

**THE RELATIONSHIPS BETWEEN PHYSICAL IMPAIRMENTS,
FUNCTIONAL LIMITATIONS AND MOVEMENT ASYMMETRIES
BEFORE AND AFTER TOTAL HIP ARTHROPLASTY**

A Longitudinal Study

by

Sumayeh Burhan Abujaber

A dissertation submitted to the Faculty of the University of Delaware in partial
fulfillment of the requirements for the degree of Doctor of Philosophy in
Biomechanics and Movement Science

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Sumayeh Burhan Abujaber

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ABSTRACT

Total hip arthroplasty (THA) is the treatment of choice for advanced hip osteoarthritis (OA). THA effectively reduces hip pain^{1,2}, improves self-reported function and quality of life compared to pre-operative levels¹⁻⁸ and most patients are highly satisfied with the outcome⁹. Despite these positive outcomes, patients continue to have physical impairments, functional limitations and altered movement patterns when compared to healthy-aged matched samples. Patients after THA demonstrate functional limitations on both self-reported and performance-based measures, when compared to healthy controls^{5,8,10}. Those patients also move with altered movement patterns during dynamic tasks such as the sit to stand task. Patients rise from the chair with a strategy that increases the loads on the non-operated limb and decreases the reliance on the operated limb^{11,12}. These asymmetrical movement patterns are concerning because the pattern of overloading of the non-operated joints after THA coincides with the non-random progression of OA in which the contralateral lower extremity joints are most likely to show degenerative changes¹³. In addition, after knee replacement, asymmetrical movement patterns have been linked to worse functional performance¹⁴.

The underlying impairments that may contribute to functional limitations and abnormal movement strategies in THA population are not known; however, muscle weakness of the lower extremity is likely a contributor. Residual muscle weakness of the operated lower extremity is still detectable even years after THA, when compared

to the non-operated side¹⁵⁻¹⁸, and to a healthy matched group^{8,19}. It is also possible that movement asymmetries presented after THA might result as learned behaviors that developed before or after surgery in the presence of pain or soon after surgery in the presence of instability or weakness.

The overall goal of this dissertation was two-fold. First, we intended to identify the primary physical impairments that contribute to functional limitations and abnormal movement patterns before and after THA. Second, we evaluated the utility of using the real-time visual feedback for reducing asymmetrical movements in patients after THA. The results from this work will allow to design targeted rehabilitation programs that may maximize functional and biomechanical recovery after THA.

In this dissertation, we conducted four studies. In the first study, we evaluated self-reported and performance-based functional recovery at 3 months after THA and we determined the contributions of physical impairments to functional limitations at 3 months post-surgery. The results of this study show that despite the improvements in self-reported and performance-based function, patients after surgery have lower level of function and strength compared to healthy controls, and that pain and strength measures differently contributed to self-reported and performance-based function. In the second study, we evaluated sit to stand biomechanics in patients before and after THA, and determined the relationships between physical impairments and altered performance during STS. The results of this study indicate that patients before and after surgery move with asymmetrical movement patterns that unload the operated limb and shift the load to the non-operated limb. We also determined that weakness in the operated limb was related to greater asymmetries in which the load on the operated

limb was lower than the non-operated limb. In the third study, we evaluated the acute effect of real-time visual feedback of weight distribution on movement symmetry during STS in before and after THA, and examined whether strength of the operated limb influenced the response to the feedback. The results of this study indicate that subjects moved with more inter-limb symmetry in the sagittal and frontal planes when they were given the feedback, but this single instance of feedback did not eliminate all asymmetries. Subjects before and after THA showed similar response to visual feedback, and muscle strength measures were not related to the feedback response. In the final study, we examined whether the Wii balance board (WBB) can be used as a clinical tool to accurately assess weight bearing asymmetry during standing from and sitting to a chair, in comparison to laboratory-grade force plates as “gold-standard”. The results of this study indicate that the WBB and laboratory force plates have agreement for measuring peak VGRF and the inter-limb symmetry ratio. Although the WBB may serve as a low-cost alternative to expensive, laboratory force plates for measuring weight bearing asymmetry in a clinical or home-based setting, the results did show a systematic bias in which the WBB recorded more symmetrical force distribution.

Overall, this dissertation provides evidence for the post-operative improvements in functional abilities and movement symmetry for patients undergoing THA. However persistent physical impairments, functional limitations and asymmetrical movement strategies were found in patients 3 months after THA. This dissertation lays down the foundation of using the real time visual feedback to reduce interlimb asymmetries. Albeit feedback did not perfectly normalize symmetrical patterns, it could be that developing structured program that utilizes higher intensity

and longer duration of visual feedback, combined with addressing underlying physical impairments may have beneficial effects on mitigating movement asymmetries and subsequently improving functional abilities.

Chapter 1

INTRODUCTION AND AIMS: PHYSICAL IMPAIRMENTS, FUNCTIONAL LIMITATIONS AND ABNORMAL MOVEMENT PATTERNS IN PATIENTS UNDERGOING TOTAL HIP ARTHROPLASTY

Hip osteoarthritis (OA) is a chronic disease characterized by progressive degeneration of cartilage and the underlying bone within the joint. Hip OA is a debilitating disorder that affects one in four people who live to the age of eighty-five²⁰ and is characterized by joint pain¹, reduced range of motion²¹, and knee and hip weakness^{15-17,22}. This physical impairments drive the self-reported and performance-based functional limitations when compared to healthy peers^{22,23}, as well as movement asymmetries^{24,25}, and abnormal movement patterns²⁶.

Total hip arthroplasty (THA) is the treatment of choice for advanced hip osteoarthritis (OA). In the United States, the hip is the second most prevalent joint to be replaced after the knee, and 82% of THA procedures are being performed for OA²⁷. The demand for THA procedures is increasing over the time. Currently, more than 300,000 primary THA procedures are performed annually, although the incidence of this surgery is expected to increase nearly 100% by 2030²⁸.

Functional Limitations after THA

THA reliably reduces hip pain^{1,2} and improves self-reported function and quality of life compared to pre-operative levels¹⁻⁸, which consequently results in high levels of patient satisfaction⁹. However, patients at least 6 months after THA continue to demonstrate muscle weakness when compared to age-matched subjects without

joint pathology. Despite the gradual recovery in muscle strength after arthroplasty^{8,15-17}, residual muscle weakness of the lower extremity is still detectable in the long-term after THA. Compared to the non-operated side, patients demonstrate isometric strength deficits of 8%-21% in the knee and the hip muscles up to 1 year after THA¹⁵⁻¹⁸. When compared to a healthy group, the deficits in the hip abductor, knee flexor and knee extensor groups become even greater and have been reported as 17%-25%, weaker than age-matched normative values^{19,22}.

Patients after THA also demonstrate functional limitations on both self-reported and performance-based measures when compared to healthy controls^{5,8,10}. Patients report 17%-20% lower perceived physical function on self-reported questionnaires^{5,8} and cover 8% less distance on 6-minute walk test (6MW). Patients after THA also take 11% more time to complete timed up and go test (TUG)⁸, and require 18%-23% longer time in the walking and stair climbing tasks¹⁰. Further, the self-reported function did not improve or was worse in 14-36% of patients one year after THA compared to pre-operative measurements²⁹. Although the functional deficits are common after THA, the physical impairments that affect functional recovery in this population are not known. Muscle weakness of the lower extremity is likely a contributor to functional limitations after THA. Elucidating the factors that lead to systemic dysfunction is necessary to develop optimal rehabilitation strategies that maximize post-operative outcomes.

Self-reported Questionnaires and Performance-based Tests

Self-reported and performance-based measures are two common methods to evaluate functional recovery after THA. Although many large studies opt to measure outcomes with self-reported questionnaires because they are inexpensive and easier to

administer^{15,30–32}, self-reported and performance-based measures are only mildly to moderately correlated with one another in patients with lower extremity pathology^{33,34,4,35,36}. Concernedly, these two different measures of functional ability reveal different recovery patterns after total knee arthroplasty (TKA) and THA^{3,36–38}. Scores on self-reported measures are influenced by a patient's pain and joint range of motion, whereas the performance-based measures are influenced by a variety of factors including strength and endurance in patients with hip OA and after TKA^{21,35,37,39}. This resulted in patients reporting improvements in the ability to complete activities of daily living, despite objective evidence of declining physical function during the same tasks^{36,37}, likewise the patient-reported function didn't reflect the early deterioration that occurs in performed function after THA³⁸. Therefore, it is suggested that these metrics of functional ability capture different aspects of function and that both measures should be utilized when evaluating functional recovery in patients who undergo THA or TKA^{35,37}. However, very few studies have systematically evaluated functional recovery after THA using both self-reported and performance-based measures^{3,8,38}; and to date, no study has identified the potentially different underlying modifiable factors that may influence both self-reported and performance-based function in patients early after THA.

Altered Movement Strategies after THA

Despite the pain relief and modest improvements in walking speed, spatial-temporal parameters and the interlimb kinematics and kinetics symmetry^{8,9,37,52}, abnormal movement patterns, that increase loads on the non-operated limb and decrease reliance on the operated limb, persist during dynamic tasks such as walking^{24,40,41}, stair climbing⁴² and rising from a chair^{11,12,43}. For example, patients

walked with reduced peak sagittal and frontal angles and moments at the hip and knee joints of the operated limb compared to the non-operated limb and to healthy controls limb. Moreover, those patients walked with greater frontal trunk inclination during gait compared to control group, this abnormal trunk strategy was suggested as a compensatory movement to hip abductor weakness, and was associated with reduced walking efficiency⁴⁴.

The sit-to-stand task (STS) task is an important metric of movement recovery after THA. This task, defined as a movement of standing from a chair to an upright posture, is a fundamental daily activity performed approximately 60 times per day by healthy adults⁴⁵. It is a biomechanically demanding task that requires greater muscle strength and produces higher joint forces than walking and stair climbing^{46,47}. Unlike most other dynamic movements, rising from a chair is a bilateral support task in which both feet are in contact with the ground. Therefore, compensatory movement strategies that favor one leg can be used to accomplish the task; which makes the STS task a sensitive measure to evaluate movement asymmetry in individuals with unilateral lower extremity pathology. Patients transfer from sitting to standing position by unloading their operated side and shifting the weight to the non-operated side^{11,43}. Those individuals after THA also display altered kinematics and kinetics during STS, in which the operated hip joint moves with reduced peak flexion angle, reduced adduction and abduction range of motion, and smaller internal extension and adduction moments; compared to the non-operated hip and to limbs of healthy group^{12,48}. While previous studies have analyzed lower limb biomechanics during STS in the THA population^{11,12,43,48}; these studies have been limited to cross sectional designs. In addition, none of these studies has evaluated trunk movement during the

STS task in patients before and after THA. Trunk movement plays an important role in completing the STS⁴⁹⁻⁵¹. Proximal adaptations may be a principal determinant of successful STS in a population in which pelvis and hip muscles demonstrate substantial weakness even years after THA. Quantifying trunk movement during STS may lead to better understand how patients before and after THA use compensatory strategies to rise out of a chair.

Concernedly, asymmetrical movement patterns present after THA, that exemplify an overloading on the non-operated side, coincide with the non-random evolution of OA in lower extremity joints, in which the contralateral hip followed by contralateral knee are mostly expected to show OA progression and subsequent replacement after THA¹³. Additionally, Christiansen and colleagues found that greater weight bearing asymmetry during STS task was related to worse functional performance in patients after total knee arthroplasty (TKA)⁵², suggesting that compensatory strategies are not sufficient to complete functional activities in a normal fashion. However, the underlying causes of presence of movement asymmetries after THA have not been investigated. Weakness of lower limb muscles might be related altered movement after THA. Understanding the proximal and distal biomechanical changes of STS task will provide new insights about STS movement strategies following THA. Elucidating the role of modifiable physical impairments, such as muscle weakness and pain, on altered movements, before and early after THA is critical to better design targeted postoperative rehabilitation interventions to maximize movement symmetry.

Altered Biomechanics, Are They Learned Behaviors?

Unloading strategies in patients after THA is suggested to be a learned behavior that developed before THA as mechanism to reduce pain or muscular demand. It is also possible that asymmetrical movement patterns developed in response to fear of movement or sensory deficits that developed after surgery^{43,53}. Hence it was recommended that rehabilitation programs focus on restoring normal movement and encourage equal weight bearing after surgery^{11,43,53}. In recent studies, real time visual feedback of weight distribution, by using two Nintendo Wii Balance Boards, has been found to reduce weight bearing asymmetry in healthy adults during a squat task⁵⁴, and in patients with neurological diseases during static standing⁵⁵. The authors of these studies suggested that visual feedback system that fed by input from Wii Balance Board (WBB) can be utilized in the clinical settings to improve weight bearing asymmetry. However, the joint-specific strategies that are used to normalize weight distribution during the chair rise have been unexamined. It is possible that lower limb joint moments and angles, or trunk angles, will become more asymmetrical and more divergent from normal in an attempt to make force under each limb more symmetrical. Therefore, it is imperative to discern how subjects who exhibit weight bearing asymmetry implement movement strategies that normalize ground reaction force between limbs. Additionally, although the WBBs have excellent test–retest reliability for measuring weight bearing asymmetry⁵⁶, there is little information on the accuracy of the WBB force measurements compared to research-grade force plates.

Aims and Hypotheses

The overall goal of this dissertation was two-fold. First, we identified primary physical impairments contribute to functional limitations and abnormal movement patterns before and after THA. Second, we evaluated the utility of using real-time visual feedback for reducing asymmetrical movement in THA population. The results from this work will lead to better rehabilitation programs that may maximize functional and biomechanical recovery after THA.

Aim 1: To characterize functional recovery 3 months after THA using performance-based and self-reported measures, and identify how physical impairments are related to the patient's perceptions and performance of functional tasks after THA.

- Hypothesis 1.1: Compared to pre-operative levels; patients will demonstrate a significant reduction in pain, increase in hip motion, and increase in hip and knee strength in the operated limb, as well as improvements in performance-based and self-reported function at three months following THA.
- Hypothesis 1.2: Patients at 3 month post-surgery will show weaker muscle strength and worse function compared to healthy individuals.
- Hypothesis 1.3: The operated hip joint pain would be the primary contributor to self-reported outcomes, while operated hip and knee strength would be the main contributors to performance-based outcomes three months following THA.
- Hypothesis 1.4: The reduction of hip pain would be the primary contributor to improvement in self-reported outcomes, while improvements in hip and knee strength would be the be the main contributors to changes in performance-based outcomes three months following THA.

Aim 2: To evaluate the sit to stand movement strategies before and after THA, and to identify how physical impairments influence these movement strategies before and after THA.

- Hypothesis 2.1: Before THA, patients will demonstrate inter-limb movement asymmetries with lower vertical ground reaction force, and smaller hip and knee moments in the operated limb compared to non-operated limb, and lateral trunk movement towards the operated side.
- Hypothesis 2.2: Three months after THA, patients will show improvements in movement symmetry that is driven by the increase in vertical ground reaction force, and hip and knee moments in the operated limb.
- Hypothesis 2.3: Despite improvements, patients 3 months after THA will still demonstrate some residual movement asymmetries.
- Hypothesis 2.4: Surgical hip pain and muscle weakness will be related to less VGRF, smaller joint moments, and greater trunk lean on the operated side before and after THA.
- Hypothesis 2.5: Pre- to post-operative improvements in hip pain and strength will be positively related to increases in VGRF, joint moments and trunk lean on the operated side.

Aim 3: To evaluate the immediate influence of real-time visual feedback of weight bearing on lower extremity kinematics and kinetics during a STS task in patients before and after THA.

- Hypothesis 3.1: During receiving visual feedback, patients would exhibit increased symmetry in weight bearing and joint kinematics and kinetics, before and after THA.
- Hypothesis 3.2: Visual feedback would lead to larger increase in sagittal plane hip and knee moment symmetry in patients 3 months after THA compared to pre-operative session.
- Hypothesis 3.3: Operated limb strength and pain will influence the magnitude of improvements in VGRF and joint moment symmetry during receiving the visual feedback, before and 3 months following THA.

Aim 4: To determine the validity of force measurements acquired from a single WBB as compared to force measurements acquired from force plates in a motion analysis laboratory.

- Hypothesis 4.1: Peak VGRF and inter-limb VGRF symmetry ratios would show absolute agreement between the WBB and force plates during a sit-to-stand and return-to-sit task (STS-RTS) in patients before and after total joint arthroplasty.

Chapter 2

CONTRIBUTIONS OF PHYSICAL IMPAIRMENTS TO SELF-REPORTED AND PERFORMANCE-BASED FUNCTIONAL RECOVERY AFTER THA (AIM 1)

Abstract

Background: Patients after total hip arthroplasty (THA) demonstrate functional limitations compared to healthy individuals. The underlying impairments that may influence self-reported and performance-based function in patients early after THA are unknown. The purpose of this work was to determine the contributions of physical impairments, including weakness, pain, and range of motion (ROM) deficits to self-reported and performance-based function 3 months after THA.

Methods: 48 subjects were tested 2-4 weeks before THA and 3 months after THA. Physical impairments included hip pain, total hip ROM, and isometric strength of the hip abductors and knee extensors. Physical function was assessed via the Hip Outcome Survey (HOS), Timed Up and Go, Stair Climbing Test, and Six Minute Walk. Regression analyses were created to determine the contributions of physical impairments to each functional outcome measure.

Results: There was significant improvement in all functional outcomes and physical impairments, except for the hip strength. Three months post-surgery, hip pain and total ROM were the primary determinants of self-reported function on the HOS, while hip and knee strength were most related to performance measures. When evaluating the relationship in change scores, reduction in pain predicted improved in physical function. Change in strength was not strongly related to change in function.

Conclusions: Self-reported and performance-based measures are influenced differently by pain and strength 3 months after THA, suggesting that both measures should be utilized for evaluating functional recovery after THA. The lack of relationship between change in hip strength and change in function after THA is likely attributed to the fact that there was no change in hip abductor strength by 3 months after THA. Because strength was related to functional performance after THA, rehabilitation protocols that address the residual strength deficits may enhance function after THA.

Introduction

Total hip arthroplasty (THA) is the treatment of choice for end-stage hip osteoarthritis (OA). THA reliably reduces pain and improves self-reported function and quality of life when compared to pre-operative limitations¹⁻⁸. Despite the success of the surgery, patients at least 6 months after THA continue to demonstrate physical impairments and functional limitations on both self-reported and performance-based measures, when compared to healthy controls^{5,8,10}. Patients report 17%-20% lower perceived physical function on self-reported questionnaires^{5,8} and cover 8% less distance on 6-minute walk test (6MW). Patients after THA also take 11% more time to complete timed up and go test (TUG)⁸, and require 18%-23% longer time in the walking and stair climbing tasks¹⁰. Further, the self-reported function did not improve or were worse in 14–36% of patients one year after THA compared to pre-operative measurements²⁹.

Functional limitations are linked to decreased quality of life, and increased risk of disability, falls, and depression in older adults⁵⁷. Although the functional deficits are common after THA, the physical impairments that affect functional recovery in

this population are not known. Elucidating the factors that lead to systemic dysfunction is necessary to develop optimal rehabilitation strategies that maximize post-operative outcomes. Lower limb muscle weakness is likely a contributor to functional limitations after THA. Weaknesses of hip and knee muscles are common impairments after THA. One month post-surgery, the isometric hip and knee muscles strength is reportedly 14%-26% lower than preoperative values⁸. Despite the gradual recovery in muscle strength after arthroplasty^{8,15-17}, residual muscle weakness in the operated limb is still detectable up to two years following THA^{15-18,58}. Compared to the non-operated side, isometric strength deficits of 8%-16% in the quadriceps and the muscles around the hip joint in the operated side were found 6 months after THA¹⁵⁻¹⁷, and patients continued to demonstrate strength deficits of 10%-21% at 1 year post-surgery¹⁶⁻¹⁸. Even 2 years after THA, patients have hip and knee muscle weakness in the operated limb, with the hip abductor muscle group constituting the largest deficit.^{15,58} When compared to a healthy group, the deficits in the hip abductor, knee flexor and knee extensor groups become even greater and have been reported as 17%-25%, weaker than age-matched normative values^{8,19}.

It is known that Knee extensors are essential to eccentrically control knee flexion during daily activities, these muscles generate the functional moments required to counteract the external moments in the sagittal plane⁵⁹. Likewise, the hip abductors have important functional role during ambulation; these muscles maintain the pelvis stability in the frontal plane especially during the single-limb stance, and enhance the advancement of contralateral “swing” limb, through assisting the forward rotation of the pelvis⁶⁰. The relation between strength of knee extensors and hip abductors, and the functional abilities has been previously documented^{47,59,61-65}. In older adults,

reduced knee extensors strength has been related to the reduced gait speed, poorer performance of chair rise and stair ascending and descending ability^{47,61-64}. A loss of hip abductors strength was also associated with worse ability to accomplish physical activities⁶⁶. Further, knee extensors strength is considered one of the main determinants of disability in patients with knee OA⁶⁷. After TKA, both hip abductor and knee extensor strength in the operated limb are key determinants of functional ability⁶⁸⁻⁷⁰. However, it is not known how changes in muscle strength before and after surgery affect functional performance after THA. In addition, other modifiable impairments specific to this patient population, such as loss of hip range of motion and joint pain, may also differentially influence functional ability, but these relationships have not been evaluated.

Self-reported and performance-based measures are two common methods to evaluate functional recovery after THA. Although many large studies opt to measure outcomes with self-reported questionnaires because they are inexpensive and easier to administer, self-report and performance-based measures are only mildly to moderately correlated with one another in patients with lower extremity pathology^{33,34,4,35,36}. Concernedly, there is a dissimilar pattern of recovery after total knee arthroplasty (TKA) or THA that is dependent on the tool used to measure outcomes^{3,36-38}. Scores on self-reported measures are influenced by a patient's pain and joint range of motion, whereas the performance-based measures are influenced by a variety of factors including strength and endurance in patients with hip OA and after TKA^{35,37,39}. Therefore, it is suggested that these metrics of functional ability capture different aspects of function and that both measures should be utilized when evaluating functional recovery in patients who undergo THA or TKA^{35,37}. Very few studies have

systematically evaluated functional recovery after THA using both self-reported and performance-based measures^{3,8,38}; and to date, no study has identified the potentially different underlying modifiable factors that may influence both self-reported and performance-based function in patients early after THA. In particular, no study has determined how the pre- to post-operative changes in these potential factors are associated with changes in self-reported and objective measures of functional ability. Therefore, the purpose of this work was to (1) characterize functional recovery 3 months after THA using performance-based measures of function and self-reported questionnaires, and (2) identify how physical impairments are related to the patient's perceptions and performance of functional tasks. Additionally, because evaluating the functional and strength differences between subjects 3 months after THA and their healthy peers will provide insights how post-operative outcomes differ than healthy controls, we planned to use healthy comparison group in this study. We hypothesized that 1) compared to pre-operative levels; patients will demonstrate a significant reduction in pain, increase in hip motion, and increase in hip and knee strength in the operated limb, as well as improvements in performance-based and self-reported function at three months following THA; 2) patients at 3 month post-surgery will show weaker muscle strength and worse function compared to healthy individuals; 3) the operated hip joint pain would be the primary contributor to self-reported outcomes, while operated hip and knee strength would be the main contributors to performance-based outcomes three months following THA.

