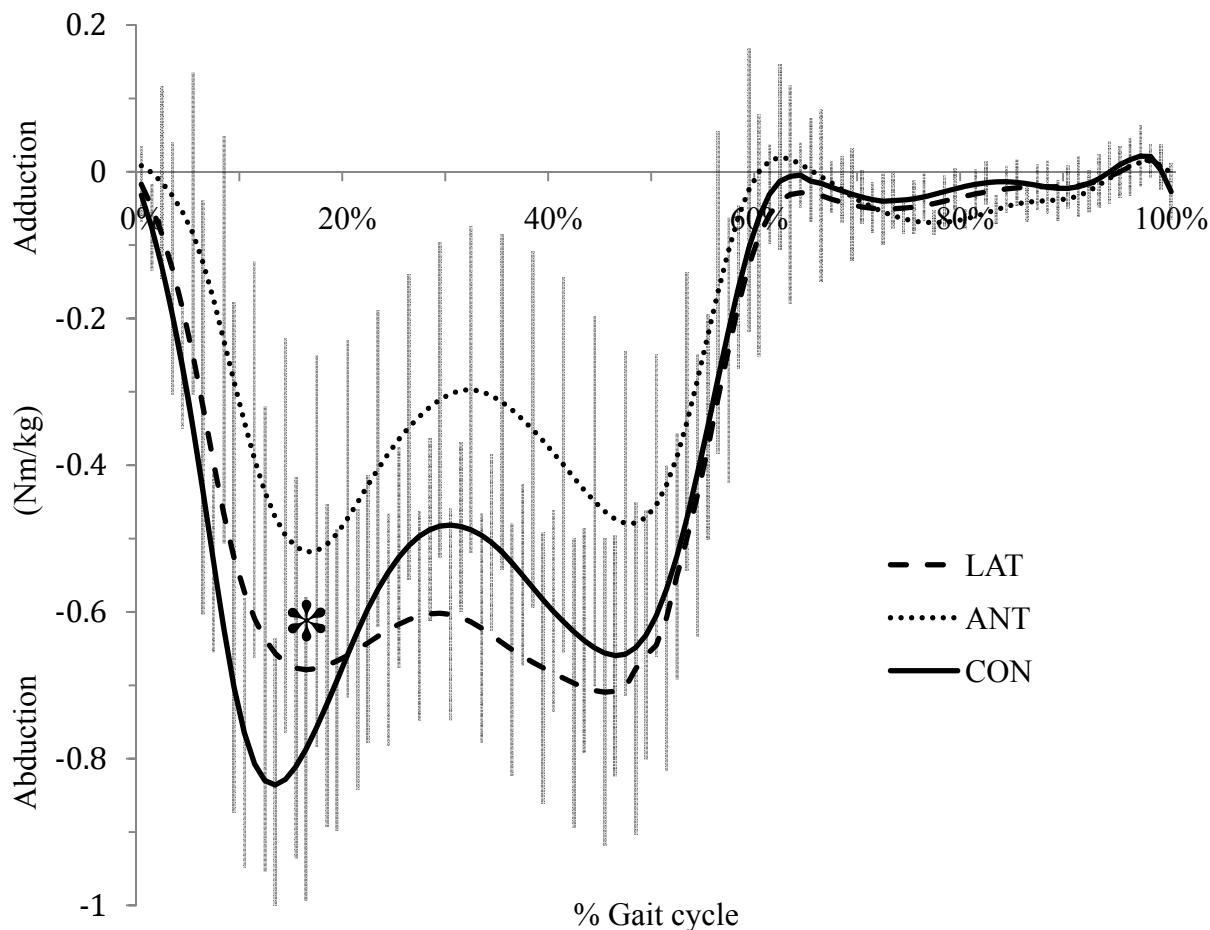


Figure 6. Hip abduction/adduction moment of THA patients operated through an anterior (ANT) or a lateral (LAT) surgical approach, as well as a control (CON) group, during stair descent. \*Significant difference between the ANT and the control group ( $p < 0.001$ ), as well as the LAT group ( $p = 0.014$ ).

Peak hip abduction moments from Foucher et al. (2008) are very similar to ours for the THA group (0.56 Nm/kg), but their control group had higher moments (0.75 Nm/kg), and they therefore found a significant difference. Note that these data are estimations as they measured moments of force in percentage of bodyweight by height, and only reported data in a histogram. Also, they reported external moments, whereas we report internal moments.

In the transverse plane, hip kinematics were similar between groups, but the LAT group showed reduced hip peak internal rotation moment of force ( $p = 0.006$ ) compared to the control group. This could be the result of a weak gluteus medius, as this muscle acts as an

external rotator when the hip is flexed. Foucher et al. (2008) reported similar values for their THA group (0.17 Nm/kg) and control group (0.22 Nm/kg). They performed gait analysis on 15 THA patients; 10 had a posterior approach and five had a lateral approach..

### *Stair Descent*

While descending stairs, both the ANT and LAT groups showed reduced hip flexion, but increased extension, resulting in very similar ROM in the sagittal plane. THA patients could be reducing their trunk inclination in order to bring back their center of gravity and have better control during the descent, potentially as a mechanism to avoid falling forward. They would therefore need to extend more their hip to reach the next step.

Both groups had a less externally rotated hip during the first double-legged stance phase, although not statistically different (CON vs. LAT:  $p=0.085$ ; CON vs. ANT:  $p=0.032$ ). They also had a reduced peak hip internal rotation moment (ANT:  $0.05 \pm 0.04$  Nm/kg; LAT:  $0.07 \pm 0.06$  Nm/kg) during the transition from double to single-legged stance, with only the ANT being significantly different from the control group ( $p=0.003$ ). These results indicate possible reduced function of the tensor fascia lata and gluteus medius, which contribute to internal hip rotation.

The hip abduction angles were very similar. However, only the ANT group produced a significantly lower hip abduction moment of force when standing on their operated leg ( $0.55 \pm 0.18$  Nm/kg), compared to the control group ( $0.9 \pm 0.26$  Nm/kg); whereas the LAT group had a peak hip abduction moment of  $0.8 \pm 0.32$  Nm/kg. This contradicts our hypothesis, as we expected lower abduction moments of force for the LAT group, because of the detachment of the gluteus medius muscle, and not in the ANT group, as no muscle is detached. Shrader et al. (2009) observed similar peak abduction moments of force in their

THA group operated through a posterolateral approach ( $0.65 \pm 0.11$  Nm/kg) and their control group ( $0.99 \pm 0.07$  Nm/kg).

Several mechanisms could be in play to explain the results obtained. Regardless of surgical approach, patients who suffer from osteoarthritis probably developed gait adaptations during the years preceding hip replacement in order to alleviate pain. These adaptations could persist after their operation and result in the observed abnormal gait patterns. If patients were indeed using strategies to alleviate pain prior to surgery, it is possible that the muscles surrounding the hip would become weaker. Consequently, these muscles would not be able to produce the same moments of force after surgery, even if the patient does not have pain anymore, and even if these muscles were not damaged during the surgery. These answers remain suggestions, and should be investigated in future research.

Limitations to this study include the lack of a preoperative gait analysis. Such a design would better isolate the effect of the surgical approach. Also, the LAT group had more implants from Stryker, whereas the ANT group had more from Wright Medical. The ANT group also had three types of acetabular components (8 Lineage, 6 Conserve Plus and 1 Dynasty). All implants are however primary THAs and are cementless systems. The groups could have been better matched for age. Nevertheless, this study is well powered by the relatively high number of participants (60) compared to other recent studies on stair climbing mechanics such as those by Shrader et al. (2009) and Foucher et al. (2008), which respectively had a total of 21 (7 THA, 7 hip resurfacing and 7 controls) and 30 (15 THA and 15 controls) participants.