Although understanding the relation between physical impairments and functional abilities before or after surgery provides useful information, it is also important to determine how the post-surgical improvements of self-reported and

performance-based function are influenced by the amount of increase or decrease of modifiable physical impairments. Therefore, we also prospectively investigated how the changes in individual physical impairments (pain, ROM and strength) between baseline and a three month post-operative evaluation specifically contribute to improvements in function during the same period. We hypothesized that 4) the reduction of hip pain would be the primary contributor to improvement in self-reported outcomes, while improvements in hip and knee strength would be the be the main contributors to changes in performance-based outcomes three months following THA.

Methods

Study design and Subjects

This study was designed as a prospective longitudinal study. In this analysis, subjects undergoing THA were derived from an on-going longitudinal study evaluating functional performance and movement patterns in patients before and after THA. Subjects with end-stage hip OA between the ages of 35 and 85, who were scheduled to undergo THA between March 2012 and April 2014, were recruited several weeks before the surgery. Subjects were referred by local orthopedic surgeons and from newspaper advertisements. Prior to enrollment, subjects were screened for eligibility using a telephone interview conducted by our research staff. Subjects in the parent longitudinal study were excluded if they have 1) neurological disorders that affect their ability to walk or rise from a chair, 2) any cardiovascular problems that limiting them their ability to climb a flight of stairs or walk for 6 minutes, 3) uncontrolled hypertension, or 4) history of cancer in the lower extremity. To avoid the

potential confounding influence of other joint impairments, subjects were also excluded from this analysis if they 1) had previous arthroplasty surgery less than 1 year from baseline (i.e. pre-operative) evaluation; or 2) plan to have an additional lower extremity arthroplasty. For a healthy comparison group, we examined a cross-sectional cohort of older adults. The inclusion/exclusion criteria for subjects in the healthy group were the same as for THA group, but subjects were also excluded if they present with symptoms of joint pathology in any lower extremity joint (Figure 1). All THA surgical procedures were performed by anterolateral or posterior approach (Table 1). All subjects received home and outpatient physical therapy following THA, except for 6 subjects who received only home therapy. Subjects in the THA group completed two testing sessions; 2-4 weeks prior to THA, and 3 months after THA. Subjects in the healthy group were only tested at one time point. Testing session included measurements of pain, strength, hip range of motion, performance-based function, and self-reported function. Healthy groups completed all measurements, except for pain assessment and self-reported function. All subjects signed informed consent forms approved by the Human Subjects Review Board at the University of Delaware prior to participation.

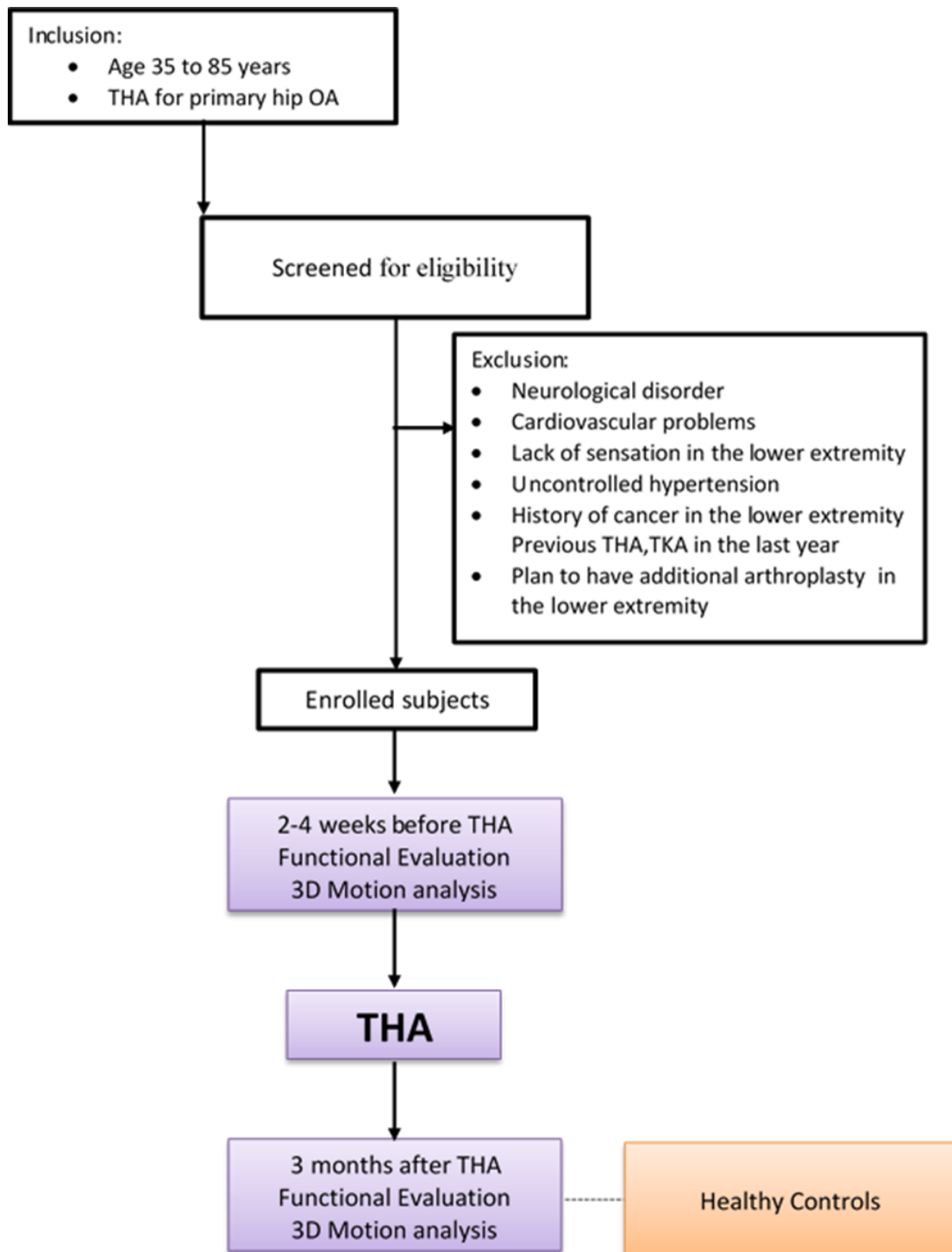


Figure 1 Study Design for Aim 1

Anthropometric measures and Pain assessment

Age, height, weight and sex were recorded, and body mass index (BMI) was calculated for each subject. Pain was assessed on a continuous scale from 0 to 10, subjects were specifically asked to “rate your average pain over the past week from 0 to 10, where 0 is no pain and 10 is the worst imaginable pain”. Pain was assessed for the affected hip, non- or less-affected hip, left knee, right knee, low back, and neck. For this analysis; only the score for the affected hip was used.

Strength measures

Hip abductor strength during isometric contraction was measured by using a handheld dynamometer (Lafayette Manual Muscle Testing System; Model 01165; Instrument Company, Lafayette, IN). In this test, subjects were positioned in side-lying, and a non-elastic strap was placed around the thigh to provide additional resistance (Figure 2). The handheld dynamometer was placed proximal to the lateral femoral condyles and its position was held constant between trials to avoid changes in the resistance moment arm. The hand-held dynamometer was secured between the strap and the thigh, and subjects were asked to push against the strap (abduct their hip) with as much force as possible. Subjects were tested bilaterally, with the affected limb tested second. Subjects performed 3 trials with rest in between trials, and the maximal attempt was used as the maximal isometric contraction. This method has been shown to be a valid and reliable in healthy adults⁷¹ and in individuals after TKA⁷⁰. Muscle strength in Newton was normalized to subject's body mass in Kg.



Figure 2 Isometric hip abductor strength test

Knee extensor strength was operationally defined as the peak isometric torque produced during a voluntary knee extension activity. Isometric knee extensors strength was assessed using an electromechanical dynamometer (Kin-Com 500 H, Chattanooga Inc, Chattanooga, TN)". Subjects were seated on the dynamometer and a force measurement arm that contained the force transducer was attached to the ankle (Figure 3). The knee of participants was positioned at 75° of knee flexion and this position was fixed throughout the test. The axis of the dynamometer was aligned with the axis of rotation of the knee joint, and the force transducer was placed two inches above the lateral malleolus. The "unaffected" side was tested first. Subjects were asked to perform two submaximal and one maximal contraction (i.e. kicks) to warm up the muscle and familiarize them with the testing procedure. Then the subjects were instructed to "kick the leg" as hard as possible for a 3 second duration. Verbal encouragement was provided. The maximal force from 3 trials was used for the analysis. Torque in Newton-meters (Nm) was calculated as the force recorded at the force transducer multiplied by the linear distance in meters between the force transducer and axis of rotation. Muscle torque was then normalized to subject's body

mass in Kg. This method has been shown to be a reliable measure in subjects with knee OA⁷² and subjects after TKA⁷³.



Figure 3 Isometric knee extensors strength test

Hip Range of Motion (ROM)

Active-assisted ROM of the affected hip joint were measured by using a hand-held goniometer. Flexion, abduction, adduction, internal rotation and external rotation measurements were evaluated as part of Harris hip score measure. Subjects were asked to move their limb into end range and the examiner provided support and a slight overpressure. Flexion, abduction, and adduction were measured in supine position. For measurement of hip flexion, subjects were asked to bring the knee as close to their chest as possible. Abduction was measured by asking the subjects to move their leg out to the side as far as possible. For adduction, subjects were asked to move the leg across the midline, and then anteriorly crossing over their opposite leg. Measurements

of hip rotation were made with subjects were in high sitting with their legs hanging down. Internal rotation was measured by asking patients to bring their lower legs out to the side, and external rotation by moving lower leg in toward the opposite leg. The total hip ROM was defined as the sum of all individual range of motions.

Performance-based tests

All subjects completed a battery of Performance-based functional tests. Performance-based tests included the Timed Up and Go (TUG), the Stair Climbing Test (SCT), and the Six-Minute Walk (6MW). The TUG test, which assesses basic mobility and dynamic balance, measures the time a subject takes to stand from a seated position in a standard height chair (46cm), walk 3 meters, turn around and walk back to the seated position, with his or her back against the chair. Subjects rise from a chair on the examiner's command and were allowed to use the arms of the chair during the standing or sitting portions of the test if subject needed to use them. The SCT test measures the time a subject required to ascend and descend 1 flight of 12 steps. A handrail is available for the subjects during testing; subjects were allowed to use the handrail only if required for safety. Subjects ascend the stair on the examiner's command. For TUG and SCT tests, subjects were asked to perform the tests as quickly as they feel safe and comfortable. The average of two trials was used in the analysis. A stopwatch was used, and time was recorded in number of seconds, to a hundredth of a second. The 6MW test measures the maximum distance a subject is able to cover in six minutes of walking over level ground. Subjects are allowed to stop and rest if required but time does not stop during any rest break. In this test, subjects were asked to cover as much distance as possible by walking as quickly as they feel safe and comfortable. The walked distance was measured in meters. These tests have been

shown as reliable tests (ICC= 0.75-0.94), and are responsive to detecting deterioration and improvement after TKA and THA⁷⁴.

Self-reported questionnaire

All subjects completed the Hip Outcome Score-Activities of Daily Living Subscale (HOS). HOS evaluates subject's perception of functional limitations secondary to hip impairment. Subjects rank 19 activities of daily living on a 0-4 ordinal scale that ranges from “Unable to Do” (0 points) to “No Difficulty” (4 points). Subject can choose “Not Applicable” answer choice if the activity is not applicable. The score were represented as a percentage where 100% is no difficulty with any task and 0% is unable to complete any task. The percentage was computed by summing all points and dividing by the total possible score (76) minus the “Not Applicable” choices. HOS has been shown to be reproducible and responsive for assessing perceived function in patients with end-stage hip OA⁷⁵.

Data analysis

Paired samples t-tests were used to examine the changes in hip pain, and physical function between the pre-operative and 3 months testing sessions. The frequencies of subjects who obtained the minimal detectable change for each of the performance-based outcome measures, were calculated. A two-factor repeated measures Analysis of variance (ANOVA) was used to detect time (pre-operative versus 3 months after THA) by limb (operated versus non-operated) differences in hip abductors and knee extensors strength. In the event of an interaction effect, follow-up paired t-tests were used as post-hoc testing. Separate univariate ANOVAs were used to examine differences between the THA and Healthy groups. Covariates of age and

BMI were used if these variables found to be different between groups in order to adjust for their effects on the dependent variables in both groups. For variables that are limb specific, each limb was entered into a separate ANOVA model. The average of both limbs in the Healthy group was used for comparison, given the absence of significant difference between limbs. To additionally characterize this patient population, we calculated percent changes from the preoperative time point to the 3-month time point , and provided estimates of the percent differences between THA outcomes at 3-month and healthy adults.

Pearson correlation analysis was used to quantify the association between functional and clinical outcomes 3 months after surgery, as well as between pre- to post-operative changes in functional and clinical outcomes. Hierarchical linear regressions were created to determine the independent contributions of clinical outcomes (pain, total ROM, hip strength, knee strength) of the affected side on functional measures (TUG, 6MW, SCT, HOS). Age and BMI are potential confounders that may influence physical function; therefore, the effect of these variables on function was accounted for by entering age and BMI in the first step, in the regression models. Hip pain was entered in second step, as hip pain in the presence of radiographic evidence of cartilage degeneration is the primary indication for THA. Hip ROM, a potentially modifiable factor that is often improved by the surgical procedure was entered in the third step. Hip abductor strength and knee extensor strength were added in the fourth and fifth steps, respectively. Lower extremity strength plays an important role in functional performance, but is often not directly improved by the surgery. Therefore, this order of testing allows us to examine the influence of physical impairments that may require targeted rehabilitation, after

accounting for the variance from confounding demographics (age and BMI) and variables that are often improved as a function of the surgery (pain and ROM). Moreover, this order of testing allowed us to determine the independent contributions of the hip-specific impairments (the variables of most interest) on subject's function, then to determine if the addition of knee extensors strength added additional, unique information beyond what could be discerned from subjects' characteristics, and the hip-specific impairments.

Separate regressions were performed for each outcome measure (TUG, 6MW, SCT, and HOS). The same analytical procedures were followed to examine the relationship between change in the clinical impairments (pre-operative to 3 months) and the change in functional outcomes (pre-operative to 3 months). For all outcome measures, the pre- to post-operative change was calculated by subtracting the pre-operative value from the value 3 months post-surgery.

For the hierarchical linear regressions, significance of each model, as well as the significant change in R^2 between each step was recorded. The change in R^2 informs us whether the addition of the variable in each step provides significant additional predictive information after accounting for the variance explained by the independent variables in the preceding steps. All statistical analyses were conducted using the Statistical Package for the Social Sciences (IBM SPSS 21.0, Chicago, IL). Significance level was set at 0.05.

Results

Forty-nine subjects who underwent THA and twenty-four healthy adults were recruited in this study (Table 1). In THA group, one subject was excluded from the analysis, as this subject was clearly an outlier in most performance outcomes at the

pre-operative session. At pre-operative visit, this subject had TUG score of 39.78 and SCT score of 67.8 which were 10.8 and 5.94 standard deviations above the mean of the pre-operative group, respectively. Therefore, a total of forty-eight subjects were included in the analysis (Table 1). One subject did not complete the hip abductor strength test for the non-operated side and one subject did not complete the test for the operated side at pre-operative session due to pain. Two subjects did not complete the knee strength testing at 3 months follow-up due to time constraints during the testing. One subject did not fill the HOS questionnaire for pre-operative session. Consequently, all analyses of knee strength included data from 46 subjects, while for analyses of pre- to post-operative changes in HOS and in hip abductor strength included 47 and 46 subjects, respectively. Of the 48 patients, 42 received both home and outpatient physical therapy. However, the length of participation in rehabilitation programs ranged from 3 to 16 weeks with 2-3 visits per week. The remaining 6 subjects did not receive outpatient physical therapy and only received home therapy that ranged between 2 and 6 weeks. For healthy group, all subjects completed performance-based tests and strength testing.

Table 1 Baseline characteristics of the THA and healthy adult groups (Mean±SD)

Variable	THA	Healthy	*p-value
Age (years)	65.3± 8.4	69.0±8.2	0.126
Height (m)	1.74 ± 0.09	1.66±0.09	0.001
Mass (Kg)	89.5±21.4	71.02±16.4	0.000
BMI (kg/m ²)	29.6±6.2	25.4±4.1	0.002
Male/Female (n)	28/20	11/13	0.202
Surgical approach: posterior / anterolateral	32/13 (3 unknown)	-----	NA
*p-value for group comparisons using independent t-test for measurement variables and chi-square test for nominal variables; BMI= body mass index			

Changes before and after THA

At 3 months after THA, there was a significant reduction in pain ($p<0.001$) and significant increase in the total hip ROM ($p<0.001$) compared to the pre-operative scores (Table 2). Hip abductor strength showed a significant main effect of limb ($F_{1,45}=55.08$, $p<0.001$) with the operated limb having weaker hip abductors strength compared to the operated side at both time points (Table 1). The limb by time interaction ($F_{1,45}=0.10$, $p=0.759$) and the effect of time were not significant ($F_{1,45}=0.004$, $p=0.95$), suggesting that there was no change in muscle strength on either leg between testing sessions (Table 2&3). For knee extensors strength, there was a significant limb by time interaction effect ($F_{1,45}=4.93$, $p=0.03$). Post-hoc tests revealed significant inter-limb strength difference pre-surgery ($p<0.001$) and at 3 months post-surgery ($p<0.001$), and a significant increase in knee strength of the operated side across time ($p=0.002$), but no change in strength of the non-operated side ($p=0.1$) (Table 2&3).

There were significant improvements for all performance-based tests and self-reported function (Table 2). Compared to the pre-operative scores, patients demonstrated 16%, 20.9%, 23.9% and 62.7% improvements in TUG, SCT, 6MWT and HOS, respectively. Out of 48 subjects, 27.1%, 52.1%, 60.4% and 87.5% of subjects achieved the minimum detectable change at 90% confidence interval (MDC90) in TUG (2.49 seconds), SCT (2.6 seconds), 6MWT (61.34 meters) and HOS (9 points), respectively. These MDCs for the performance-based tests were previously

established in subjects with OA who underwent TKA and THA⁷⁴, while MDC for the HOS was reported from patients after hip arthroscopy⁷⁶.

Comparison with healthy adults

Healthy group and subjects 3 months after surgery were significantly different on height, mass and BMI (Table 1). Therefore, BMI was entered as a covariate in the univariate ANOVAs that examined differences between the THA and Healthy groups. Compared with the healthy group, patients at 3 months following THA took 20% more time to complete the TUG test ($F_{1,69}=7.26$, $p=0.009$), and were 24% slower on SCT ($F_{1,69}=4.19$, $p=0.044$). Patients also walked 14% less distance on 6MW test ($F_{1,69}=8.33$, $p=0.005$) (Table 2). Furthermore, patients had 46% less hip abductor strength on the operated side ($F_{1,69}=25.49$, $p=.000$), and had 25% significant deficit on the non-operated hip abductors strength ($F_{1,69}=4.28$, $p=0.042$). Additionally, patients had 5% less knee extensors strength in the operated side but this difference was not significant ($F_{1,67}=0.96$, $p=0.330$), however patients had significantly 15% stronger knee extensors on the non-operated side ($F_{1,67}=4.52$, $p=0.037$) (Table 2).

Table 2 Functional and clinical outcomes for subjects before THA (Pre), After THA (Post) and for Healthy adults

Variable	Pre (mean±SD)	Post (mean±SD)	Healthy (mean±SD)	*p-value (Pre vs. Post)	#p-value (Post vs. Healthy)
TUG (s)	9.39±2.79	7.62±1.71	6.34±1.23	<0.001	0.009
SCT(s)	17.38±8.32	12.51±3.66	10.12±2.43	<0.001	0.044
6MWT (m)	454.7±103.9	548.6±93.6	637.34±78.3	<0.001	0.005
HOS (%)	56.5±16.8	85.5±11.6	-----	<0.001	-----
Op. hip strength (N/kg)	1.38±0.78	1.36±0.68	2.53±0.96	0.602	<0.001
Non. hip strength (N/kg)	1.89±0.80	1.90±0.77		0.277	0.042
Op. Knee strength (Nm/kg)	1.20±0.61	1.41±0.62	1.49±0.50	0.005	0.330
Non. Knee strength (Nm/kg)	1.62±0.68	1.71±0.69		0.100	0.037
Hip Pain	5.5±2.3	1.0±1.2	-----	0.000	-----
Total hip ROM (°)	167.1±29.8	198.9±26.2	-----	0.000	-----
Pre= pre-operatively, Post=3 months post-operative, Op. = operated, Non. =non-operated. HOS: Hip Outcome Score; TUG: Timed Up and Go; SCT: Stair Climbing Test; 6MW: Six Minute Walk. *p-values for changes between pre-operative to post-operative values using paired t-test. #p-values for group comparisons between THA group 3 months post-operative, and healthy adults using univariate ANOVAs after accounting for BMI.					

Table 3 Changes in muscle strength across time using 2X2 factorial ANOVA

Variable	Pre-operative		3 mo. After THA		p-value
	Op	Non	Op	Non	
Hip Strength (N/Kg)	1.38±0.78	1.89±0.80	1.36±0.68	1.90±0.77	
Limb					<0.001
Time					0.951
Interaction					0.759
Knee Strength (Nm/Kg)	1.20±0.61	1.62±0.68	1.41±0.62	1.71±0.69	
Limb					<0.001
Time					0.006
Interaction					0.03

Contributions of physical impairments to functional outcomes

Three months after surgery

Age was significantly correlated with TUG ($r=0.334$), and with SCT ($r=0.321$). BMI was positively correlated with SCT and negatively with 6MW ($r=0.269$, and $r=-0.424$, respectively). Hip pain was negatively correlated with functional scores in HOS ($r=-0.374$), but did not demonstrate any significant relationship with performance-based functional scores (Table 4). Total hip ROM was directly correlated with HOS ($r=0.349$), and inversely correlated with TUG time ($r=-0.320$). Hip abductor and knee extensor strength showed a significant inverse correlation with TUG ($r=-0.431$ and -0.497 respectively) and SCT ($r=-0.501$ and -0.671 respectively), and direct correlation with 6MW ($r=0.520$ and 0.659 respectively), but had no relation with self-reported function (Table 4).

Regression analysis revealed that hip pain contributed to HOS scores and explained 15.7% of variance after accounting for the variance explained by age and BMI (Table5). Adding the total hip ROM explained an additional 8.7% of variance in HOS, but hip and knee strength did not add to the prediction of HOS (Table 5). Hip pain did not contribute to the TUG, SCT and 6MW scores. Total hip ROM explained an additional 7.2% of variance in TUG time. Hip and knee strength explained additional variance in TUG (11.4% and 7.1%, respectively), SCT (17.9% and 16.4%, respectively) and 6MW (14.9% and 11.7%, respectively) even after accounting for the variance explained in the preceding steps (Table 5).

Table 4 Relationship between Functional outcomes and physical impairments 3 months after THA

	HOS	TUG	SCT	6MW
Age	-.025	.334**	.321*	-.207
BMI	-.178	.203	.269*	-.424**
Hip Pain	-.374**	-.083	-.007	.052
Total ROM	.349**	-.320*	-.197	.170
Hip Strength	.184	-.431**	-.501**	.520**
Knee Strength	.169	-.497**	-.671**	.659**
HOS: Hip Outcome Score; TUG: Timed Up and Go; SCT: Stair Climbing Test; 6MW: Six Minute Walk.				
** Correlation is significant at the 0.01 level (2-tailed).				
*Correlation is significant at the 0.05 level (2-tailed).				

Table 5 Hierarchical linear regression for functional measures 3 mo. after THA

Hip Outcome Score					
Model	R	R²	R² Change	P-value change	P-value model
1.	.196	.039	.039	.429	.429
2.	.442	.195	.157	.007	.026
3.	.532	.283	.087	.031	.008
4.	.550	.303	.020	.287	.011
5.	.559	.312	.009	.473	.018
Timed Up and Go					
Model	R	R²	R² Change	P-value change	P-value model
1.	.462	.214	.214	.006	.006
2.	.462	.214	.000	.963	.017
3.	.535	.286	.072	.048	.007
4.	.632	.400	.114	.009	.001
5.	.686	.471	.071	.027	<.001
Stair Climbing Test					
Model	R	R²	R² Change	P-value change	P-value model
1.	.501	.251	.251	.002	.002
2.	.507	.257	.007	.542	.005
3.	.524	.275	.018	.325	.009
4.	.673	.453	.179	.001	.001
5.	.786	.617	.164	<.001	<.001
Six Minute Walk					
Model	R	R²	R² Change	P-value change	P-value model
1.	.551	.304	.304	<.001	<.001
2.	.551	.304	.000	.974	.002
3.	.561	.315	.011	.418	.003
4.	.681	.464	.149	.002	<.001
5.	.762	.581	.117	.002	<.001
Model 1=Age + BMI					
Model 2=Age + BMI + Hip pain					
Model 3=Age + BMI + Hip pain + Total ROM					
Model 4=Age + BMI + Hip pain + Total ROM + Hip Strength					
Model 5=Age + BMI + Hip pain + Total ROM + Hip Strength + Knee Strength					

Pre-operative to post-operative changes

Age and BMI did not show any relationship with changes in any functional measures. Reduction in pain, increase in total hip ROM and increase in knee extensor strength showed significant correlations with improvements in HOS score and all performance-based function measures (Table 6). Increased hip strength was only significantly correlated with improvement in SCT time and 6MW distance (Table 6). Hierarchical linear regression revealed that change in pain from baseline to 3 months after THA significantly contributed to the improvements in HOS. Change in pain explained an additional 24.6% of variance after accounting for age and BMI (Table 7). Conversely, addition of change in total hip ROM, and the change in hip and knee muscle strength did not contribute to the change in HOS after accounting for the variance explained in the preceding steps of the model. The change in hip pain significantly contributed to the improvements in TUG, SCT and 6MW scores explaining an additional 9.6%, 10.1% and 15.3% beyond the variance explained by age and BMI. Increased total hip ROM significantly contributed to the greater improvements in 6MW distance, explaining an additional 9.3% of the variance. Change in knee extensor strength significantly contributed to the change in 6MW distance explaining additional 9.2% of variance after accounting for the variance explained in the preceding steps of the model. However, change in hip or knee strength did not contribute to the change in TUG and SCT scores (Table 7).

Table 6 Relationship between pre- to post-operative changes in physical impairments and functional outcomes

	HOS	TUG	SCT	6MW
Age	.048	-.067	-.080	.007
BMI	-.128	-.108	-.079	-.095
Hip Pain	-.510**	.283*	.295*	-.402**
Total ROM	.344**	-.348**	-.277*	.423**
Hip Strength	.089	-.131	-.268*	.290**
Knee Strength	.375**	-.282*	-.287*	.512**
HOS: Hip Outcome Score; TUG: Timed Up and Go; SCT: Stair Climbing Test; 6MW: Six Minute Walk.				
** Correlation is significant at the 0.01 level (2-tailed).				
*Correlation is significant at the 0.05 level (2-tailed).				

Table 7 Hierarchical linear regression for pre- to post-operative changes in functional measures

Hip Outcome Score					
Model	R	R2	R2 Change	P-value change	P-value model
1.	.128	.017	.017	.705	.705
2.	.512	.262	.246	.001	.006
3.	.541	.293	.030	.198	.007
4.	.543	.295	.003	.700	.015
5.	.565	.319	.024	.255	.018
Timed Up and Go					
Model	R	R2	R2 Change	P-value change	P-value model
1.	.149	.022	.022	.623	.623
2.	.345	.119	.096	.040	.155
3.	.429	.184	.065	.082	.081
4.	.429	.184	.001	.852	.143
5.	.457	.209	.024	.287	.155
Stair Climbing Test					
Model	R	R2	R2 Change	P-value change	P-value model
1.	.134	.018	.018	.684	.684
2.	.344	.119	.101	.036	.155
3.	.386	.149	.030	.238	.158

4.	.422	.178	.029	.248	.160
5.	.439	.193	.015	.407	.200
Six Minute Walk					
Model	R	R2	R2 Change	P-value change	P-value model
1.	.097	.009	.009	.819	.819
2.	.403	.162	.153	.009	.062
3.	.505	.255	.093	.031	.017
4.	.541	.292	.037	.159	.016
5.	.620	.385	.092	.022	.004
Model 1=Age+ BMI Model 2=Age+ BMI + Hip pain Model 3=Age+ BMI + Hip pain + Total ROM Model 4=Age+ BMI + Hip pain + Total ROM + Hip Strength Model 5=Age+ BMI + Hip pain + Total ROM + Hip Strength + Knee Strength					

Discussion

This study was conducted to determine how physical impairments are related to functional recovery after THA. Our first hypothesis was mostly supported, as hip pain was largely resolved and subjects demonstrated greater hip range of motion and better functional outcomes 3 months after THA (Table 2). Despite these improvements, there was no significant change in hip strength. The results of this study also support our second hypothesis as compared to healthy group, subjects 3 months after THA continue to have lower performance-based functional abilities, most notably for the demanding task of climbing stairs, as well as weaker hip abductor strength in both limbs. The third hypothesis was supported by the results, as three months after THA, hip pain and total hip ROM were the primary determinants of self-perceived function on the HOS, while strength of hip and knee muscles were most related to performance measures. Our fourth hypothesis was partially supported. Although greater reduction in pain was a determinant for improvement in self-reported function and performance-based function, there was little change in strength;

therefore, change in hip strength was not strongly related to improvements in performance-based measures of recovery.

Overall, the magnitude of improvement was greater for the self-reported questionnaire when compared to the change in performance-based measures. Subjects reported 63% greater function based on the scores from the HOS, while only demonstrating a 16% and 21% improvement in TUG and SCT times and 24% greater distance walked during the 6MW test. Our findings support the fact that THA can positively impact functional capacity as early as 3 months after surgery^{3,6,8}, although the magnitude of change may be related to the metrics used to quantify functional improvement. These findings support previous findings after joint arthroplasty in which early and larger improvement are seen for self-reported physical functioning, with a gradual recovery in the performance-based measures during the first postoperative year^{3,6,8}. Despite the post-operative improvements in functional performance in THA group, comparison with healthy group showed diminished functional performance. Patients at 3 months after THA required 20% and 24% longer time to complete TUG and SCT tasks respectively, and covered 14% less distance on 6MW test compared to healthy individuals..

Knee extensors strength of the operated side significantly increased 3 months after surgery, but there was no change in the hip abductor strength compared to the pre-operative level. The lack of improvement in the hip abductors of the operated side can be explained by the early deterioration in hip muscle strength that exists after THA a consequence of the surgery. Judd et al have shown that hip and knee strength showed substantial decline at 1 month after THA⁸. Our 3 month results indicate that hip muscle strength is restored to pre-operative levels, but on average there was no

improvement compared to strength prior to surgery. Concernedly, we found that both the hip and knee muscles on the operated side were weaker than the non-operated limb at both time points. The knee extensors were 18%-26% weaker compared to the non-operated limb, while the hip abductors were 27%-28% weaker than non-operated limb.

These findings are in line with previous findings that found minimal strength recovery and persistent strength asymmetries between limbs. Judd and colleagues evaluated 26 patients before and after THA⁸ and found that hip abductor strength did not improve at 3 months compared to pre-operative scores. Other authors have found that this persistent weakness contributes to strength asymmetries between limbs one¹⁶⁻¹⁸ and two years after THA¹⁵.

Moreover, when compared to healthy individuals, patients after THA showed 46% and 25% weaker hip abductors in the operated limb and non-operated limb, respectively. Hip abductor strength deficit was previously reported in patients 3-4 months after THA^{8,19}. However, we observed no difference in knee strength between patients 3 months post-surgery and those in healthy individuals. Contrary to our finding, Judd and colleagues⁸ showed no change in knee strength at 3 months after surgery with greater and substantial deficit ($\approx 25\%$) compared to healthy that persist up to one year⁸.

Collectively, the residual strength and functional deficits at 3 months after surgery from this study, with the long-standing inter-limb strength asymmetry, and the functional limitations that persist at least one year post-operatively^{5,8,10,15-18}, suggest that current rehabilitation interventions early after surgery may not be sufficient to restore the normal strength and subsequently, normal function. In this study, subjects after surgery did not receive a standard rehabilitation intervention; it is likely that the

diversity in physical therapy duration may contribute to trajectory of their strength and functional recovery. These findings highlight the need for standardized and progressive strengthening exercises and/or post-surgical exercise programs that continue beyond 3 months post-operative. Strengthening exercise programs that begin 4 to 12 months after THA have improved outcomes in two randomized controlled trials by Trudelle-Jackson et al.⁷⁷ and Unlu et al.⁷⁸. These investigators found that strengthening programs initiated even up to one year after THA can improve hip and knee strength, gait speed, self-reported function and postural stability.

The relationship between pain, range of motion, strength and functional outcomes do support our third hypothesis. Three months after THA, hip pain and total hip ROM were the primary determinants of self-perceived function on the HOS, while strength of hip and knee muscles was not. Instead, hip abductor and knee extensor strength were the primary determinants of functional performance. This discrepancy suggests that patient's perception of functional abilities is primarily influenced by the intensity of pain, stiffness and flexibility of the operated hip while the ability to perform these tasks quickly or for longer duration is influenced by muscle strength. Although, greater total ROM was also a significant contributor of less time required to complete the TUG test, it only explained a small additional portion of the variance (7%) after controlling for age, BMI, and hip pain. These results are in line with the previous studies conducted in patients with hip OA³⁹, knee OA³⁵, and after joint arthroplasty^{36,37}. These previous studies suggested that self-reported measures are influenced by measures of pain and hip ROM while the performance-based measures are influenced by factors including strength and endurance.

In the present study, we prospectively investigated how changes in physical impairments (pain, ROM and strength) contribute to improvements in function after THA. We found that change in pain contributed to improvements in all functional measures but to a greater extent to those in self-reported questionnaire. Reduced pain was the primary determinant of improved self-reported function on HOS, it was also related to the reduced time required to complete TUG, SCT, and to the increased distance in 6MW. Change in hip abductor strength did not show any contributions to functional improvements; but change in knee strength slightly contributed to improvements in functional performance. This finding is not unexpected given the lack of substantial increase in hip strength and the significant increase in knee strength after surgery. Notably, the change in knee strength and total ROM were contributors only to improvement in 6MW distance, indicating that changes in these impairments were reflected only on more demanding task (6MW) that requires longer time and more endurance than the other two tests (TUG, SCT).

This study is not without limitations. Many perioperative factors may influence the persistent strength deficit. Surgical approaches, such as the anterolateral approach that require partial cutting of the hip abductor mechanism may prolong muscle strength recovery after surgery⁷⁹, while posterior approach has the benefits of preserving these muscles. Consequently, the anterolateral approach reduces post-operative hip abductors strength to a greater extent than posterior approach⁷⁹. At one year after THA, the higher incidence of positive Trendelenburg test when using anterolateral approach compared to posterior approach indicates the greater weakness of hip abductors in patients operated by anterolateral approach⁸⁰. All subjects in our study underwent an anterolateral or posterior approach; however, examining the

differences between two approaches was beyond the scope of this paper. Other surgical factors, including femoral offset, may also influence strength recovery. Femoral offset; defined as the perpendicular distance between the long axis of the femur and the center of rotation of the femoral head, influences the hip abductor strength. McGrory and colleagues found a positive correlation between femoral offset and isometric hip abductor strength, and suggested that greater femoral offset allows for better mechanical advantages for the abductors and consequently greater hip abductors strength⁸¹. We did not assess radiographs in this sample and were therefore unable to examine the potential confounding factor of surgical placement in the analysis of muscle strength.

Our analysis also only consisted of patients undergoing unilateral THA and we excluded individuals in whom a contralateral joint replacement was planned or occurred in the previous year. Because staged procedures and previous joint arthroplasties are common (18% in our sample; Figure 4), our patient sample may not represent the general THA population. However, excluding those subjects will allow controlling the confounding factors that may influence functional recovery. Further, evaluating actual physical activity level at home sitting will provide more objective measurement for physical function; however this component was not included in our study.

Conclusion

The findings of this study add to the existent evidence that self-reported and performance-based measures capture different aspects of disabilities that are influenced by different underlying impairments. Our study suggests that both methods should be utilized to evaluate functional recovery when the purpose of the intervention

is to reduce disabilities, as those measures provide distinct but complementary information. In the majority of patients, the hip pain is dramatically resolved by the surgery; however, weakness of the hip and knee muscles in the surgical side still signifies a major impairment after THA. Developing rehabilitation protocols that address these strength deficits is imperative. Future work examining the effect of targeted progressive strengthening exercises at post-operative rehabilitation phase or that continue beyond 3 months post-operative on the functional recovery is warranted. Although increasing strength and ROM, while reducing pain may improve function, it is also possible that improvements in function after THA, or conversely, the persistent deficits compared to control subjects, could be influenced by other physical and psychological factors that were not assessed in this study. Future studies should evaluate the effect of fear of movement, joint stability, balance, endurance, and hip flexion and extension strength on functional recovery. Moreover, as this study focused on functional recovery and the relationships with underlying impairments in the first three months after surgery, further research is needed to examine whether these impairments perpetuate a stable relationships in the longer term beyond 3 months.

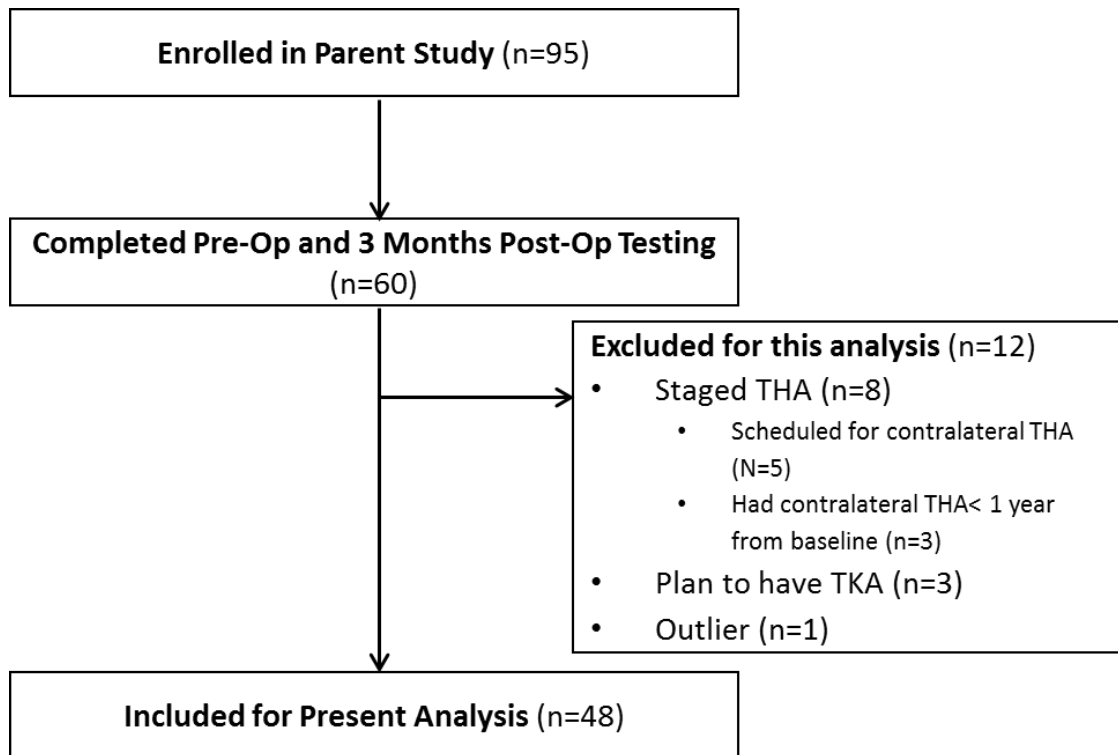


Figure 4 Flowchart of subject enrollment

Chapter 3

INTERLIMB MOVEMENT ASYMMETRY DURING THE SIT TO STAND TASK AND THE RELATED PHYSICAL IMPAIRMENTS BEFORE AND AFTER UNILATERAL TOTAL HIP ARTHROPLASTY (AIM 2)

Abstract

Background: Total hip arthroplasty (THA) is an effective option to reduce pain and improve function in patients with end stage hip osteoarthritis (OA). However, asymmetrical movement patterns are evident in patients after surgery during the sit-to-stand task. While few studies have evaluated STS biomechanics after THA, these studies have been limited to cross sectional designs, in which trunk movement strategies that might be utilized during STS task were not examined. Therefore, the longitudinal changes of STS movement patterns between pre-surgery and post-surgery time points are unknown. Consequently, it is also unidentified whether change in physical impairments such as pain and weakness are related to change in movement patterns after THA.

Purpose: The purpose of this longitudinal study was to evaluate the sit to stand (STS) movement patterns before and after THA and to identify the physical impairments that relate to asymmetrical movement patterns.

Methods: Thirty-nine subjects completed three dimensional motion analysis of the STS task before and after THA. Vertical ground reaction force (VGRF), hip and knee flexion moments, hip adduction moment and lateral trunk angle were computed. Physical impairments included hip pain, and isometric strength of the hip abductors and knee extensors.

Results: pre-operatively, subjects exhibited inter-limb movement asymmetries with lower vertical ground reaction force and smaller frontal and sagittal moments on the operated limb. Although there were significant improvements in movement symmetry 3 months after THA compared to pre-operative values, differences between limbs existed after THA in which there were greater forces and moments on the non-operated limb. Hip and knee strength was related to the compensatory movement pattern during STS.

Conclusion: Despite the improvements in biomechanical symmetry compared to pre-operative values, patients after surgery still performed the STS task with general unloading of the operated limb. Strength measure was related to unloading of the operated limb before and after THA, and that the change in strength was related to change in operated limb loading. This study suggests that improving the hip and knee strength may improve movement symmetry during STS.

Introduction

Osteoarthritis (OA) is the most common musculoskeletal disorder and one of the leading causes of pain and disability⁸². The lifetime risk of symptomatic hip osteoarthritis is estimated to be 25.3% by age of 85²⁰. Patients with end stage hip OA experience high levels of pain, and demonstrate substantial weakness in the knee and hip muscles^{15-17,22}. Those patients have functional limitations on self-reported and performance-based tests, when compared to healthy peers^{22,23} or to population-based group⁸³. They also move with inter-limb movement asymmetries^{24,25}, and abnormal movement patterns during different tasks, when compared to healthy controls²⁶.

Total hip arthroplasty (THA) is the treatment of choice for end-stage hip OA. More than 300,000 primary THA procedures are performed annually, the incidence of

this surgery is expected to increase nearly 100% by 2030²⁸. THA effectively results in substantial pain reduction^{1,2,6,84}, physical function improvements^{1-6,84,85}, and gradual muscle strength recovery^{15,16}, compared to pre-surgery measures. However, patients continue to demonstrate functional limitations^{5,10,84}, and physical impairments^{15-17,84}. Those patients also exhibit inter-limb movement asymmetries that increase loads on the non-operated limb and decrease reliance on the operated limb in various motor tasks such as gait^{24,40,86}, stair climbing⁴² and sit to stand (STS) tasks^{11,12,43}.

Sit to stand task (STS) task, defined as a movement of standing up from a chair to an upright posture, is a fundamental daily activity performed approximately 60 times per day by healthy adults⁴⁵. STS task is a biomechanically demanding task that requires greater joint forces and moments than those required during walking and stair climbing⁴⁶. Performing STS task also requires greater muscle strength relative to those during walking and stair climbing activities⁴⁷. As a bilateral support task, compensatory strategies during STS can be utilized to achieve the STS task; which makes it a sensitive measure to evaluate movement asymmetry. Movement asymmetry after THA is evident; patients transfer from sitting to standing position by unloading their operated side and shifting the weight to the non-operated side^{11,43}. Those individuals after THA also display altered kinematics and kinetics during STS, in which the operated hip joint moves with reduced peak flexion angle, reduced adduction and abduction range of motion, and smaller internal extension and adduction moments; compared to the non-operated hip and to limbs of healthy group^{12,48}.

Concernedly, such asymmetrical movement patterns, that exemplify an overuse on the contralateral side, are coincided with the non-random evolution of OA

in lower extremity joints, in which the contralateral hip followed by contralateral knee are mostly expected to show OA progression and subsequent replacement after THA¹³. Moreover, it has been shown by Christiansen and colleagues that greater weight bearing asymmetry during STS task was related to worse functional performance in patients after total knee arthroplasty (TKA)⁵². However, the underlying causes of presence of movement asymmetries after THA have not been investigated.

While previous studies have analyzed the lower limb biomechanics during STS in the THA population^{11,12,43,48}, these studies have been limited to cross sectional designs. Therefore, the longitudinal changes of STS movement patterns after THA are unknown. Consequently, it is also unidentified whether change in physical impairments such as pain and weakness are related to change in movement patterns after THA. Understanding how movement patterns change after THA, and identifying underlying physical impairments that contribute to movement asymmetries are imperative to develop targeted rehabilitation protocols to normalize movement patterns after THA.

Lower limb muscle weakness is likely a contributor to altered movement patterns in THA population. Weaknesses of hip and knee muscles are common impairments before and after THA. One month post-surgery, the isometric hip and knee muscles strength declined by 14%-26% relative to the preoperative value⁸⁴. Despite the gradual recovery in muscle strength^{8,15-17}, residual muscle weakness in the operated limb is still detectable up to two years following THA. Compared to the non-operated side, isometric strength deficits of 8%-16% in the knee extensor and the muscles around the hip joint in the operated side were found 6 months after THA¹⁵⁻¹⁷,

with the persistence of 10%-21% strength deficits 1 year post-surgery. Even 2 years after THA, the hip and knee muscle weakness in the operated limb was reported with the hip abductors showing the largest difference between limbs^{15,87}. In addition, the isometric hip abductors and knee extensors strength in the operative limb remained 25% and 17% less than those obtained in a healthy group, respectively^{19,84}.