This study demonstrates that both the lateral and anterior surgical approach do affect the mechanics of stair climbing after THA. The anterior group, however, had fewer differences compared to the control group, and their magnitude was usually lesser than the

lateral group. The results of this study suggest that patients operated through an anterior group have slightly better stair climbing ability, but abnormalities still persist. Future research could include a preoperative assessment, as well as the analysis of muscle activation patterns of the muscles at play with electromyography (EMG).

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## General Discussion

As the anterior approach to the hip is still not commonly used in hip replacements (Canadian Institute for Health Information, 2009), there is consequently less literature on the subject. However, its use is thought to allow better joint mechanics after surgery, as it spares the abductor and extensor hip muscles, contrary to the more popular posterior and lateral approaches. Only two very recent studies have inquired into the biomechanical aspect of the anterior approach, but only for walking (Klausmeier, et al., 2010; Mayr, et al., 2009). None, to our knowledge, has looked at stair climbing. These studies have focused on early recovery (six, twelve and 16 weeks post-surgery), and suggest that the anterior approach allowed earlier recovery in some aspects of gait. While assessing the gait biomechanics early after THA, performing such an analysis later on, when the participants have recovered from the surgery, is also important. Making so will ensure that early improvements in gait are carried on and that these improvements either stabilize or further improve over time.

Mayr and colleagues (2009) compared the preoperative and postoperative gait kinematics of a group of 16 patients who had an anterior approach and 17 patients who had an anterolateral approach. They only performed, however, within-group statistics. In other words, they did not perform statistical tests between the anterior and anterolateral group. While this allows measuring improvement, it does not compare the variables to normative data. While they provide reference values, those are from a group of young fit adults (27.9 years old, range 23-36; BMI 21.9, range 18.5 - 25), and are therefore not matched to the patient groups.

Klausmeier and colleagues (2010) did have a matched control group, and they also looked at the kinetics of the patient's gait. Interestingly, both their anterior and anterolateral

surgical approach groups had reduced peak hip abduction moment at early stance, with no significant improvement between preoperative assessment and either postoperative assessment. While these studies document the early recovery of patients operated through an anterior approach, there is no study, to our knowledge, that provide gait data when patients have recovered from the surgery.

The main observation we can make from the results of this research is that the THA patients who had hip replacement through an anterior approach did not exhibit better gait mechanics than those who had a lateral approach, compared to the control group. Hence, our main hypothesis has not been verified, and we cannot endorse the use of the anterior approach as being superior to the lateral approach in terms of restoring normal walking and stair climbing mechanics approximately ten months after surgery. There are, however, several limitations to this study that must be taken into account, and most of them are addressed in the two articles above. The following section will summarize the main findings of this study, as well as address its limitations.

For stair ascent, the anterior group did appear to have slightly better mechanics than the lateral group. Indeed, they had a more adducted hip, slightly greater hip frontal plane range of motion, more knee transverse plane range of motion, higher peak internal rotation moment, and higher power generated at the knee (see Table 7, page 56). There were, however, very few significant differences between both THA groups (knee peak power and knee peak abduction moment). The vast majority of the differences were from either THA group compared to the control group.

One of the main variables we were interested in was the peak hip abduction moment of force (see Tables 4 and 8, and Figures 4b and 6), as this moment is produced by the abductor muscle group, which is theoretically unharmed with the anterior surgical approach