It is known that knee extensors have main role for generating the antigravity moments at the knee, and hip abductors are essential for providing lateral stability during the STS task^{12,59}. The relation between strength of knee extensors and the STS functional and biomechanical performance has been previously documented. It has been shown that knee extensor weakness is related to impaired performance of STS in elderly individuals⁶²⁻⁶⁴. It has been reported in patients after TKA that inter-limb asymmetry of knee extensor strength was directly related to weight bearing asymmetry during STS^{52,88}, and that hip abductor strength was a contributor to better performance on 5-Chair Rise Test⁶⁹. However, the relationships between muscle strength and movement strategies before and after THA have not been evaluated. It is also likely that joint pain may influence movement strategies, but such relationship has not been evaluated in the THA population.

In addition to lower extremity angles and moments, trunk positioning and trunk movement play an important role in the overall movement strategies during STS performance^{49,50}. For example, flexing the trunk toward the knees before rising from the chair results in higher hip moments, longer movement time and delayed seat-off compared to starting the task from an erect position^{49,50}. Additionally, abnormal movement strategies of trunk have been previously quantified in patients with end-stage knee OA, who rise from a chair with higher maximal trunk flexion and higher

lateral trunk lean on the non-operated side when compared with the control group⁵¹. However, no study has evaluated trunk movement strategies that might be utilized during STS task in patients before and after THA. Examination of proximal adaptations may be important for a population in which pelvis and hip muscles demonstrate substantial weakness. Identifying the trunk movement strategies during STS performance may lead to better understand whether patients before and after THA utilize compensatory/or consequential trunk movement.

Understanding the proximal and distal biomechanical changes of STS task will provide new insights about STS movement strategies following THA. Elucidating the role of modifiable physical impairments, such as muscle weakness and pain, on altered movements, before and early after THA is critical to better design targeted postoperative rehabilitation interventions to maximize movement symmetry. Therefore, the purpose of this study was to prospectively investigate the sit to stand movement strategies before and after THA, and to identify how muscle strength and joint pain influence these movement strategies before and after THA. We hypothesized that: **1)** Before THA, patients will demonstrate inter-limb movement asymmetries with lower vertical ground reaction force, and smaller hip and knee moments in the operated limb compared to non-operated limb, and lateral trunk movement towards the operated side. **2)** Three months after THA, patients will show improvements in movement symmetry that is driven by the increase in vertical ground reaction force, and hip and knee moments in the operated limb. **3)** Despite improvements, patients 3 months after THA will still demonstrate some residual movement asymmetries. **4)** Surgical hip pain and muscle weakness will be related to less VGRF, smaller joint moments, and greater trunk lean on the operated side before

and after THA. Although understanding the relation between clinical impairments (i.e. pain, and strength) and movement patterns before or after surgery provides useful information, it is also important to determine how the post-surgical changes in STS biomechanics are influenced by the amount of increase or decrease of modifiable physical impairments. Therefore, we also prospectively investigated this relationship between impairments and movement patterns and hypothesized that **5)** Pre- to post-operative improvements in hip pain and strength will be positively related to increases in VGRF, joint moments and trunk lean on the operated side.

Methods

Subjects

This study was a prospective longitudinal study. In this analysis, subjects undergoing THA were derived from an on-going longitudinal study evaluating functional performance and movement patterns in patients before and after THA. Subjects with end-stage hip OA between the ages of 35 and 85, who were scheduled to undergo THA between March 2012 and April 2014, were recruited several weeks before the surgery. Subjects were referred by local orthopedic surgeons and from newspaper advertisements. Prior to enrollment, subjects were screened for eligibility using a telephone interview conducted by our research staff. Subjects in the parent longitudinal study were excluded if they have 1) neurological disorders that affect their ability to walk or rise from a chair, 2) any cardiovascular problems that limiting them their ability to climb a flight of stairs or walk for 6 minutes, 3) uncontrolled hypertension, or 4) history of cancer in the lower extremity. To avoid the potential confounding influence of other joint impairments, subjects were also excluded from

this analysis if they 1) had previous arthroplasty surgery less than 1 year from baseline (i.e. pre-operative) evaluation; or 2) plan to have an additional lower extremity arthroplasty (Figure 5). All surgical procedures were performed by anterolateral or posterior approach (Table 1). All subjects received home and outpatient physical therapy following THA, except for 2 subjects who received only home therapy. All subjects completed two testing sessions; 2-4 weeks prior to THA, and 3 months after THA. Testing session included functional evaluation and three dimensional (3D) motion analysis. All subjects signed informed consent forms approved by the Human Subjects Review Board at the University of Delaware prior to participation.

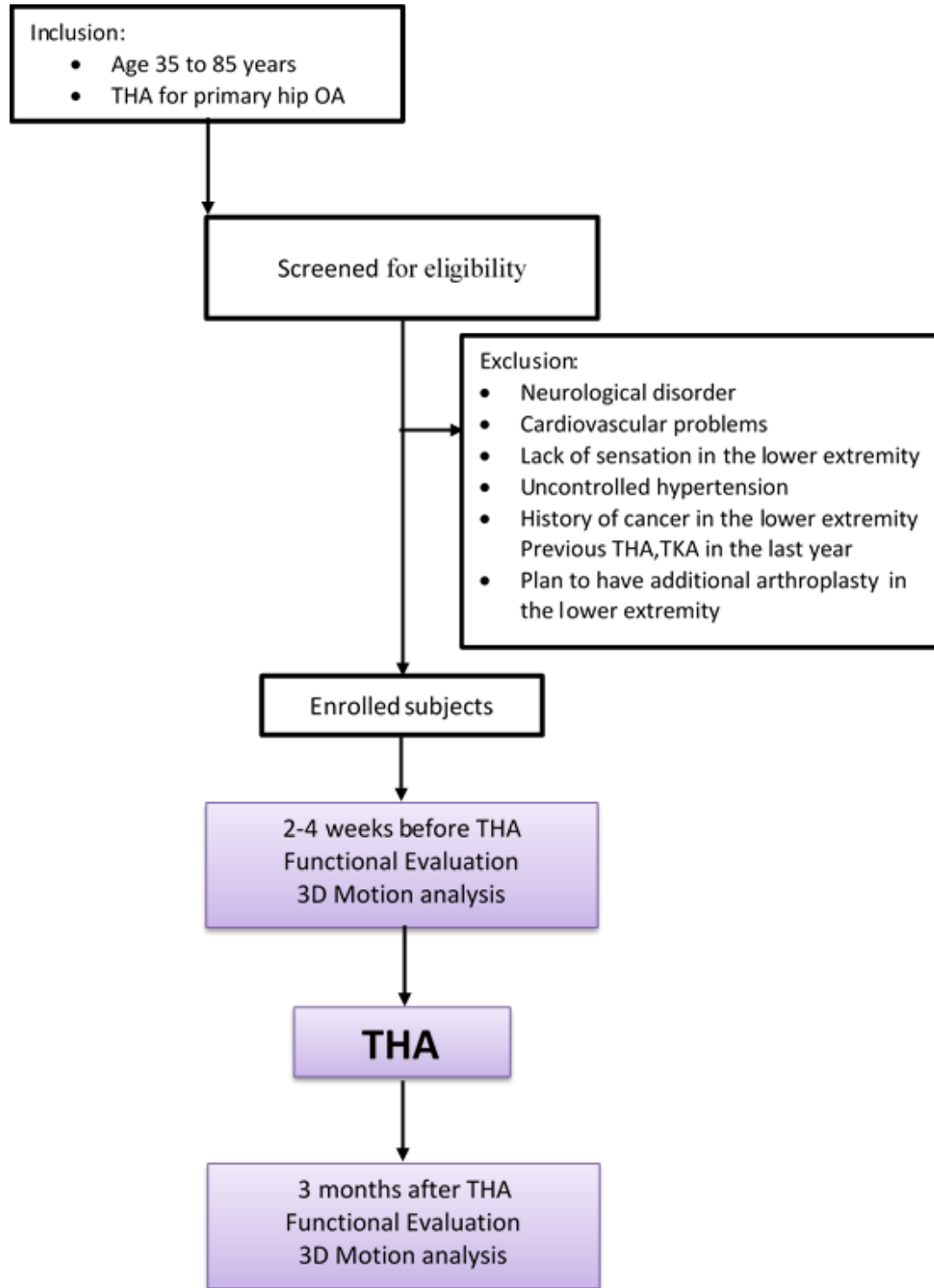


Figure 5 Study design for aim 2

Anthropometric measures and Pain assessment

Age, height, weight and sex were recorded, and body mass index (BMI) was calculated for each subject. Pain was assessed on a continuous scale from 0 to 10, subjects were specifically asked to “rate your average pain over the past week from 0 to 10, where 0 is no pain and 10 is the worst imaginable pain”. Pain was assessed for the affected hip, non- or less-affected hip, left knee, right knee, low back, and neck. Only the score for the affected hip was used in this analysis.

Strength measures

Hip abductor strength during an isometric contraction was measured by using a handheld dynamometer (Lafayette Manual Muscle Testing System; Model 01165; Instrument Company, Lafayette, IN). In this test, subjects were positioned in side-lying, and a non-elastic strap was placed around the thigh to provide additional resistance. The handheld dynamometer was placed proximal to the lateral femoral condyles and its position was held constant between trials to avoid changes in the resistance moment arm. The hand-held dynamometer was secured between the strap and the thigh, and subjects were asked to push against the strap (abduct their hip) with as much force as possible. Subjects were tested bilaterally, with the affected limb tested second. Subjects performed 3 trials with rest in between trials, and the maximal attempt was used as the maximal isometric contraction. This method has been shown to be a valid and reliable in older adults⁷¹ and in individuals after TKA⁷⁰. Muscle strength in Newton was normalized to subject's body mass in Kg.

Knee extensor strength was operationally defined as the peak isometric torque produced during a voluntary knee extension activity. Isometric knee extensors strength was assessed using an electromechanical dynamometer (Kin-Com 500 H, Chattanooga

Inc, Chattanooga, TN)". Subjects were seated on the dynamometer and a force measurement arm that contained the force transducer was attached to the ankle. The knee of participants was positioned at 75° of knee flexion and this position was fixed throughout the test. The axis of the dynamometer was aligned with the axis of rotation of the knee joint, and the force transducer was placed two inches above the lateral malleolus. The "unaffected" side was tested first. Subjects were asked to perform two submaximal and one maximal contraction (i.e. kicks) to warm up the muscle and familiarize them with the testing procedure. Then the subjects were instructed to "kick the leg" as hard as possible for a 3 second duration. Verbal encouragement was provided. The maximal force from 3 trials was used for the analysis. Torque in Newton-meters (Nm) was calculated as the force recorded at the force transducer multiplied by the linear distance in meters between the force transducer and axis of rotation. Muscle torque was then normalized to subject's body mass in Kg. This method has been shown to be a reliable measure in subjects with knee OA⁷² and subjects after TKA⁷³.

Motion Analysis

Sit to stand (STS) task was analyzed by using a three dimensional 8-camera motion capture system (VICON, Oxford Metrics, London, England) synchronized with two embedded force platforms (Bertec Corp., Worthington, OH, USA). Sixteen-millimeter spherical retro-reflective markers were placed bilaterally on anatomical structures that were used to define the trunk and lower extremity segments during the static trial. Markers were placed on the acromio-clavicular joint, iliac crest, greater trochanter, lateral femoral condyle, lateral malleolus, head of the 5th metatarsal, and 2 markers on the heel (Figure 6). Medial markers were used to compute knee and ankle

joint centers during a static trial. Functional hip joint centers were determined using a built-in algorithm that calculates the most likely intersection of all axes (effective joint center) and most likely orientation of the axes (effective joint axis) between the pelvis and femur based on a separate dynamic trial in which subjects performed hip flexion, extension and abduction during single leg stance⁸⁹. To track segments movement during the dynamic trials, rigid thermoplastic shells with 4 markers were attached to the trunk (Mid-thoracic area lateral to the spine) and bilaterally on the lower legs and thighs, and a shell with 3 markers was placed on the pelvis below the line between the 2 posterior superior iliac spines.

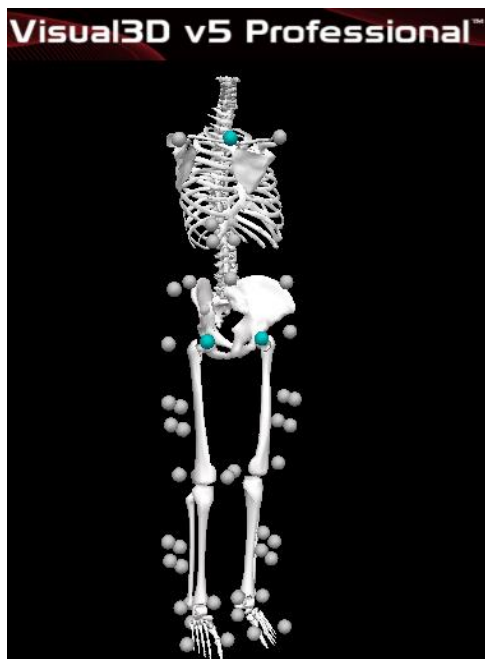


Figure 6 3D model template with the anatomical and tracking markers

Marker data and force platforms data were sampled at 120 Hz and 1080 Hz, and were filtered at 6 Hz and 40 HZ respectively, using a second-order phase corrected Butterworth filter. Visual 3D (v5.00.25) software program was utilized to compute joint angles and joint moments for each limb by using kinematics and inverse dynamic analysis techniques. Joints angles were calculated using Euler X-Y-Z sequence corresponding to flexion/extension, abduction/adduction, and then rotation sequences. Joints moments were expressed as external moments normalized to body mass and height (Nm/Kg*m).

Movement task

Patients were asked to perform 3 sit-to-stand trials. Subjects were instructed to stand from a piano stool of an adjustable height and without armrests or backrests (Figure 7). The height of the stool was set to the subject's knee joint line. Subjects were instructed not to use the arms to assist with rising from the chair. Subjects were also asked to practice the task before collecting three STS trials. For subject's safety, the stool was secured to the floor with adhesive tape to prevent movement during the task. Start stand, and end stand events were determined using the velocity and position of the acromio-clavicular (i.e. shoulder) marker, respectively. The start stand event was created when velocity of the acromio-clavicular marker exceeded a threshold of 0.1 m/s in the forward direction of movement. End stand was identified when the acromio-clavicular marker reached the highest position in upward direction.



Figure 7 Marker and laboratory set-up for the sit to stand task

Outcome variables

Peak and averaged vertical ground reaction force (VGRF), sagittal plane hip and knee moments, frontal plane hip moments, and frontal plane trunk kinematics were evaluated during STS. Peak external hip flexion moment, peak external knee flexion moment, peak and total external hip adduction moment were computed for each limb (Operational definitions and calculations are provided in Table 8). To characterize the loading pattern in our group, VGRF was measured to evaluate the maximum and the average amount of vertical force applied to the ground under each limb. The external knee and hip flexion moments were evaluated to identify any joint specific compensation during the movement. These moments represent the rotational

force applied by external forces (ground reaction force) and inertial properties that act to flex the knee and hip in the sagittal plane. These moments must be counterbalanced by internal moments produced by quadriceps and hip flexors muscles and soft tissue around the joints. Therefore, the external flexion moments are surrogate measures of the extensor muscle function of the lower extremity. Hip abductors account for frontal stability during STS by balancing the external adduction moment, so the peak and total external hip adduction moment were also computed during STS for each limb.

The frontal plane trunk kinematics were evaluated by measuring the lateral trunk angle. The lateral trunk angle was defined as the frontal plane angle of the trunk segment in relation to the pelvis segment. This angle was calculated at the time of maximum bilateral VGRF. Maximal bilateral VGRF is defined as the maximal summed value of the left and right VGRFs. Positive values for lateral trunk angle in degrees ($^{\circ}$) correspond with movement toward the operated side, while negative values represent angles toward the non-operated side.

Table 8 Operational definition and/or calculation for outcome variables

Outcome Variables	Operational Definition/Calculation
Peak VGRF	Maximum VGRF value between the start-stand to end-stand events. VGRF was measured in Newton then normalized to subject's body weight (N/BW).
Averaged VGRF	The average VGRF between the start-stand and end-stand events. VGRF was measured in Newton then normalized to subject's body weight (N/BW).
Peak hip flexion moment	Maximum external hip flexion moment between the start-stand and end-stand events. External moment was measured in Nm normalized to body mass and height (Nm/Kg.m)
Peak knee flexion moment	Maximum external knee flexion moment between the start-stand and end-stand events. External moment was measured in Nm normalized to body mass and height (Nm/Kg.m)
Peak hip adduction moment	Maximum external hip adduction moment between the start-stand and end-stand events. External moment was measured in Nm normalized to body mass and height (Nm/Kg.m)
Total hip adduction moment	Sum of the external hip adduction moment that occurred between the start-stand and end-stand events. This summed external moment was measured in Nm normalized to body mass and height (Nm/Kg.m)
Lateral trunk angle	The frontal plane angle of the trunk segment in relation to the pelvis segment at the time of maximal bilateral VGRF force. Positive values represent a lean toward the operated side, negative values indicate a lean toward the non-operated side.

Data analysis

For hypotheses 1-3, a two-way repeated measures analysis of variance (ANOVA) (time x limb) was used to detect main and interaction effects of VGRF and joint moments. The same analysis was used to measure changes in hip abductor and knee extensor strength. In the event of an interaction effect, follow-up paired t-tests were used. The one sample t-test was used to determine if lateral trunk angle at each time point was significantly different from zero. Changes in lateral trunk angle and change in hip pain were assessed using paired t-tests. For descriptive purposes, percent difference between limbs for VGRF and joint moments (i.e. by subtracting the operated from non-operated and then divided by non-operated value) and percent change between pre-operative to post-operative points (i.e. by subtracting the value at pre-op from value at 3 months and then divided by pre-op value) were computed and reported.

Pearson correlation analyses were used to quantify the association between biomechanical variables and physical impairments (hip pain, hip abductor strength, and knee extensor strength) in the affected side at pre-operative and at 3 month session. Changes in biomechanical variables (between pre-operative to post-operative timepoints) and changes in physical impairments (between pre-operative to post-operative timepoints) were also assessed for correlation.

Results

Out of fifty-four subjects who completed both functional and motion analysis sessions in the parent study, thirty nine subjects were enrolled in this study (Figure 8 & Table 9). Of the enrolled subjects, one subject did not complete the hip abductor strength test for the operated side at pre-operative session due to pain. One subject did

not complete the knee strength testing at 3 months follow-up due to time constraints during the testing session. Consequently, all correlation analyses that include knee strength or hip abductor strength included data from thirty-eight subjects.

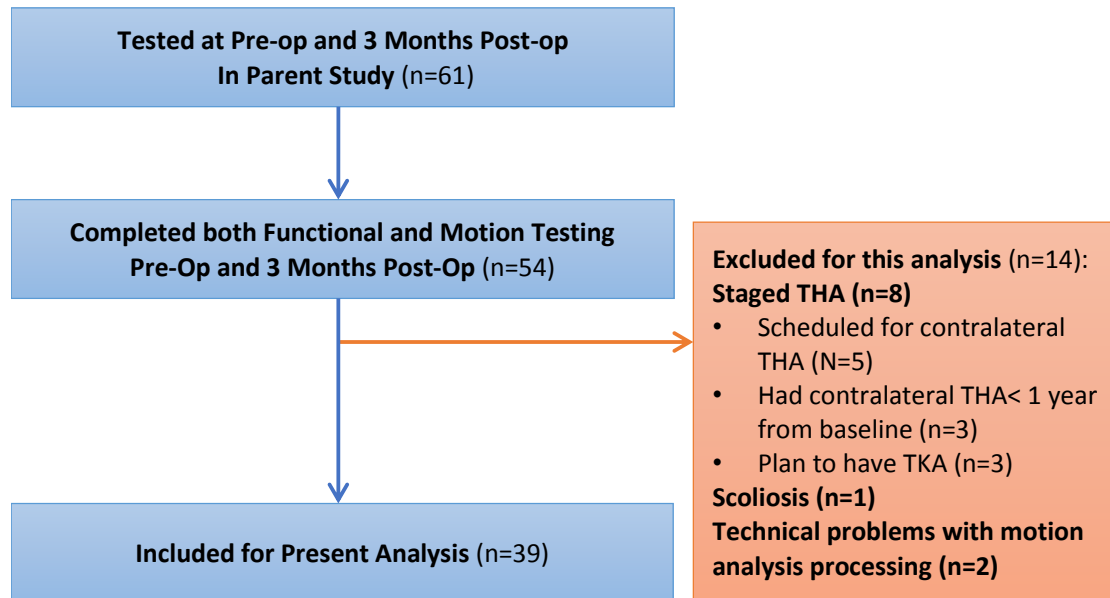


Figure 8 Flow chart of enrolled subjects

Table 9 Baseline characteristics of the THA group (Before THA)

Variable	Mean(SD)
Age (years)	64.1 (8.5)
Height (m)	1.73 (0.10)
Mass (Kg)	88.9 (22.2)
BMI (kg/m ²)	29.4 (5.8)
Sex: Male/Female (n)	23/16
Affected side: Right/Left (n)	22 (56%)/17 (44%)
Surgical approach. Posterior/Anterolateral	28/9 (2 unknown)

Peak VGRF showed a significant limb by time interaction ($F_{1,38}=16.03$, $p<0.001$) (Figure 9, and Table 10). Post hoc tests revealed a significant increase in peak VGRF on the operated ($p=0.001$) and a significant decrease in the non-operated side ($p=0.011$) compared to pre-operative values. Despite these changes, there were significant inter-limb differences at the pre-operative ($p<0.001$) and post-operative ($p<0.001$) sessions with higher peak VGRF under the non-operated limb. Similarly, the averaged VGRF also showed a significant limb by time interaction ($F_{1,38}=18.95$, $p<0.001$). Post hoc tests revealed a significant decrease in the non-operated Average VGRF ($p<0.001$), while the increase in the operated side approached significance ($p=0.065$). Similar to the peak VGRF, the non-operated limb had greater average force at the pre-operative ($p<0.001$) and post-operative ($p<0.001$) sessions.

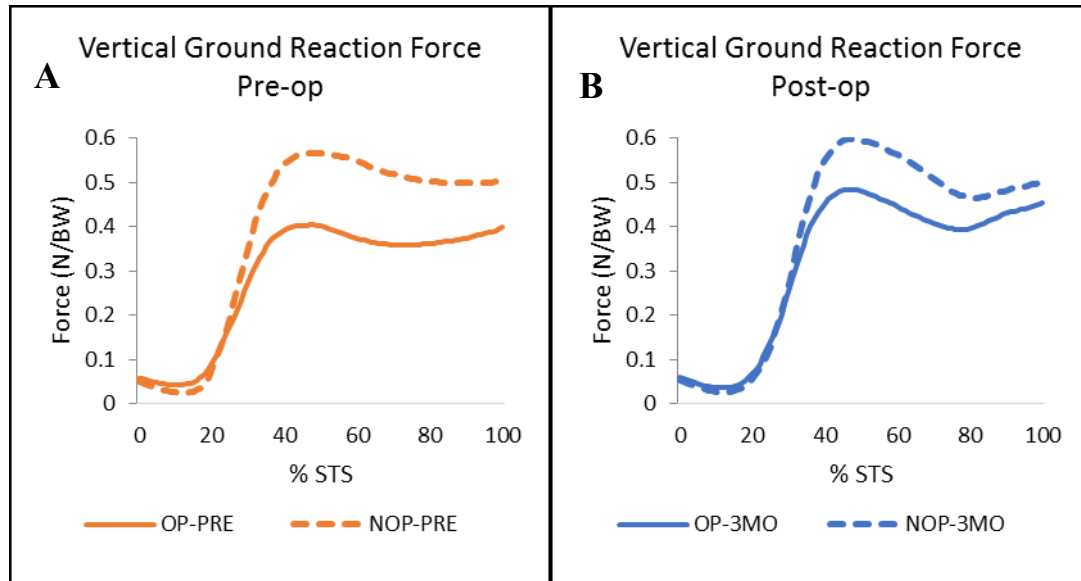


Figure 9 Average time series curves for VGRF for the non-operated (NOP) and operated (OP) limbs, pre-operatively (A), and 3 months post-operatively (B).

Table 10 Biomechanical outcomes and physical impairments at pre-operative and post-operative time points

Variable	Pre-operative		3 months pot-operative	
	OP	NOP	OP	NOP
Peak VGRF (N/BW)	0.50 (0.06)	0.66 (0.05)	0.53 (0.05)	0.64 (0.05)
Ave. VGRF (N/BW)	0.31 (0.04)	0.42 (0.05)	0.32 (0.04)	0.38 (0.04)
Peak hip flexion moment (Nm/Kg.m)*	0.36 (0.09)	0.48 (0.11)	0.39 (0.09)	0.44 (0.11)
Peak hip adduction moment (Nm/Kg.m)*	0.08 (0.04)	0.14 (0.06)	0.09 (0.04)	0.12 (0.06)
Total hip adduction moment (Nm/Kg.m)*	2.56 (2.04)	4.93 (2.97)	3.29 (2.16)	4.60 (2.71)
Peak knee flexion moment (Nm/Kg.m)*	0.39 (0.09)	0.58 (0.10)	0.44 (0.09)	0.57 (0.11)
Knee extensor strength (Nm/Kg)	1.24 (0.64)	1.67 (0.71)	1.45 (0.65)	1.75 (0.74)
Hip abductor strength (N/Kg)	1.45 (0.81)	1.95 (0.82)	1.46 (0.69)	1.99 (0.77)
Operated Hip pain	5.43 (2.36)		1.08 (1.29)	
Lateral trunk angle (Degrees)	4.31 (6.07)		2.43 (6.55)	
* Moments magnitudes were reported as absolute values.				
OP: operated side. NOP: Non-operated side				

Peak hip flexion moment showed a significant limb by time interaction ($F_{1,38}=13.50$, $p=0.001$) (Figure 10, and Table 10). There was a significant increase in peak hip flexion moment of the operated side ($p=0.032$), and a significant decrease in the non-operated side ($p=0.04$) at 3 months after surgery compared to pre-operative values. However, there was a greater peak hip flexion moment in the non-operated limb pre-operatively ($p<0.001$) and post-surgery (0.002) sessions.

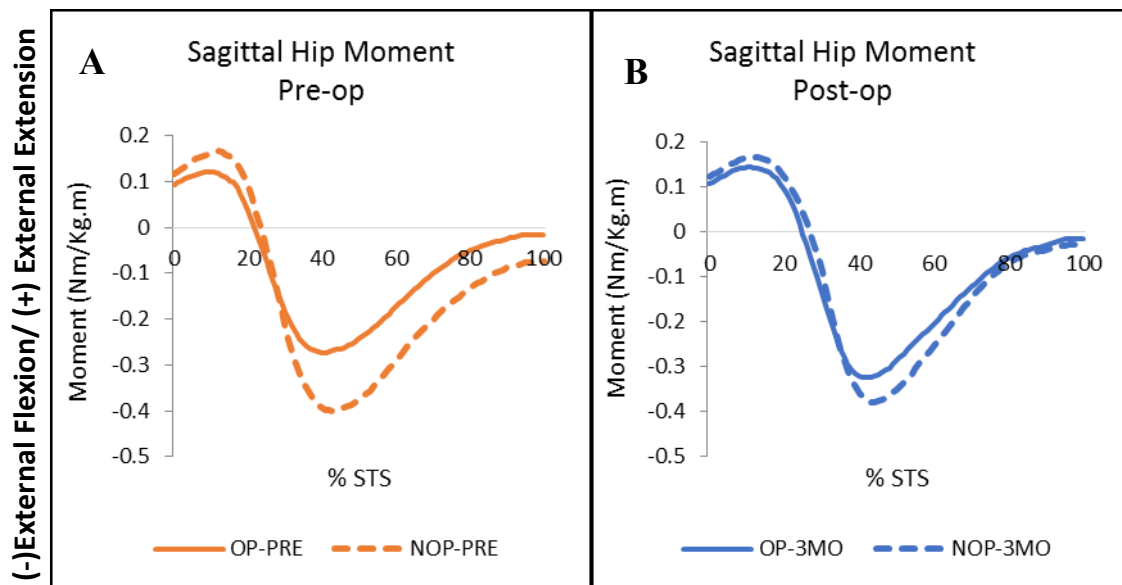


Figure 10 Average time series curves for sagittal hip moment for the non-operated (NOP) and operated (OP) limbs, pre-operatively (A), and 3 months post-operatively (B).

For peak hip adduction moment (Figure 11, and Table 10), there was a significant effect of limb ($F_{1,38}=18.65$, $p=0.000$), but the limb by time interaction

only approached significance ($F_{1,38}=3.91$, $P=0.055$). There was no significant effect of time ($F_{1,38}=0.02$, $p=0.899$). This outcome indicates that there were significant inter-limb differences at both time points with higher peak hip adduction moment in the non-operated side. For the total hip adduction moment, there was a significant effect of limb ($F_{1,37}=19.16$, $p=0.000$). The time ($F_{1,37}=1.56$, $p=0.528$) and interaction effects ($F_{1,37}=2.49$, $p=0.123$) were not significant. At both time points, there was significantly greater total hip adduction moment in the non-operated side.

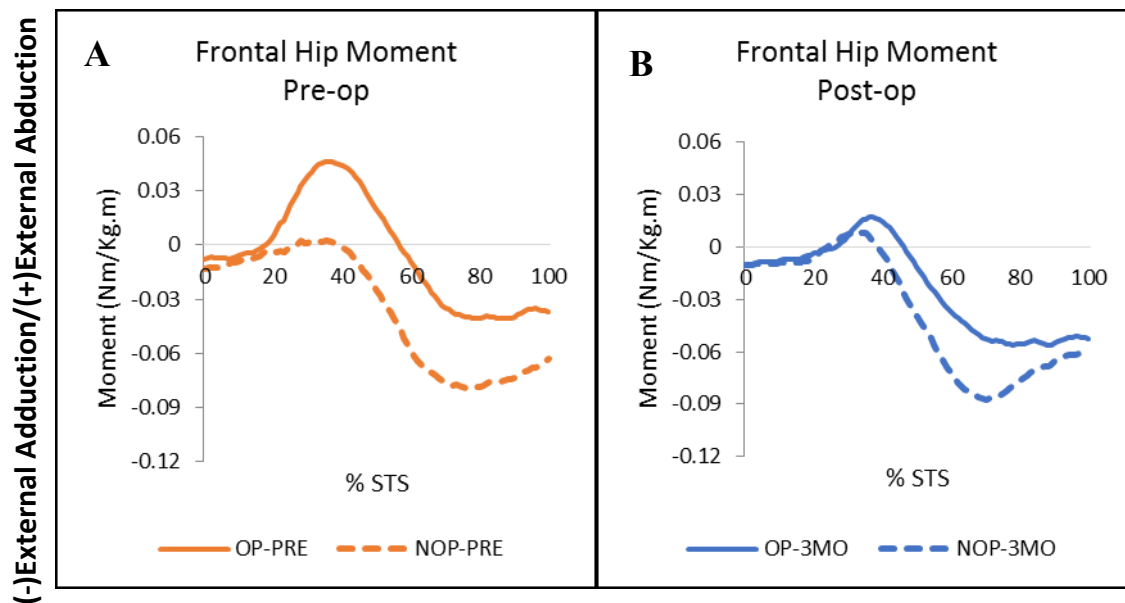


Figure 11 Average time series curves for frontal hip moment for the non-operated (NOP) and operated (OP) limbs, pre-operatively (A), and 3 months post-operatively (B).

Peak knee flexion moment (Figure 12, and Table 10) showed a significant limb by time interaction ($F_{1,38}=10.7$, $p=0.003$). There was a significant increase ($p<0.001$) in the operated side at 3 months compared to pre-operative value, while the non-operated side did not show any significant change ($p=0.783$). At both time points, there were significant asymmetries, with greater sagittal knee moments in the non-operated limb ($p<0.001$).

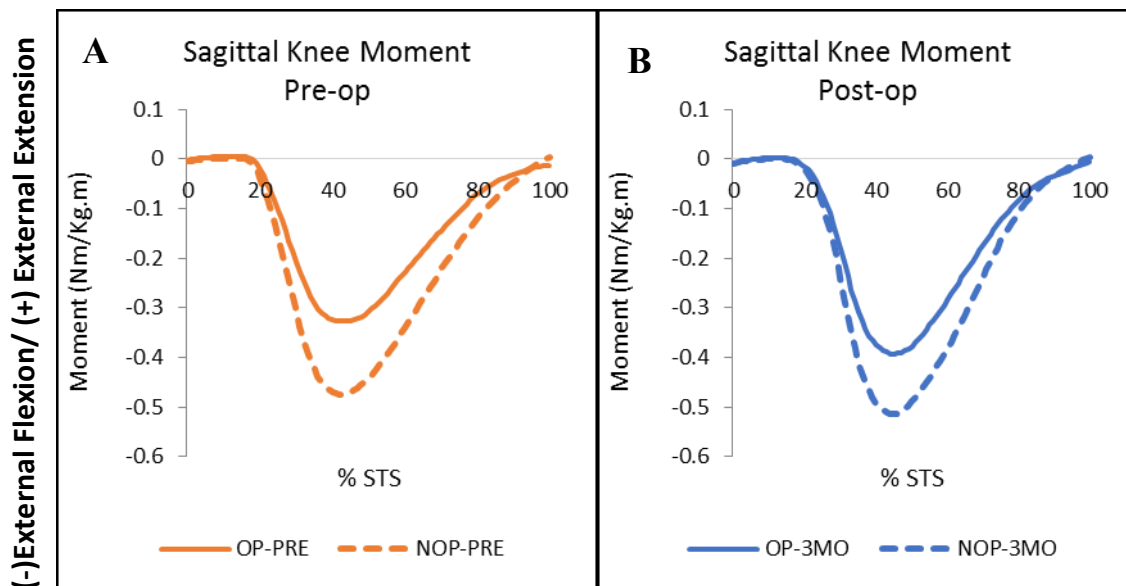


Figure 12 Average time series curves for sagittal knee moment for the non-operated (NOP) and operated (OP) limbs, pre-operatively (A), and 3 months post-operatively (B).

For trunk movement, at the time of maximum bilateral VGRF subjects had a significant lateral trunk angle towards the operated side ($p<0.001$, and $p=0.026$, pre-operatively and postoperatively, in order). Prior to surgery, the peak lateral trunk angle was 4.3° , and it was 2.4° three months after surgery (Table 10). Paired t-tests revealed a significant decrease in lateral trunk angle ($p=0.036$) after surgery. There was a high degree of variability with respect to trunk movement during the task (Figure 13).

Maximum bilateral VGRF occurred around 45% of STS phase (Figure 14)

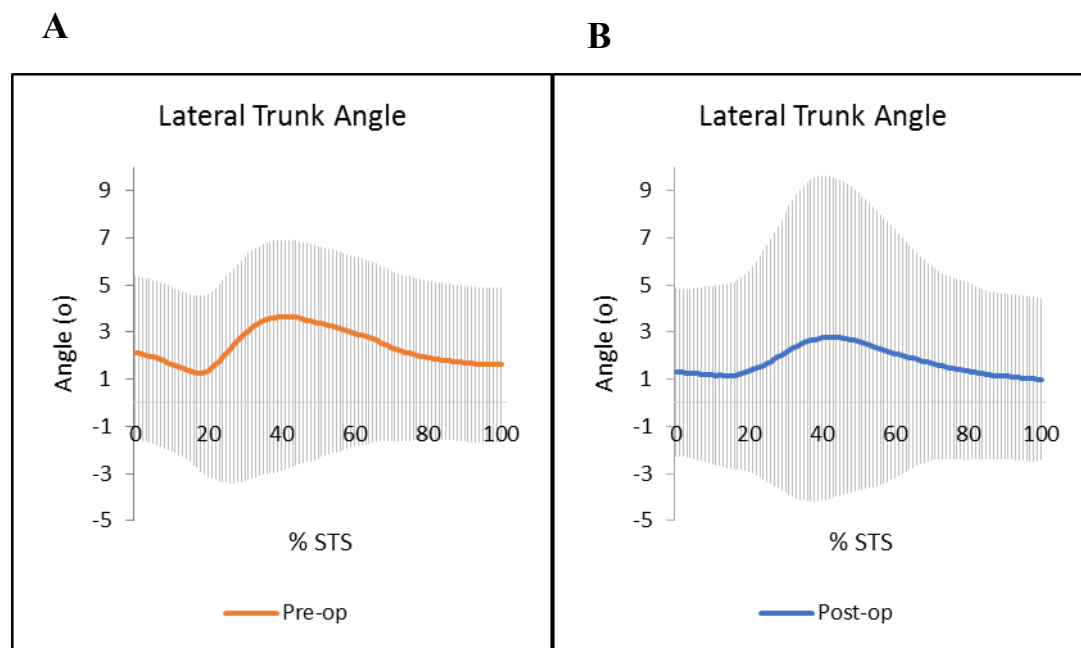


Figure 13 Average time series curves for lateral trunk angle pre-operatively (A), and 3 months post-operatively (B). Error bars represent 1 standard deviation.

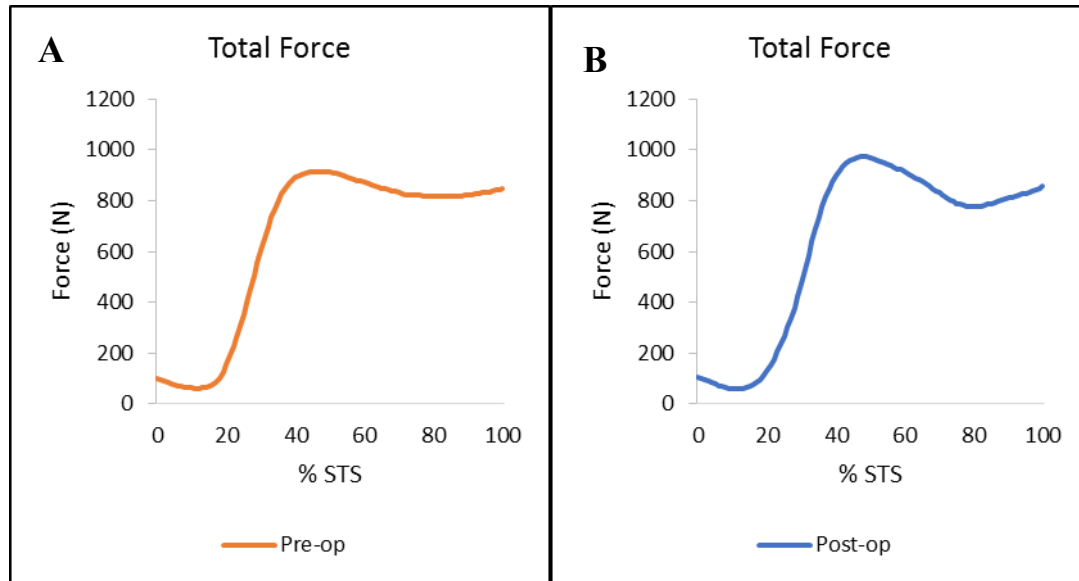


Figure 14 Average time series curves for total VGRF pre-operatively (A), and 3 months post-operatively (B).

Hip abductor strength (Table 10) showed a significant main effect of limb ($F_{1,37}=41.55$, $p<0.001$) with the operated limb having weaker hip abductors strength compared to the operated side at both time points. The limb by time interaction ($F_{1,37}=0.15$, $p=0.698$) and the effect of time were not significant ($F_{1,37}=0.10$, $p=0.751$), suggesting that there was no change in muscle strength on either leg between testing sessions (Table 10). For knee extensor strength (Table 10), there was a significant limb by time interaction effect ($F_{1,37}=4.77$, $p=0.035$). Post-hoc tests revealed significant inter-limb strength difference pre-surgery ($p<0.001$) and at 3 months post-surgery ($p<0.001$), but also a significant increase in knee strength of the operated side across time ($p=0.004$). There was no change in strength of the non-

operated side between timepoints ($p=0.229$). Hip abductor strength of the operated side was (27%) and (26%) weaker than those in the non-operated side, before and 3 months post-surgery, respectively (Table 10). Similarly, knee extensors of the operated limb were (25%) and (16%) weaker than the non-operated side before and 3 months post-surgery, respectively (Table 10). For pain scores, there was a significant reduction 3 months after surgery ($p<0.001$) (Table 10).

For the relationships between biomechanical variables and physical impairments at pre-operative time point, hip abductor strength showed a significant positive correlation with peak VGRF ($r=0.343$), and peak knee flexion moment ($r=0.361$), in which greater strength was correlated with greater peak VGRF and peak knee flexion moment (Table 11). Knee extensor strength showed a significant positive correlation with peak knee flexion moment ($r=0.443$). Hip pain did not show significant correlation with any of biomechanical variables. At 3 months post-surgery, knee extensor strength was positively correlated with Peak knee flexion moment ($r=0.514$) (Table 12). We also found that lower joint moments in the operated limb were associated with lower VGRF at both time points ($r=0.357-0.515$) (Tables 13 & 14). For pre-operative to post-operative changes, reduction in pain showed a significant relationship with increase in peak knee flexion moment ($r=-0.329$) (Table 15). Increase in hip strength was also correlated with increase in peak knee flexion moment ($r=0.333$).

Table 11 Pearson correlations between pre-operative biomechanical outcomes and physical impairments

Variable	Hip Pain	Hip strength	Knee strength
Peak VGRF	-0.270	0.343*	0.225
Averaged VGRF	-0.065	0.152	0.198
Peak hip flexion moment	-0.144	0.184	0.280
Peak hip adduction moment	0.149	-0.044	0.188
Total hip adduction moment	0.147	-0.006	0.143
Peak knee flexion moment	-0.144	0.361*	0.443**
Lateral Trunk flexion angle	0.019	-0.049	-0.108
** Correlation is significant at the 0.01 level (2-tailed).			
*Correlation is significant at the 0.05 level (2-tailed).			

Table 12 Pearson correlations between post-operative biomechanical outcomes and physical impairments

Variable	Hip Pain	Hip strength	Knee strength
Peak VGRF	0.000	0.173	0.234
Averaged VGRF	0.032	-0.119	0.201
Peak hip flexion moment	0.036	-0.042	0.102
Peak hip adduction moment	0.148	-0.289	-0.060
Total hip adduction moment	0.108	-0.148	0.065
Peak knee flexion moment	0.225	0.129	0.514**
Lateral Trunk flexion angle	0.110	0.174	-0.004
** Correlation is significant at the 0.01 level (2-tailed).			
*Correlation is significant at the 0.05 level (2-tailed).			

Table 13 Pearson correlations between the pre-operative biomechanical outcomes

Variable	Peak VGRF	Averaged VGRF	Peak hip flexion moment	Peak hip adduction moment	Total hip adduction moment	Peak knee flexion moment
Averaged VGRF	.716**					
Peak hip flexion moment	.484**	.515**				
Peak hip adduction moment	.311	.371*	.287			
Total hip adduction moment	.357*	.371*	.130	.934**		
Peak knee flexion moment	.364*	.244	.083	.010	-.023	
Lateral Trunk flexion angle	.013	.186	.092	-.002	-.024	.029
** Correlation is significant at the 0.01 level (2-tailed).						
*Correlation is significant at the 0.05 level (2-tailed).						

Table 14 Pearson correlations between the post-operative biomechanical outcomes

Variable	Peak VGRF	Averaged VGRF	Peak hip flexion moment	Peak hip adduction moment	Total hip adduction moment	Peak knee flexion moment
Averaged VGRF	.529**					
Peak hip flexion moment	.226	.159				
Peak hip adduction moment	.267	.421**	-.109			
Total hip adduction moment	.304	.400*	-.152	.876**		
Peak knee flexion moment	.411**	.137	-.136	-.004	.093	
Lateral Trunk flexion angle	.204	.168	.201	.305	.272	0.053
** Correlation is significant at the 0.01 level (2-tailed).						
*Correlation is significant at the 0.05 level (2-tailed).						

Table 15 Pearson correlations between pre- to post-operative changes in biomechanical outcomes and physical impairments

	Hip Pain	Hip strength	Knee strength
Peak VGRF	-0.267	0.182	0.283
Averaged VGRF	0.009	0.166	0.269
Peak hip flexion moment	-0.223	0.062	0.181
Peak hip adduction moment	0.137	-0.083	0.036
Total hip adduction moment	0.205	-0.033	-0.228
Peak knee flexion moment	-0.331*	0.338*	0.272
Lateral Trunk flexion angle	0.109	0.227	-0.183

Discussion

In this study, we evaluated the movement patterns during sit-to-stand performance in patients before and after unilateral THA. We hypothesized that patients prior to surgery would show movement asymmetries in STS biomechanical variables. Our results support this hypothesis, as patients had lower frontal and sagittal moments in the operated side during the chair rise task. We also hypothesized that patients would show improvement in biomechanical variables by 3 months after THA, but inter-limb differences would still persist. This hypothesis was also supported by our results. There were significant improvements in distal and proximal kinetics and kinematics, but subjects continued to rely on the non-operated leg 3 months after surgery. We also hypothesized that pain and weakness would influence biomechanical asymmetries. Our results suggest that both hip and knee strength influence sagittal plane biomechanics before and after THA.