(Matta, et al., 2005). This muscle group is very important during gait, as it is responsible for stabilizing the pelvis in the frontal plane (Clark & Haynor, 1987). During stair ascent, participants from both THA groups had similar hip abduction moments (ANT:  $-0.552 \pm 0.1$  Nm/kg; LAT:  $-0.559 \pm 0.24$  Nm/kg), both of which were smaller, albeit not significantly different, from the control group ( $-0.67 \pm 0.16$  Nm/kg). However, the ANT group showed significantly smaller hip abduction moment in stair descent ( $-0.55 \pm 0.18$  Nm/kg), not only compared to the control group ( $-0.90 \pm 0.26$  Nm/kg;  $p < 0.001$ ), but also compared to the LAT group ( $-0.80 \pm 0.32$  Nm/kg;  $p = 0.014$ ). The same results were obtained from level walking, further confirming that the gait of patients having an anterior approach for hip replacement did not return to normal, and did not have better hip abduction moments than those operated through a lateral approach. These values were surprising, as the study from Klausmeier and colleagues (2010) report hip abduction moment of  $0.81 \pm 0.22$  Nm/kg during gait for a cohort of twelve THA patients who had an anterior approach. There might be difference between our methodologies, but their control and anterolateral approach groups had very similar values to ours.

This reduced hip abduction moment could be due to the more abducted hip position of both THA groups. During the transition between double- to single-legged stance in gait and stair ascent (15% of gait cycle), the ANT and LAT participants placed their hip in  $7 \pm 2.4^\circ$  and  $7.6 \pm 2.5^\circ$  of adduction, respectively, whereas the control participants had a  $9.5 \pm 2.8^\circ$  angle. This increase in abduction in THA patients could be caused by an increase in step width, a mechanism that is thought to increase stability (Maki, 1997).

As the results concerning the peak hip abduction moments were not anticipated, we inquired into the possible causes of such differences. One possibility was that the orientation and size of the prostheses influence the abductor lever arm. Hence, we measured this on

digital x-rays (anteroposterior view). As a longer abductor lever arm could increase the mechanical advantage of the abductor muscle group and therefore increase the abductor moment, we performed an independent t-test and a correlation test between these two variables. There was no significant difference between the anterior and lateral groups in abductor lever arm ( $p=0.4$ ). There was also no correlation between the peak hip abductor moment and the abductor lever arm for walking ( $r=-0.025$ ;  $p=0.877$ ) and stairs ascent ( $r=0.06$ ;  $p=0.711$ ). The abductor lever arm was significantly correlated to the peak hip abduction moment in stair descent ( $r=0.345$ ;  $p=0.029$ ). However, the relationship is negative, whereas in theory, a greater abductor lever arm would produce a greater peak hip abductor moment. Regardless, since there was no correlation between these variables for both walking and stair ascent, this finding does not appear to be clinically significant.

Another limitation was the type of prosthesis that was used. Ideally, all patients should have had the same prosthesis and the same head size. However, with all the exclusion criteria, recruitment of the participants would have taken too much time. In our cohort, more patients in the anterior group had an implant by Wright Medical ( $n=15$ ), all had a Profemur stem and the cup was either a Lineage or a Conserve Plus. The remaining five had a Stryker Accolade stem and Trident cup. In the lateral group, more patients had a Stryker Accolade stem with a Trident cup ( $n=13$ ), while the remaining seven had a Wright Medical Profemur stem and Conserve Plus cup. We considered both prosthesis equivalent for this study, as they are somewhat similar cementless systems.

Burroughs et al. (2005) showed that head size influences range of motion. We analyzed head size of our THA participants. An independent t-test revealed no significant difference ( $p=0.268$ ) between the anterior ( $34.8 \pm 6.6$  mm) and the lateral group ( $37.3 \pm 7.4$  mm). It is therefore unlikely that the size of the femoral head influenced our results.

An interesting aspect of this study is that we have also looked at the kinematics and kinetics of the knee and ankle joints, as impairments at the hip can influence these articulations. Both THA groups had increased ankle dorsiflexion and knee flexion during walking. These results are similar to those from Perron and colleagues (2000), where these adaptations were correlated to a decreased hip extension at push-off. In other words, the knee and ankle compensated with greater range of motion for a reduction in mobility at the hip. It is still unclear if these adaptations could increase the likelihood of joint degeneration at the knee and ankle.