Prior to THA, subjects preferentially shifted their weight toward the non-operated side, and unloaded the operated side. This was apparent in the 24% and 26% lower peak and averaged VGRF, respectively, on the operated limb compared to the non-operated side. Previous authors have found similar asymmetries in patients with hip OA using instrumented shoes⁹⁰ and conventional motion analysis.⁹¹ The reduction in VGRF seen in our sample was a likely factor that contributed to the attenuation of joint moments on the operated limb. Subjects had peak hip and knee flexion moments that were 23% and 30% less on the operated side compared to the non-operated side. Although there have been no longitudinal studies of this task before and after THA, our results are similar to other findings in patients with hip OA. Patients with mild-moderate hip OA have been shown to have 19%-20% lower sagittal hip and knee joint

moments in the operated side⁹¹. These findings suggest that the asymmetrical movement patterns may start early in the course of the disease and progress substantially by the time the patient is ready to undergo THA.

THA did have a positive influence on movement patterns and there was a fairly consistent pattern of improved symmetry 3 months after THA. These improvements were particularly evident for the peak VGRF and sagittal hip and knee moments, which demonstrated a 7% 15% increase in the operated limb and concomitant decrease of 4%-8% on the non-operated limb. There was also a significant improvement in proximal asymmetries, as lateral trunk angle was reduced to 2.4° after surgery, from an initial angle of 4.3° pre-operatively. This suggests that subjects after surgery moved with their trunk closer towards vertical line when arising from the chair, which may indicate less compensatory strategies. Differences in loading at the floor-foot interface, as indicated by the difference in VGRF, may require the substantial compensatory trunk shift towards the operated limb.

Despite a trend of improved symmetry at 3 months, most of the biomechanical variables still showed substantial interlimb differences after THA. Even after THA, subjects had 15% and 13% higher peak VGRF and Average VGRF, respectively, on the operated limb. Similar persistent interlimb differences were also seen for the joint moments in the sagittal plane for the hip and knee, and in the frontal plane for the hip in our study. While we only evaluated subjects 3 months after THA, other studies have suggested that altered movement patterns do not resolve in the long-term. Boonstra et al. reported that at one year following THA, patients placed 17% greater VGRF under the non-operated limb⁴³. Even 4 years after THA, Talis et al. found that patients had 22% greater VGRF on the non-operated side during the STS task¹¹. Lamontagne and

colleagues¹², the first who analyzed 3D joint biomechanics of STS task after THA and compared to healthy peers, reported lower hip kinematics and kinetics of the operated hip in twenty patients, who were 6-15 months after THA, compared to the non-operated and to the healthy controls hips. These previous results collectively with data from current study indicate the persistent of altered loading pattern on the long term after THA, particularly for those at the level of the hip joint.

Asymmetrical movement patterns before and after surgery, which suggest an overuse on the contralateral side, are of concern. First, the pattern of overloading found in this study coincides with the non-random progression of OA in lower extremity joints. In an observational study, Shakoor et al. found that the contralateral hip joint followed by contralateral knee joint are the next most likely joints to show OA progression and subsequent replacement after THA¹³. It is possible that continued reliance on the non-operated limb expedites the cartilage wear and symptomatic progression on the non-operated limb and contralateral joints, although future prospective studies are needed to substantiate this possibility. Persistent movement asymmetries are also concerning because greater weight bearing asymmetry during STS task was related to worse functional performance in patients after total knee arthroplasty (TKA)⁵². It is possible that favoring the non-operated limb to complete functional tasks, does not completely compensate for the functional deficits associated with the surgical limb. It is logical to expect a similar phenomenon in patients with movement asymmetries after unilateral THA. Identifying underlying physical impairments that contribute to movement asymmetries are imperative to develop targeted rehabilitation protocols to normalize movement patterns after THA, which may in turn, maximize functionality too.

The knee extensors generate the antigravity moments at the knee, and hip abductors are essential for providing lateral stability during the STS task^{12,59}. Weakness of knee extensor has been shown to relate to poor performance of STS in elderly individuals⁶²⁻⁶⁴. After TKA, the inter-limb asymmetry of knee extensor strength was directly related to weight bearing asymmetry during STS^{52,88}, and that hip abductor strength was a contributor to better performance on 5-Chair Rise Test⁶⁹. Given these previous findings, as well as the fact that lower extremity muscle weakness and pain are characteristic impairments in patients awaiting THA, we expected that impairments of the operated limb would influence the STS biomechanics symmetry. This hypothesis was partially supported. Hip strength was related to lower vertical forces and sagittal knee moments prior to surgery. Although we anticipated that subjects with weaker hip abductors would exhibit lower external hip adduction moment, this relationship was not found. It is possible that the frontal plane hip moments are not as reliant on hip abductor muscle strength because the STS is a bilateral task. During unilateral activities, the pelvis has to be stabilized by strong contraction of the hip abductors. During a bilateral task, the subject can rely on the non-operated limb to stabilize the pelvis during dynamic activities. We did find that weaker knee strength was related to lower sagittal knee moments at both time points. This finding is in line with previous study by Samuel et al. that showed isometric knee strength was positively correlated ($r = 0.51-0.67$) with peak knee flexion moments during the chair rise performance in healthy subjects⁵⁹. Although it was suggested that weakness of knee extensors is related to asymmetry in VGRF in patients after TKA^{52,88}, we did not find a relationship between knee strength and VGRF of the operated limb in our sample.

Contrary to our expectation, hip pain was not related to any biomechanical variable before and after THA. Change in pain was only related to change in knee flexion moment, although the association between these variables was small ($r=0.331$). This suggests that lower force and moments in the operated side is not necessarily driven by pain during the STS task. Similar findings were reported by Eitzen et al. who did not find a relationship between hip pain and weight bearing asymmetry in patients with mild to moderate hip OA. Similarly, the lack of association between knee pain and the unloading of the operated limb was documented in patients with mild knee OA⁹², at end-stage knee OA⁵¹, and after TKA⁵². It is possible that the lack of association at each time point is related to the way in which pain was assessed. In our protocol, we asked subjects to rate their average pain on a scale of 0-10, not the pain experienced during the STS task. If we had questions patients about pain associated with the task, we may have seen a correlation between pain and movement asymmetries. Interestingly, our results indicate that improvement in hip-specific joint impairments was related to kinetics improvement at the level of knee joint.

Weakness in the hip abductor muscle group is related to greater trunk and pelvis rotation in the frontal plane during gait in patients with end-stage hip OA (In press). We expected that subjects would consistently shift their trunk toward the operated side to decrease the biomechanical demand on hip abductors by lateralization the VGRF and subsequent reduction in the external adduction moment. However, lateral trunk angle was not related to hip weakness or joint pain. Patients also did not show a consistent proximal strategy to rise out of the chair, as is demonstrated by the marked variability in the frontal trunk angle at both time points (Table 4, Figure 12). Prior to surgery, 69% of subjects had a lateral trunk angle toward the operated side

(ranged from 0.5° to 15.1°), whereas in 23% of subjects shifted toward the non-operated side (ranged from -0.7° to -4.7°). 8% of the subjects did not shift either way and had an angle that approximated 0 degrees. Similar trends were found after surgery, in which 61% of subjects moved toward the operated side, 31% subjects moved toward the non-operated side (ranged from -0.5 to -12.4) and 8% of subjects remained in midline. We also sought to see whether the same individuals adopted the same pattern (toward or away from the affected side) at each time point. There was no consistent pattern on an individual level. The large variability in trunk movement at both time points and the random change after surgery may suggest that subjects perform the task with different strategies and that classification of different strategies is warranted as potentially various physical impairments are driving the variability in proximal compensations.

It is possible that factors beyond strength and joint pain are related to biomechanical asymmetries before and after surgery. A learned behavior strategy could be a factor that contributes to the movement asymmetry. It was suggested by Talis et al. that unloading of operated side reflects a “strategy of underuse” that may be learned before the surgery as a pain avoidance strategy. While after surgery, this strategy may be developed as a result of fear of movement, or due to the postoperative rehabilitation program that aims to minimize the risk of dislocation and early loosening. It was also suggested as a consequence of sensory deficit of the operated hip joint (i.e. lack of afferent impulses) that may be induced during surgery^{43,53}. Talis et al. suggested that during the STS task, a complex motor task that requires intact sensory receptors, subjects with sensory deficit after THA have difficulty controlling the operated hip hence they use it inadequately. Consequently they account more on

intact joint receptors of the non-operated side to achieve the task⁴³. Therefore, considering the loading asymmetry as learned behavior, it is important to address this asymmetry during rehabilitation after surgery by utilizing special components, such as visual feedback of forces under each limb during STS, to stimulate the patient to load both legs equally^{11,43,53}. Our sample also included subjects with anterolateral and posterior surgical approaches. The anterolateral approach requires partial cutting of the hip abductor mechanism and may prolong muscle strength recovery after surgery⁷⁹. This perioperative factor may influence STS biomechanics after surgery.

This study is the first to have investigated the 3D lower limb joint kinetics and trunk compensations in patients before and 3 months after THA during the performance of the STS task. In summary, the main findings from this study were that 1) patients before and after THA presented with inter-limb movement asymmetries. 2) THA results in improvement of STS biomechanics. 3) Hip and knee strength related to the compensatory movement pattern during STS. 4) Therefore, future studies evaluating interventions that improving strength of operated limb muscles and utilizing special technique as visual feedback to maximize movement symmetry are warranted for older adults undergoing THA.

Chapter 4

INFLUENCE OF WEIGHT BEARING VISUAL FEEDBACK ON MOVEMENT SYMMETRY DURING SIT TO STAND TASK (AIM 3)

Abstract

Background: Weight bearing asymmetry during sit to stand task is common in individuals with hip osteoarthritis and after total hip arthroplasty (THA). Those individuals predominantly shift their weight to the non-affected limb and unload the affected limb during the chair rise. This alteration in ground reaction force also attenuates the hip and knee joint moments on the affected limb. Movement asymmetry is suggested to be utilized as a learned behavior that developed before or after THA. Including symmetry training to the rehabilitation programs in THA population may improve the movement symmetry. The purpose of this study was to evaluate the acute influences of real-time visual feedback of weight distribution on the interlimb joint movement symmetry during STS before and after THA, and examined whether the response to visual feedback is different between individuals awaiting THA and those who underwent THA, and whether the response could be influenced by the physical impairments of the operated limb.

Methods: Twenty-eight patients before THA and twenty-four patients after THA were participated in this study. Patients underwent 3D motion analysis of STS task and completed 3 trials of STS without visual feedback followed by 3 trials with visual feedback. Feedback during STS was given through the use of a custom-written software program that runs on a laptop computer. The input to the feedback system is

via two faceplates that transmits the weight under each limb. The visual display was on a monitor in front of patient, consists of two cylinders for each limb that fill or empty based on the percentage of weight that is distributed to each limb. Outcome measures to evaluate the interlimb symmetry, which is defined as the difference between limbs, were the vertical ground reaction force (VGRF), joint kinematics and kinetics. Paired tests were used to examine the change in symmetry index between two conditions. Pearson correlation analysis was used to examine the relationship between physical impairments and the magnitude of response to visual feedback.

Results: VGRF and joint kinetics asymmetry were significantly reduced with visual feedback in patients before and after THA. Strength of the hip and knee muscles was not related to the change in symmetry measures between conditions. There was no difference in response to visual feedback between patients before surgery and after surgery.

Conclusions: our results suggest that weight bearing feedback could have beneficial effect on movement symmetry in THA population during the STS task. Structured pre-operative and/or post-operative feedback program can be potentially utilized in the clinical setting. However, further research should assess the training effect of such visual feedback on movement symmetry, and to determine whether utilizing feedback program lead to long-term benefits on movement symmetry and function after THA.

Introduction

Sit to stand task (STS) task is a fundamental daily activity performed frequently by healthy adults⁴⁵. STS task is a biomechanically demanding task that requires greater joint forces and moments than those required during walking and stair

climbing⁴⁶. Performing STS task also requires greater muscle strength relative to those during walking and stair climbing activities⁴⁷. As a bilateral support task, compensatory strategies during STS can be utilized to achieve the STS task; which makes it a sensitive measure to evaluate movement asymmetry.

Weight bearing asymmetry is common in individuals with unilateral lower extremity pathologies such as osteoarthritis (OA), and after total joint replacement. Individuals with mild to moderate hip OA⁹¹, end-stage hip OA⁹³, and after total hip arthroplasty (THA)^{11,43,53} predominantly support their weight on the non-affected limb. This results in 17-22% less force under the affected limb^{11,43}. This alteration in ground reaction force also attenuates the hip and knee joint moments on the affected limb^{12,48,91}.

Although a certain level of weight bearing and joint kinetics asymmetry is present in the general healthy population^{11,12,48,91,94,95}, this level of asymmetry is accentuated in subjects after THA^{12,48}. Asymmetrical movement patterns in which there is a persistent overloading of the contralateral side is a concern. This pattern of overloading coincides with the non-random progression of OA in lower extremity joints. Shakoor et al. found that the contralateral hip joint followed by contralateral knee joint are the next most likely joints to show OA progression and subsequent replacement after THA¹³. It is possible that continued reliance on the non-operated limb expedites the cartilage wear and symptomatic progression on the non-operated limb and contralateral joints. In addition to the risk of contralateral disease progression, greater weight bearing asymmetry during STS task was related to worse functional performance in patients after TKA⁵². It is possible that favoring the non-operated limb to complete functional tasks does not completely compensate for the

functional deficits associated with the surgical limb. It is logical to expect a similar phenomenon in patients with movement asymmetries after unilateral THA.

The unloading strategy in patients after THA may also be a learned behavior that develops before THA in the presence of joint pain or weakness. It is also possible that post-operative factors, such as joint instability, decreased proprioception or fear of movement perpetuate the movement asymmetries and learned behavior after THA^{43,53}.

Considering the loading asymmetry as a learned behavior, it is important to address this movement impairment through targeted strategies, such as biofeedback of movement patterns. Previous works have shown that real time visual feedback of weight bearing distribution, transmitted via two Wii balance boards (WBB) interfaced with custom and commercially available software^{54-56,96} improved the weight bearing symmetry in healthy adults during a squat task⁵⁴. Subjects performed 6 squats with and without visual feedback, and there was a significant reduction in weight bearing asymmetry when feedback was provided. In patients with neurological diseases, 3 trials were performed with and without visual feedback of weight bearing asymmetry for both static standing and sit to stand tasks. In this population, there was a significant reduction of weight bearing asymmetry during static standing⁵⁵. Symmetry retraining through the visual feedback for patients during post-operative rehabilitation after TKA has also been shown to improve movement symmetry and function^{97,98}, suggesting that the addition of symmetry retraining to existing rehabilitation protocols may be advantageous for improving movement symmetry. Although visual feedback of weight bearing may reduce weight bearing asymmetry, the joint-specific kinetics and kinematics that are used to normalize ground reaction forces are unknown. It is possible that joint moments and angles, or trunk angles, will become more

asymmetrical and more divergent from normal in an attempt to make force under each limb more symmetrical.

Therefore, it is imperative to discern how subjects who exhibit weight bearing asymmetry implement movement strategies that normalize ground reaction force between limbs. In addition, given that pain and muscle weakness are likely contributors to movement asymmetry before and after THA, we sought to determine whether such impairments preclude/affect biomechanical response to visual feedback. The purpose of this study was to evaluate the immediate influence of real-time visual feedback of weight bearing on lower extremity kinematics and kinetics during a STS task in patients before and after THA. We hypothesized that 1) During receiving visual feedback, patients would exhibit increased symmetry in weight bearing and joint kinematics and kinetics, before and after THA; 2) Visual feedback would lead to larger increase in sagittal plane hip and knee moment symmetry in patients 3 months after THA compared to pre-operative session; 3) Operated limb strength and pain will influence the magnitude of improvements in VGRF and joint moment symmetry during receiving the visual feedback, before and 3 months following THA.

Methods

Subjects

In this analysis, subjects undergoing THA were derived from an on-going longitudinal study evaluating functional performance and movement patterns in patients before and after THA. Subjects with end-stage hip OA between the ages of 35 and 85, who were scheduled to undergo THA between March 2012 and April 2014, were recruited several weeks before the surgery. Subjects were referred by local

orthopedic surgeons and from newspaper advertisements. Prior to enrollment, subjects were screened for eligibility using a telephone interview conducted by our research staff. Subjects in the parent longitudinal study were excluded if they had 1) neurological disorders that affect their ability to walk or rise from a chair, 2) any cardiovascular problems that limiting them their ability to climb a flight of stairs or walk for 6 minutes, 3) uncontrolled hypertension, or 4) history of cancer in the lower extremity. To avoid the potential confounding influence of other joint impairments, subjects were also excluded from this analysis if they 1) had previous arthroplasty surgery less than 1 year from baseline (i.e. pre-operative) evaluation; or 2) plan to have an additional lower extremity arthroplasty. All surgical procedures were performed by anterolateral or posterior approach (Table 1). Subjects who completed testing session that included functional evaluation and three dimensional (3D) motion analysis of sit to stand task and received visual feedback condition at either before and after THA were enrolled for this study. All subjects signed informed consent forms approved by the Human Subjects Review Board at the University of Delaware prior to participation.

Anthropometric measures and Pain assessment

Age, height, weight and sex were recorded, and body mass index (BMI) was calculated for each subject. Pain was assessed on a continuous scale from 0 to 10, subjects were specifically asked to “rate your average pain over the past week from 0 to 10, where 0 is no pain and 10 is the worst imaginable pain”. Pain was assessed for the affected hip, non- or less-affected hip, left knee, right knee, low back, and neck. For this analysis; only the score for the affected and unaffected hip were used.

Strength measures

Hip abductor strength during isometric contraction was measured by using a handheld dynamometer (Lafayette Manual Muscle Testing System; Model 01165; Instrument Company, Lafayette, IN). In this test, subjects were positioned in side-lying, and a non-elastic strap was placed around the thigh to provide additional resistance. The handheld dynamometer was placed proximal to the lateral femoral condyles and its position was held constant between trials to avoid changes in the resistance moment arm. The hand-held dynamometer was secured between the strap and the thigh, and subjects were asked to push against the strap (abduct their hip) with as much force as possible. Subjects were tested bilaterally, with the affected limb tested second. Subjects performed 3 trials with rest in between trials, and the maximal attempt was used as the maximal isometric contraction. This method has been shown to be a valid and reliable in healthy adults⁷¹ and in individuals after TKA⁷⁰. Muscle strength in Newton was normalized to subject's body mass in Kg.

Knee extensors strength was operationally defined as the peak isometric torque produced during a voluntary knee extension activity. Isometric knee extensors strength was assessed using an electromechanical dynamometer (Kin-Com 500 H, Chattanooga Inc, Chattanooga, TN)". Subjects were seated on the dynamometer and a force measurement arm that contained the force transducer was attached to the ankle. The knee of participants was positioned at 75° of knee flexion and this position was fixed throughout the test. The axis of the dynamometer was aligned with the axis of rotation of the knee joint, and the force transducer was placed two inches above the lateral malleolus. The "unaffected" side was tested first. Subjects were asked to perform two submaximal and one maximal contraction (i.e. kicks) to warm up the muscle and familiarize them with the testing procedure. Then the subjects were instructed to "kick

the leg” as hard as possible for a 3 second duration. Verbal encouragement was provided. The maximal force from 3 trials was used for the analysis. Torque in Newton-meters (Nm) was calculated as the force recorded at the force transducer multiplied by the linear distance in meters between the force transducer and axis of rotation. Muscle torque was then normalized to subject’s body mass in Kg. This method has been shown to be a reliable measure in subjects with knee OA⁷² and subjects after TKA⁷³.

Motion Analysis

The STS task was analyzed by using a three dimensional 8-camera motion capture system (VICON, Oxford Metrics, London, England) synchronized with two embedded force platforms (Bertec Corp., Worthington, OH, USA). Sixteen-millimeter spherical retro-reflective markers were placed bilaterally on anatomical structures that were used to define joint segments during the static trial. Markers were placed on the iliac crest, greater trochanter, lateral femoral condyle, lateral malleolus, head of the 5th metatarsal, and 2 markers on the heel. Rigid thermoplastic shells with 4 markers were secured bilaterally on the lower legs and thighs and were used to track the motion of the segments during the dynamic walking trials. Pelvic motion was tracked using a rigid thermoplastic shell with 3 markers placed below the line between the 2 posterior superior iliac spines. Medial markers were used to compute knee and ankle joint centers during a static trial. Functional hip joint centers were determined using a built-in algorithm that calculates the most likely intersection of all axes (effective joint center) and most likely orientation of the axes (effective joint axis) between the pelvis and femur based on a separate dynamic trial in which subjects performed hip flexion, extension and abduction during single leg stance⁸⁹. To track segments movement, rigid

thermoplastic shells with 4 markers were attached to the trunk and bilaterally on the lower legs and thighs, and a shell with 3 markers was placed on the pelvis. Start stand, and end stand events were determined using the velocity and position of the acromio-clavicular (i.e. shoulder) marker, respectively.

Marker data and force platforms data were sampled at 120 and 1080, and were filtered at 6 Hz and 40 HZ, respectively. Visual 3D (v5.00.25) software program was utilized to compute joint angles and joint moments for each limb by using kinematics and inverse dynamic analysis techniques. Joints angles were calculated using Euler X-Y-Z sequence corresponding to flexion/extension, abduction/adduction, and then rotation sequences. Joints moments were expressed by as external moments normalized to body mass and height (Nm/Kg*m).

Experimental Approach

Subjects were asked to perform STS task in two conditions: without visual feedback (No-VF) and with visual feedback (VF). Subjects performed 3 trials of STS without visual feedback followed by 3 trials with visual feedback. Two practice trials preceded each condition to familiarize the subjects with the procedure. Subjects were instructed to stand from a piano stool of an adjustable height and without armrests or backrests. The height of the stool was set to the subject's knee joint line. Subjects were instructed not to use the arms to assist with rising from the chair. For subject's safety, the stool was secured to the floor with adhesive tape to prevent movement during the task.

Feedback during STS was given through the use of a custom-written software program that runs on a laptop computer. The input to the feedback system is via two force plates that transmit the weight under each limb. The visual feedback of left and

right weight distribution was displayed on a monitor in front of patient that consisted of two cylinders, those cylinders fill or empty based on the percentage of weight that is distributed to each limb (Figure 15). In the VF condition, patients were asked to put equal weight under each limb by trying to use the muscles and joints of the lower limbs in a similar way, and to keep their trunk in midline while using the feedback from the monitor to guide the weight under each limb.



Figure 15 Visual Feedback display during the STS task

Outcome variables

To measure the weight bearing distribution and the joint-specific kinematics and kinetics the following biomechanical variables were assessed: average vertical ground reaction force (VGRF), peak hip flexion moment, peak hip adduction moment, peak knee flexion moment, average hip sagittal angle, and average knee sagittal angle. All variables were assessed during the rising portion of the task. VGRF was measured in Newton then normalized to subject's body weight (N/BW), while joint moments were expressed as external moments that measured in Nm and normalized to body mass and height (Nm/Kg.m).

The symmetry index was computed for each variable. The symmetry index is a measure of difference between limbs and is calculated as the non-operated side subtracted from the operated side ($SI = \text{Operated} - \text{Non-Operated}$). Negative values represent inter-limb asymmetry in which the operated side has lower value. Perfect symmetry is when the Interlimb difference equals zero.

Lateral trunk angle was also evaluated to evaluate potential proximal compensatory strategies. Lateral trunk angle was calculated as the frontal plane angle of the trunk segment in relation to the pelvis segment at the time of maximum bilateral VGRF. Positive value for lateral trunk angle in degrees ($^{\circ}$) corresponds with movement toward the operated side, negative values indicate a lean toward the non-operated side.

Because the goal in this study was to determine the immediate effects of visual feedback on joint kinetics and kinematics in patients with weight bearing asymmetry, only subjects with weight bearing asymmetry were included in the analysis. Therefore, subjects with inter-limb difference in VGRF within ± 0.05 (N/BW) were excluded, while subjects with inter-limb difference beyond $+0.05$ or -0.05 were included in this

analysis. The interlimb difference of 0.05 was selected as the cutoff point based on data from 23 healthy subjects who exhibited mean absolute interlimb difference in VGRF of 0.03 (CI₉₅: 0.02-0.04) during the sit to stand task.

Data analysis

Mean and standard deviations for discrete biomechanical variables for both limbs, their symmetry indices, and for the physical impairments (hip pain, hip strength, and knee strength) were computed at pre-operative and post-operative time points. Paired t-tests were used to examine the difference between limbs. To test the response to visual feedback on the movement symmetry, paired t-test was used to compare the differences in symmetry index (i.e. interlimb difference) between the two conditions (No-visual feedback, and visual feedback) for each outcome variable, for subjects before THA, and at 3 months after THA. Given that patients before THA and after THA may not be the same subjects, independent t-tests were also used to evaluate whether the change in symmetry index between the two conditions, is different in patients at 3 months post-surgery than those before surgery. Effect sizes (Cohen's d) were calculated to describe the magnitude of "visual feedback", and were interpreted as large (0.8), moderate (0.5) and small (0.2).

Pearson correlation analyses were used to quantify the association between physical impairments of the operated limb (hip pain, hip abductor strength, and knee extensor strength), and the change in symmetry index that occurred between the two conditions. Pearson correlation analyses were also used to examine whether change in symmetry of VGRF was associated with the change in symmetry of joint kinetics and kinematics. Change in symmetry index between conditions was obtained by

subtracting the symmetry index at the “No-visual feedback” condition, from that in the “visual feedback” condition.

Results

Thirty-nine subjects completed motion analysis and functional evaluation before and after THA (same subjects in aim 2). The visual feedback condition was completed by 34 subjects before THA and by 35 subjects after THA. Of these subjects, 6 showed interlimb-differences less than ± 0.05 N/BW before THA, and eleven showed interlimb-differences less than ± 0.05 N/BW after THA. These subjects were considered to have symmetrical movement patterns and were excluded from this analysis. Therefore, total of 28 and 24 subjects were included in the analysis before and after THA, respectively (Table 16). For hip pain, hip strength and knee strength measures, significant differences were found between limbs at both time points ($p < 0.005$).

Table 16 Subject's characteristics and clinical measures before and after THA.

Variable	Mean(SD)	Mean(SD)
	Before THA	After THA
Age (years)	64.0 (8.6)	63.1 (8.0)
Height (m)	1.74 (0.10)	1.73 (0.11)
Mass (Kg)	90.16 (20.4)	88.7 (21.7)
BMI (kg/m²)	29.6 (5.5)	29.6 (6.1)
Sex. Male/Female (n)	19/9	12/12
Affected side. Right/Left (n)	14/14	12/12
Surgical approach. Posterior/Anterolateral	20/6 (2 unknown)	16/6 (2unknown)
Op. Hip Pain (1-10)	5.55 (2.20)	1.08 (1.31)
Nop. Hip Pain (1-10)	0.33 (1.04)	0.26 (0.86)
Op. Hip abductor strength (N/Kg)	1.46 (0.79)	1.42 (0.66)
Nop. Hip abductor strength (N/Kg)	2.04 (0.82)	1.94 (0.80)
Op. Knee extensor strength (Nm/Kg)	1.32 (0.66)	1.40 (0.60)
Nop. Knee extensor strength (Nm/Kg)	1.81 (0.74)	1.69 (0.69)
BMI: body mass index. Op: operated side. Nop: non-operated side		

Visual feedback (VF) before THA

During “No-visual feedback” condition, subjects before THA had significant interlimb differences for VGRF and joint kinetics ($p < 0.001$), but sagittal hip and knee kinematics were not different between limbs ($p > 0.05$) (Table 17). Visual feedback significantly improved the symmetry index of VGRF with a moderate effect size ($p < 0.001$, $ES = 0.49$) (Table 17, Figure 16). For joint kinetics, there was no improvement in peak hip flexion moment symmetry when receiving VF ($p = 0.20$) (Table 17, Figure 17), but there was significant improvement for peak knee flexion moment ($p < 0.001$,

ES=0.53) (Table 17, Figure 18), and for peak hip adduction moment ($p=0.001$, ES=0.50) (Table 17, Figure 19). Hip and knee flexion angle did not show significant changes during VF condition (Table 17, Figures 20&21). There was no change in lateral trunk angle did not change between two conditions (Table 17).

The increase in VGRF symmetry with VF was positively associated with change in symmetry of peak hip adduction moment and peak knee flexion moment ($r=0.55$, $p=0.003$ and $r=0.550$, $p=0.002$, respectively). Hip pain of the operated limb was directly correlated with change in symmetry of peak hip flexion moment ($r=0.380$, $p=0.047$), but negatively correlated with change in sagittal hip and knee angle symmetry indices ($r=-0.451$, $p=0.016$, and $r=-0.448$, $p=0.017$, respectively). However, hip and knee strength did not show any relationship to the change in symmetry of any biomechanical variable (Table 18).

Table 17 Discrete biomechanical variables and their symmetry indices in both conditions, in subjects before THA

Variable	No-VF condition (Mean (SD))			VF condition (Mean (SD))			Change in Interlimb MD between conditions		
	OP	NOP	Interlimb MD	OP	NOP	Interlimb MD	Change Mean(SD)	**P- value	ES
VGRF (N/BW)	0.30 (0.04)	0.42 (0.04)	-0.12 (0.05)*	0.33 (0.05)	0.42 (0.05)	-0.09 (0.07)*	0.03 (0.05)	0.000	0.49
Peak hip flexion moment (Nm/Kg.m)	0.35 (0.09)	0.49 (0.11)	-0.14 (0.10)*	0.37 (0.11)	0.49 (0.13)	-0.12 (0.10)*	0.02 (0.07)	0.161	0.20
Peak knee flexion moment (Nm/Kg.m)	0.39 (0.09)	0.60 (0.09)	-0.22 (0.10)*	0.43 (0.08)	0.60 (0.09)	-0.17 (0.10)*	0.05 (0.07)	0.000	0.50
Peak hip adduction moment (Nm/Kg.m)	0.08 (0.04)	0.16 (0.07)	-0.08 (0.08)*	0.12 (0.07)	0.16 (0.05)	-0.04 (0.07)*	0.04 (0.05)	0.001	0.53
Average sagittal hip angle (Degrees)	50.53 (9.86)	51.80 (9.61)	-1.26 (3.57)	49.94 (9.77)	51.26 (9.57)	-1.32 (3.45)	-0.06 (0.07)	0.669	0.01
Average sagittal knee angle (Degrees)	58.58 (8.34)	58.60 (9.11)	-0.02 (4.86)	58.26 (6.13)	58.07 (6.96)	0.19 (4.64)	-0.21 (1.37)	0.426	0.04
Lateral Trunk Angle (Degrees)	3.69 (6.04)			3.42 (6.59)			-0.27 (2.17)	0.518	0.04
No-VF: No visual feedback condition. VF: Visual feedback condition. MD: Mean difference. ES: effect size									
* Significant interlimb difference using paired t-test									
**P-value of change in interlimb difference between the two conditions using paired t-test.									

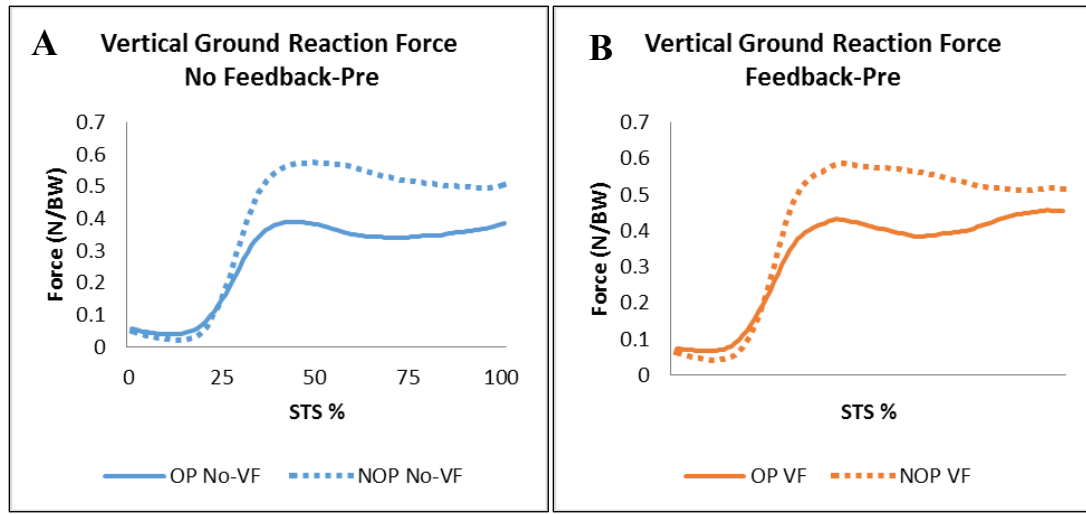


Figure 16 Average time series curves for VGRF for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), pre-operatively.

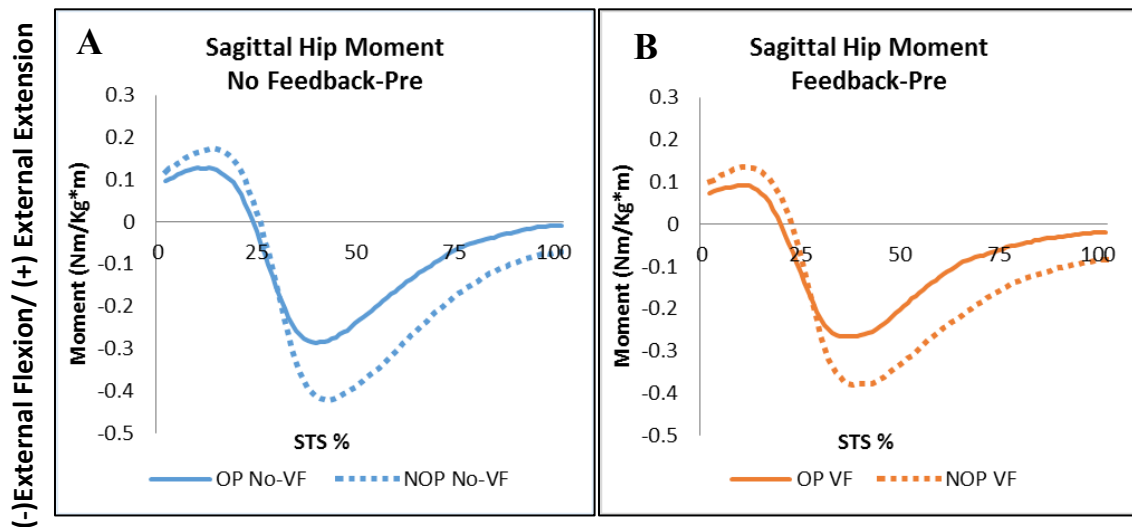


Figure 17 Average time series curves for sagittal hip moment for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), pre-operatively.

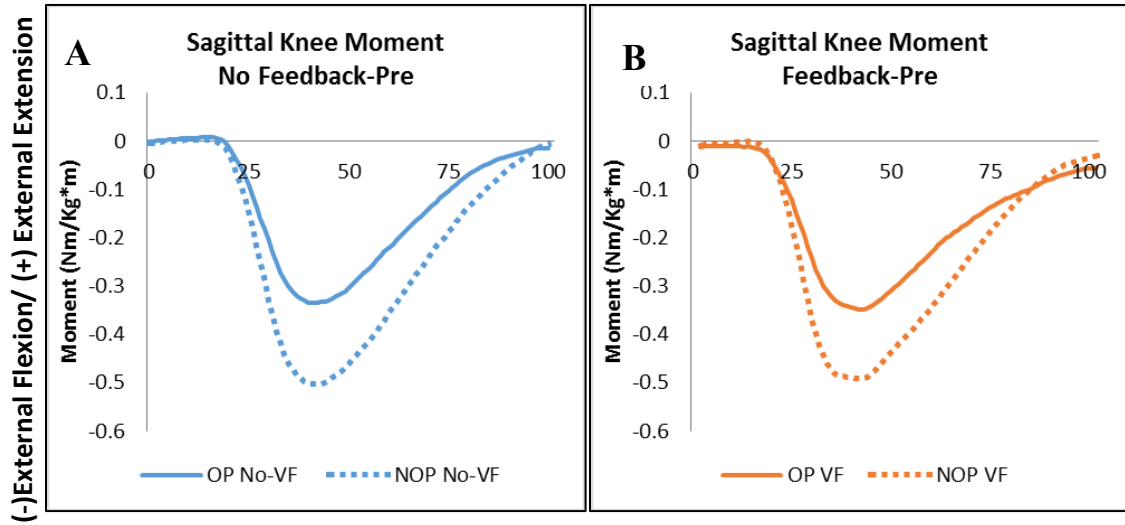


Figure 18 Average time series curves for sagittal knee moment for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), pre-operatively.

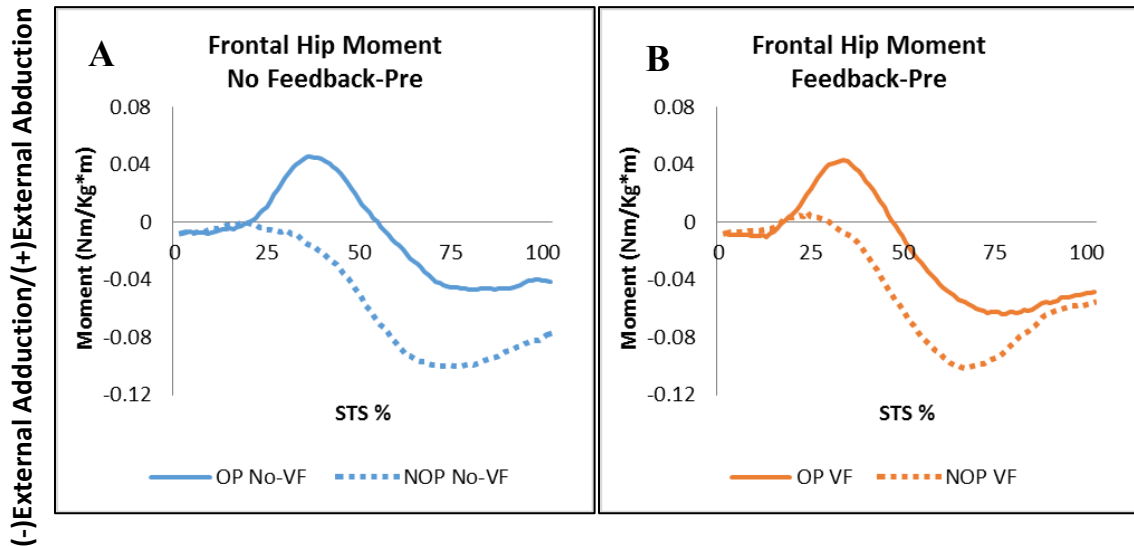


Figure 19 Average time series curves for frontal hip moment for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), pre-operatively.

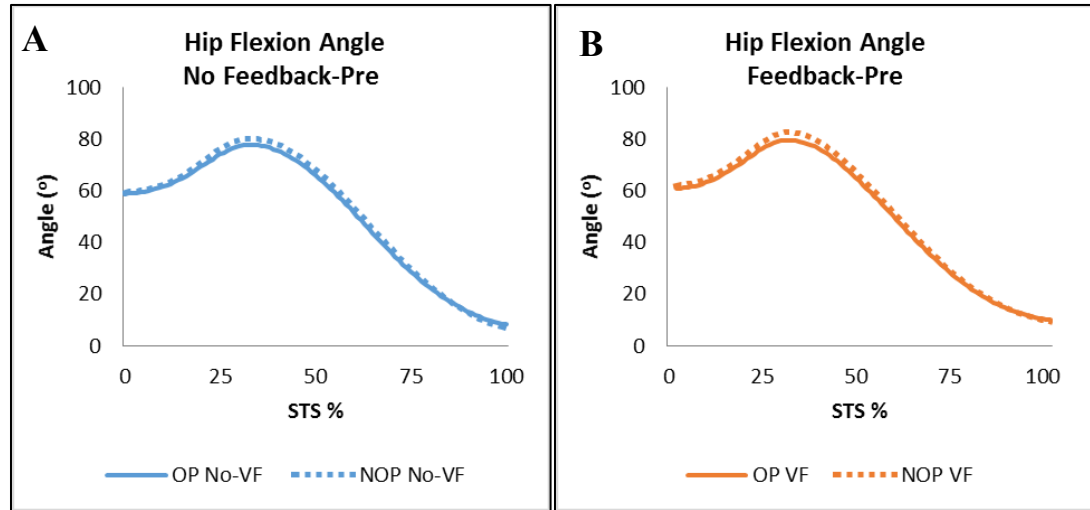


Figure 20 Average time series curves for sagittal hip angle for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), pre-operatively.

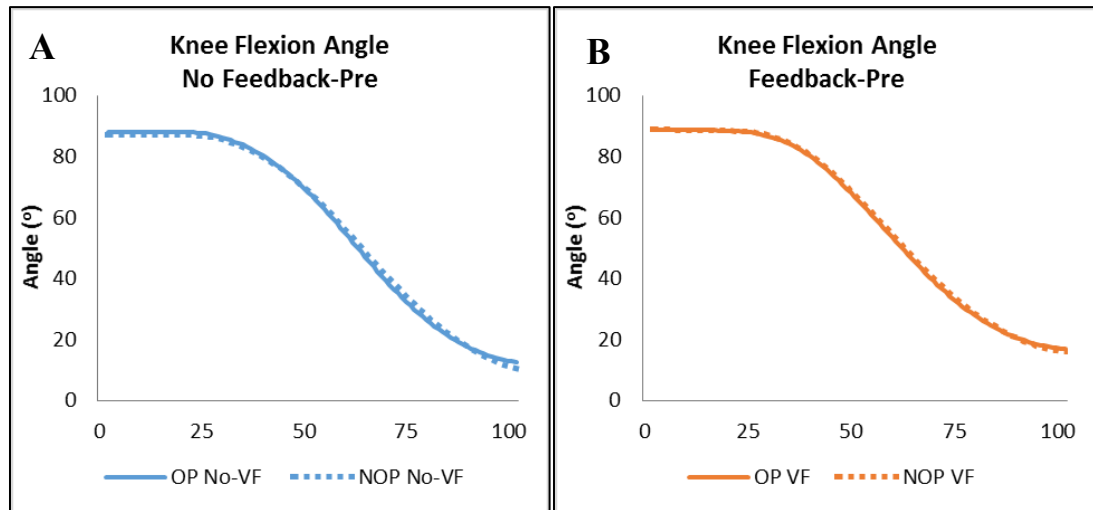


Figure 21 Average time series curves for sagittal knee angle for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), pre-operatively.

Table 18 Pearson correlation between physical impairments, change in VGRF symmetry, with the change in biomechanical symmetry between two conditions, at pre-operative session

Variable	Δ VGRF symmetry	Δ HFM symmetry	Δ HADM symmetry	Δ KFM symmetry	Δ SHA symmetry	Δ SKA symmetry
Δ HFM symmetry	0.298					
Δ HADM symmetry	0.548**	0.160				
Δ KFM symmetry	0.550**	0.010	0.053			
Δ SHA symmetry	0.247	0.061	-0.139	0.090		
Δ SKA symmetry	0.226	-0.187	-0.189	0.312	0.385*	
Hip pain	0.027	0.380*	0.339	0.074	-0.451*	-0.448*
Hip strength	0.037	-0.240	-0.056	0.352	0.055	0.068
Knee strength	-0.022	-0.087	-0.228	0.110	0.006	-0.069
Δ : change in symmetry index between two conditions. HFM : peak hip flexion moment. HADM : peak hip adduction moment. KFM : peak knee flexion moment. SHA: sagittal hip angle. SKA: sagittal knee angle.						

Visual feedback (VF) after THA

During the “No-visual feedback” condition, subjects 3 months after THA had significant interlimb differences for VGRF and joint kinetics ($p < 0.001$), but there was no interlimb difference in the sagittal hip ($p = 0.736$) and knee ($p = 0.765$) kinematics (Table 19). Similar to findings at pre-operative session, providing VF for subjects 3 months after surgery significantly improved symmetry index of VGRF with moderate effect size ($p = 0.005$, $ES = 0.66$) (Table 19, Figure 22). For joint kinetics, the symmetry of peak hip flexion moment did not show significant change when receiving VF ($p = 0.280$) (Table 19, Figure 23), but there was significant improvement in the symmetry index with small effect sizes in peak knee flexion moment ($p = 0.011$, $ES = 0.34$) (Table 19, Figure 24), and peak hip adduction moment ($p = 0.023$, $ES = 0.42$) (Table 19, Figure 25). The symmetry index of hip and knee flexion angles did not show any significant changes during VF condition (Table 19, Figures 26&27). Lateral trunk angle did not change between two conditions (Table 19).

The increase in VGRF symmetry with VF was positively associated with change in symmetry of peak hip flexion, peak hip adduction and peak knee flexion moments ($r = 0.528$, $p = 0.008$; $r = 0.719$, $p < 0.001$; and $r = 0.487$, $p = 0.016$; respectively). Change in symmetry in hip flexion moment was associated with change in symmetry of hip adduction moment ($r = 0.677$, $p < 0.001$). Pain and strength did not show any relationship to the change in symmetry of any biomechanical variable (Table 20).

Patients before THA and after THA showed similar response to visual feedback; the magnitude of change in symmetry index that resulted when visual feedback was provided was not significantly different between patients at two time points (Table 21).