Concerning the methodology, there are inherent errors in every biomechanical analyses. The location of the center of rotation of each joint and segment is estimated with skin markers positioned on the participants' body. The skin and underlying soft tissue, however, move over the bones while performing movements, and create artefact (Leardini et al., 2005), which influences the location of the joint centers. Also, the center of rotation of the hip is measured using anthropometric data obtained through cadaveric studies (Dempster, 1955), and therefore do not reflect the actual individual anatomy of the participant. There is currently research being done to measure and eventually control skin artefact (Cereatti et al., 2009). Alternative methods of measuring the joints center, such as 3D fluoroscopy, are being used (Glaser et al., 2008) in order to increase the precision of the joint center location. This method, however, has a very limited field of view, rendering impossible the analysis of the whole body during gait.

In this study, not all hip replacements were performed by the same surgeon. Seventeen out of the 20 patients who had an anterior approach were operated on by a surgeon who has performed hip replacements with this approach for several years. Three experienced surgeons performed the hip replacements for the group operated through a lateral approach.

As with femoral head size, our strict selection criteria did not allow us to complete the study in a reasonable amount of time if we had only taken patients from a single surgeon. Having more surgeons, however, allows us to generalize slightly more the results to the general population undergoing hip replacement.

Another limitation was that this study does not have a preoperative gait assessment. Such values are important, as they can provide a baseline to which we can compare the postoperative results, in order to determine if there is amelioration in gait performance for the patients. This also allows controlling for preoperative function, which has been shown to greatly predict postoperative function measured as gait velocity (Ward, et al., 2008).

In conclusion, while this study does have limitations, it does provide reliable data on the 3D kinematics and kinetics of a rather large (for this type of study) cohort of participants who had hip replacement. Having the participants perform three different tasks allowed us to observe that better results in a certain task, in this case stair ascent, are not necessarily transposed to other tasks. This presses the importance of assessing different motions while evaluating postoperative performance of patients undergoing hip replacement, or any other type of lower-limb surgery. While our data failed to demonstrate better walking and stair climbing abilities in patients operated through a muscle sparing anterior approach, both groups showed similar impairments compared to the control group. Many other factors could have influenced the gait mechanics of the THA participants. Preoperative gait adaptations, pain avoidance strategies or unconscious prosthesis unloading are some factors that could explain our results. Our study design did not allow us to control for these variables. Future research is therefore necessary to elucidate the causes of the dissimilarities with the control group, and explore other methods of reducing these differences.

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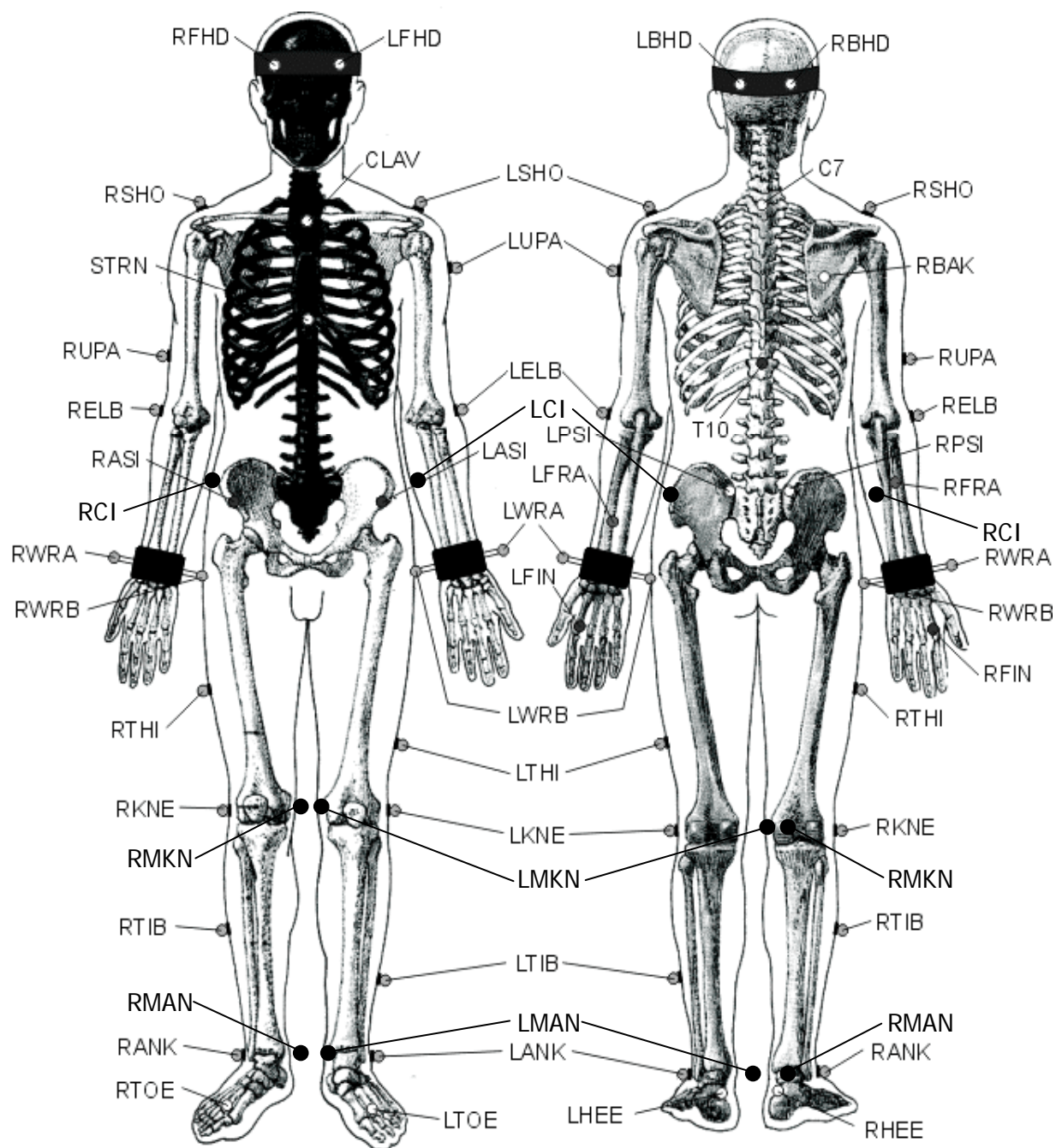
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## Appendix A

### University of Ottawa Motion Analysis Model (UOMAM)



## Appendix B

### University of Ottawa Motion Analysis Model (UOMAM)

#### markerset

<b>Head</b>	
LFHD & RFHD	Left temple
LBHD & RBHD	Left back of head
<b>Torso</b>	
C7	7th cervical vertebrae
T10	10th thoracic vertebrae
CLAV	Jugular notch
STRN	Xiphoid process
RBAK	Middle of right scapula
<b>Arms</b>	
LSHO & RSHO	Acromio-clavicular joint
LUPA & RUPA	Upper arm
LELB & RELB	Lateral epicondyle
LFRA & RFRA	Forearm
LWRA & RWRA	Wrist bar thumb side
LWRB & RWRB	Wrist bar pinkie side
LFIN & RFIN	Dorsum of the hand head of 2nd metacarpal
<b>Pelvis</b>	
LASI & RASI	Anterior superior iliac crest
LPSI & RPSI	Posterior superior iliac spine
LIC & RIC	Iliac crest
<b>Legs</b>	
LTHI & RTHI	Lateral thigh
LMKN & RMKN	Medial epicondyle of the knee
LKNE & RKNE	Lateral epicondyle of the knee
LTIB & RTIB	Lateral shank
LANK & RANK	Lateral malleolus
LMAN & RMAN	Medial malleolus
<b>Feet</b>	
LTOE & RTOE	2nd metatarsal head of foot
LHEE & RHEE	Posterior calcaneus