Table 19 Discrete biomechanical variables and their symmetry indices in both conditions, at 3 months after THA

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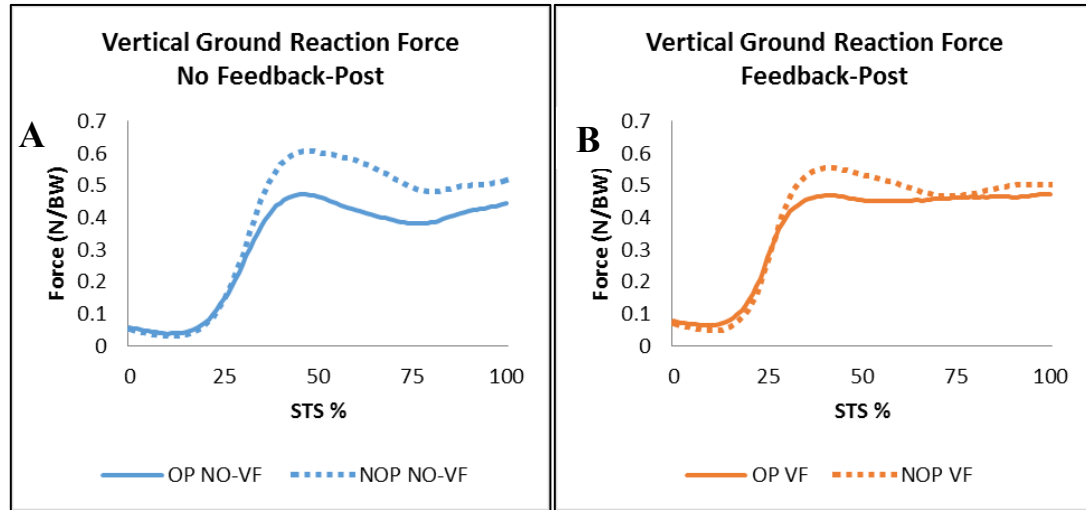


Figure 22 Average time series curves for VGRF for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), post-operatively.

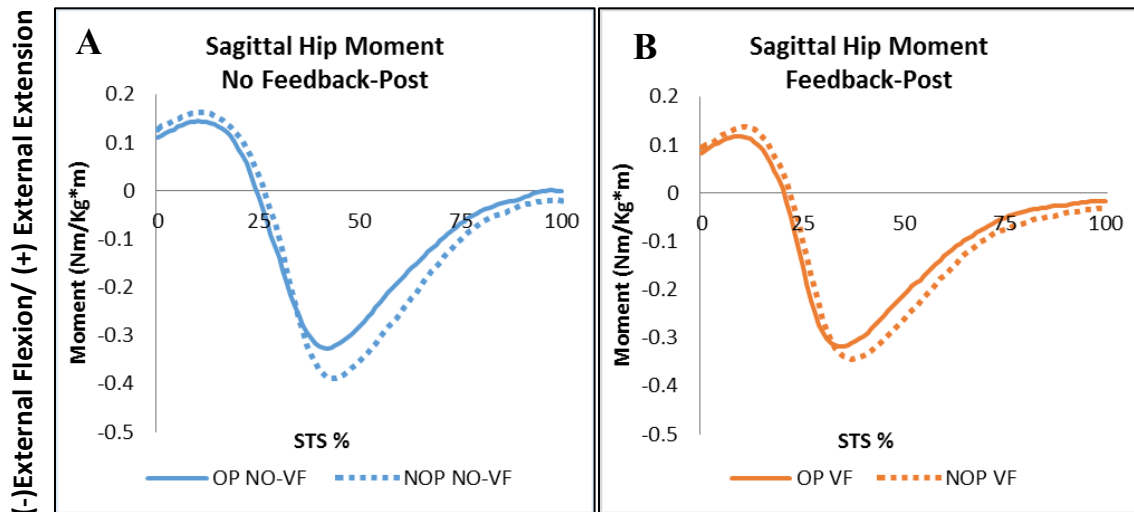


Figure 23 Average time series curves for sagittal hip moment for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), post-operatively.

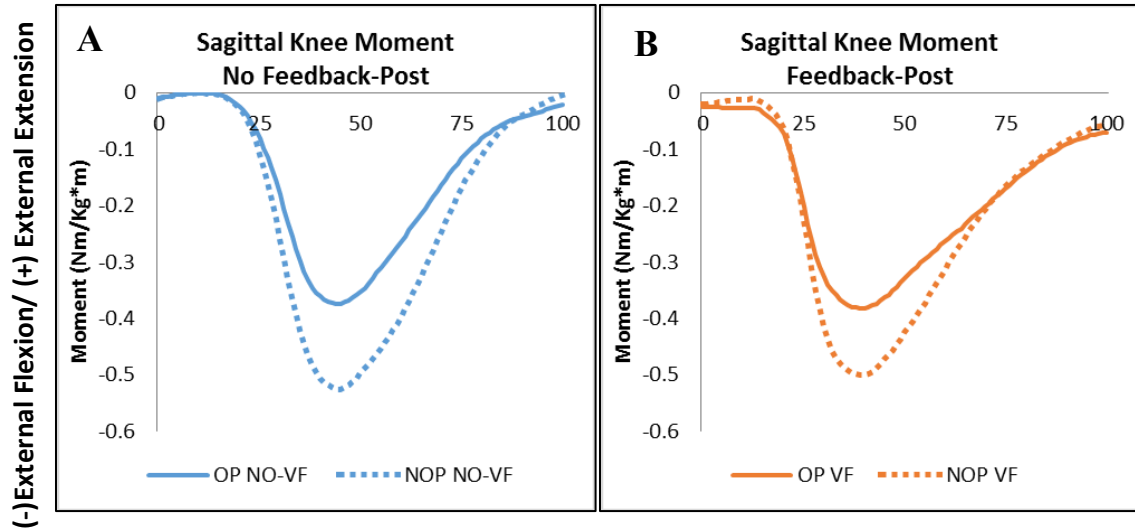


Figure 24 Average time series curves for sagittal knee moment for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), post-operatively.

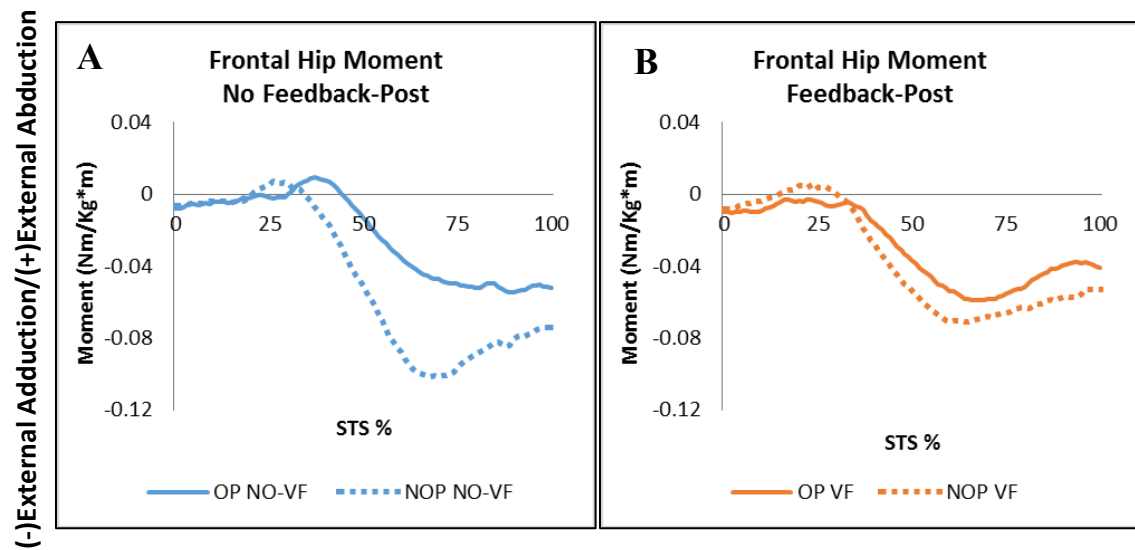


Figure 25 Average time series curves for frontal hip moment for the non-operated (NOP) and operated (OP) limbs, during **No-visual feedback (No-VF)** condition (A), and during **visual feedback (VF)** condition (B), post-operatively.

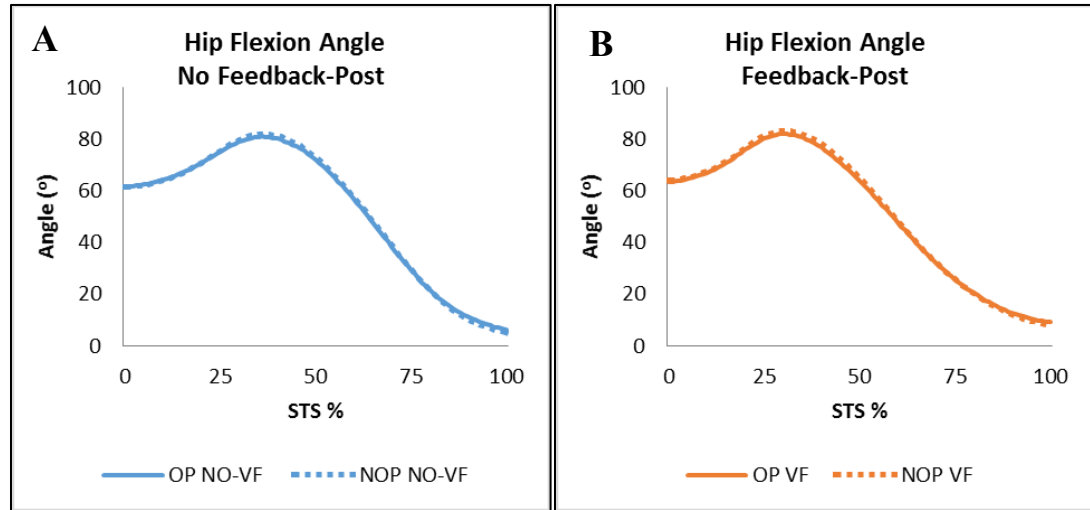


Figure 26 Average time series curves for sagittal hip angle for the non-operated (NOP) and operated (OP) limbs, during No-visual feedback (No-VF) condition (A), and during visual feedback (VF) condition (B), post-operatively.

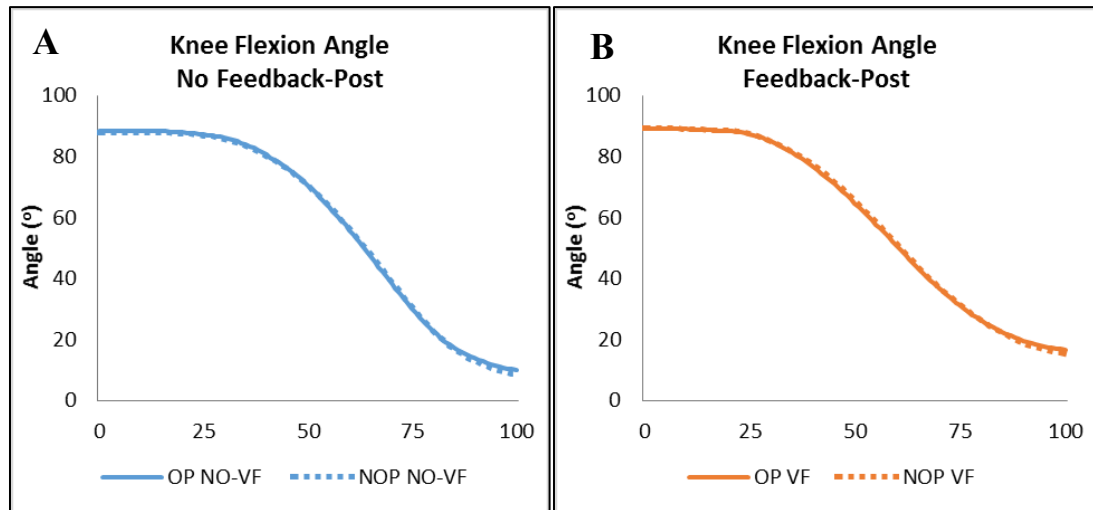


Figure 27 Average time series curves for sagittal knee angle for the non-operated (NOP) and operated (OP) limbs, during No-visual feedback (No-VF) condition (A), and during visual feedback (VF) condition (B), post-operatively.

Table 20 Pearson correlation between physical impairments, change in VGRF symmetry, with the change in biomechanical symmetry between two conditions, 3 months post-operative

Variable	Δ VGRF symmetry	Δ HFM symmetry	Δ HADM symmetry	Δ KFM symmetry	Δ SHA symmetry	Δ SKA symmetry
Δ HFM symmetry	0.528**					
Δ HADM symmetry	0.719**	0.677**				
Δ KFM symmetry	0.487*	0.104	0.368			
Δ SHA symmetry	-0.185	0.012	-0.068	-0.247		
Δ SKA symmetry	0.062	-0.269	0.021	0.353	0.156	
Hip pain	0.225	0.183	0.066	0.035	0.115	0.345
Hip abductor strength	-0.202	0.182	0.071	-0.024	-0.046	-0.292
Knee extensor strength	-0.103	-0.354	-0.036	0.280	-0.051	0.203
Δ: change in symmetry index between two conditions. HFM: peak hip flexion moment. HADM: peak hip adduction moment. KFM: peak knee flexion moment. SHA: sagittal hip angle. SKA: sagittal knee angle.						

Table 21 Change in symmetry index between the between “No-Visual feedback” and “Visual Feedback” conditions, before THA and after THA

Variable	Change in Interlimb MD (symmetry index)between “No-Visual feedback” and “Visual Feedback” conditions		
	Before THA	After THA	
	Mean (SD)	Mean (SD)	*P-value
VGRF (N/BW)	0.03 (0.05)	0.04 (0.06)	0.918
Peak hip flexion moment (Nm/Kg.m)	0.02 (0.07)	0.02 (0.07)	1.000
Peak knee flexion moment (Nm/Kg.m)	0.05 (0.07)	0.04 (0.08)	0.889
Peak hip adduction moment (Nm/Kg.m)	0.04 (0.05)	0.03 (0.06)	0.554
Average sagittal hip angle (o)	-0.06 (0.07)	0.00 (0.97)	0.798
Average sagittal knee angle (o)	-0.21 (1.37)	-0.06 (1.73)	0.534
*P-value for difference in magnitude of symmetry improvement between before and after THA groups, using independent t-test.			

Discussion

Movement asymmetries after THA was suggested to reflect a learned strategy that may be developed before the surgery as a pain avoidance strategy that persist after surgery, or after surgery as a result of fear of movement, sensory deficits, or due to unloading instructions during the early postoperative rehabilitation program. Hence it was recommended to include targeted strategies to normalize movement during rehabilitation^{11,43,53}. In recent studies, real time visual feedback of weight distribution, by using two Nintendo Wii Balance Boards, has been found to reduce weight bearing asymmetry in healthy adults during a squat task⁵⁴, and in patients with neurological diseases during static standing⁵⁵. Despite the potential benefit of this feedback, the joint-specific strategies used to normalize weight distribution during the chair rise have not been examined. If patients do increase weight bearing symmetry, it is important that there is also improved joints kinetic and kinematic symmetry. Symmetrical weight bearing (VGRF) during chair rising does not guarantee a symmetrical joint moments⁹⁴ and it is possible that joint moments and angles, or trunk angle, will become more asymmetrical and more divergent from normal in an attempt to make force under each limb more symmetrical.

In this study we sought to identify the immediate effects of visual feedback of weight bearing during the STS task on joint-specific kinetics and kinematics symmetry, in subjects scheduled for THA who exhibit weight bearing asymmetry. We hypothesized that those patients would move with more symmetrical movement patterns with visual feedback. Our results support this hypothesis and subjects before and after THA performed the task with reduced VGRF and joint kinetics asymmetry

when visual feedback was provided. We also hypothesized that magnitude of increase in symmetry would be larger in patients at 3 months post-surgery than those before surgery. This hypothesis was not supported by the results. The magnitude of change in symmetry following visual feedback did not differ between patients tested before surgery and those after surgery. We further expected that pain and strength of the operated limb would influence the patient's response to visual feedback at both time points. This hypothesis was partially supported by our results. Pain score was positively related to the magnitude of change in joint kinetics and kinematics symmetry only at pre-operative time, but strength was not related to change in symmetry for biomechanics outcomes at either time points.

Real time visual feedback of the weight (VGRF) under each limb positively impacts the joint kinetics symmetry, in patients before and after THA. When subjects received the visual feedback, they stood up with more symmetrical weight distribution. This was also shown in joint kinetic symmetry; subjects showed less asymmetry in sagittal knee moment and frontal hip moment. Although visual feedback did not increase the symmetry at sagittal hip moment, it did not at the same time negatively influence it. Noticeably, the increase in movement symmetry following the visual feedback was driven mostly by increase in the operated limb biomechanics (Tables 18 and 19), indicating that visual feedback may result in increased loading on the operated leg, rather than an unloading of the non-operated side.

Besides that visual feedback in general increased the symmetry of VGRF and joint kinetics, these increases in symmetry were associated. With visual feedback, the more the patient moved with greater weight bearing symmetry, the larger the joint kinetics symmetry was displayed. This result supports that the effect of visual

feedback on weight bearing symmetry was also concomitantly reflected on joint kinetics symmetry. However, the joint kinematics symmetry was upheld between two conditions, indicating that subjects did not implement a kinematic compensatory strategy to normalize their weight bearing distribution.

We expected that response to visual feedback would be larger in subjects after surgery than those who wait for surgery, given that hip pain is largely resolved and muscle strength is improved following the surgery. However, both groups showed similar response to the visual feedback. Additionally, we found that subject's response was not related to strength measures of the operated limb at either time points; suggesting that strength of hip or knee does not importantly influence how subjects respond to visual feedback. However, pain scores before surgery influenced the change in hip flexion moment.

Our findings highlighted the positive influences of visual feedback of weight distribution on movement symmetry, and suggest that such feedback could be used by the clinicians to improve movement symmetry in THA population, and such feedback program may be advantageous to patients before and after THA regardless their strength measures. Developing a structured pre-operative and/or post-operative feedback program may have beneficial effect on movement symmetry in THA population. However, developing such feedback program should be preceded by longitudinal research to assess the learning effect and the long-term benefits for using the visual feedback on function and movement symmetry in THA population. It has been shown that patients 6 months after TKA who received weight bearing symmetry biofeedback during post-operative rehabilitation, showed similar or superior functional performance and biomechanical symmetry measures particularly for the peak knee

flexion moment during STS task, to those subjects who only received standard of care rehabilitation with no symmetry training⁹⁷. However, the inferences about the long term effect of feedback in the aforementioned study could not be made, given that the comparison was made with a cross sectional group.

Feedback program could be incorporated in the clinical environment by using a low cost and feasible tool such as Nintendo Wii Balance Board. Wii Balance Board interfaced with custom available software have been used previously to assess and provide visual feedback of the weight bearing asymmetry^{55,96,99}, and have been shown to possess an excellent test–retest reliability for measuring weight bearing asymmetry⁵⁶. However, the accuracy of force measurement obtained from WBB compared to those measured by the laboratory force plates during STS task has not been examined. In order to consider the WBB as a valid tool to measure the forces under each limb, further research is warranted to prove that.

Some limitations exist in this study. A single session with only three trials during the visual feedback condition might be not enough to reveal significant response in the sagittal hip moment. It is possible that if subject had more repetitions in the visual feedback condition, that larger effect might be shown. That lack of response may be due to weakness of hip extensor muscles, however; this measure was not assessed in this study. Previous research has found that subjects with higher magnitude of weight bearing asymmetry showed higher response to the visual feedback^{54,55}, however, this relation was not examined in this study.

In summary, this is the first study that evaluates the immediate influence of real-time visual feedback on symmetry measures of joint kinetics and kinematics. This study serves as a first step to determine the potential effectiveness of this feedback on

STS movement symmetry. We found that visual feedback of VGRF reduced the movement asymmetry in subjects before and after THA. Further research should assess the training effect of such visual feedback and to determine whether using the visual feedback lead to long term benefits on function and movement symmetry.

Chapter 5

VALIDITY OF THE NINTENDO WII BALANCE BOARD TO ASSESS WEIGHT BEARING ASYMMETRY DURING SIT-TO-STAND AND RETURN-TO-SIT TASK (AIM 4)

Abstract

Weight bearing asymmetry is common in patients with unilateral lower limb musculoskeletal pathologies. The Nintendo Wii Balance Board (WBB) has been suggested as a low-cost and widely-available tool to measure weight bearing asymmetry in a clinical environment; however no study has evaluated the validity of this tool during dynamic tasks. Therefore, the purpose of this study was to determine the concurrent validity of force measurements acquired from the WBB as compared to laboratory force plates. Thirty-five individuals before, or within 1 year of total joint arthroplasty performed a sit-to-stand and return-to-sit task in two conditions. First, subjects performed the task with both feet placed on a single WBB. Second, the task was repeated with each foot placed on an individual laboratory force plate. Peak vertical ground reaction force (VGRF) under each foot and the inter-limb symmetry ratio were calculated. Validity was examined using Intraclass Correlation Coefficients (ICC), regression analysis, 95% limits of agreement and Bland-Altman plots. Force plates and the WBB exhibited excellent agreement for all outcome measurements (ICC =0.83-0.99). Bland-Altman plots showed no obvious relationship between the difference and the mean for the peak VGRF, but there was a consistent trend in which VGRF on the unaffected side was lower and VGRF on the affected side was higher

when using the WBB. However, these consistent biases can be adjusted for by utilizing regression equations that estimate the force plate values based on the WBB force. The WBB may serve as a valid, suitable, and low-cost alternative to expensive, laboratory force plates for measuring weight bearing asymmetry in clinical settings.

Introduction

Asymmetrical movement patterns are common in patients with unilateral weakness or pain. Individuals with unilateral lower limb musculoskeletal pathologies such as osteoarthritis, or after procedures such as total joint arthroplasty or anterior cruciate ligament reconstruction, preferentially unload the affected side and shift the weight to the non-affected side during sit-to-stand and squat tasks^{11,43,51,52,90–92,96,100}. These asymmetries are particularly concerning in patients before and after total joint arthroplasty because weight bearing asymmetry is related to worse functional performance⁵². Those individuals exhibit more asymmetrical movement patterns when compared to healthy matched group¹¹. Restoring movement symmetry is an important component of rehabilitation for patients after total joint arthroplasty; however methods to quantify inter-limb differences in loading during functional tasks are not always available or feasible in clinical settings. Despite that using two bathroom scales is a feasible method to measure weight bearing asymmetry in clinical environment, their use are limited to static measurements¹⁰¹. Research-grade force plates in motion analysis laboratories are the “gold-standard” for accurate measurement of weight bearing asymmetry. Using these force plates, the vertical ground reaction force (VGRF) under each foot can be precisely measured. This equipment is not available in most rehabilitation centers because it is expensive, difficult to transport and requires technical expertise to operate. Recently, the

Nintendo Wii Balance Board (WBB) has been suggested as a commercially-available and low-cost tool to measure loading patterns, balance and force symmetry in a clinical environment^{54-56,96,102,103}. In recent studies, the WBB has been interfaced with custom and commercially available software, to evaluate weight bearing asymmetry in healthy individuals and people with neurological or musculoskeletal conditions^{54-56,96}. Although the WBBs have excellent test-retest reliability for measuring weight bearing asymmetry⁵⁶, the validity of the force measures acquired from the WBB have not been examined.

WBBs are becoming more common as a rehabilitation tool to both measure interlimb force symmetry and provide feedback to patients about interlimb force symmetry during dynamic activities^{54-56,96-98}. However, there is little information on the accuracy of the WBB force measurements compared to research-grade force plates. Previous work has evaluated the use of two WBBs, with one under each foot. Using two WBBs requires more complicated data acquisition software, and would likely be prone to more errors in signal acquisition from two separate input devices. Differences in calibration or auto-zeroing of each Balance Board may also provide less accurate information. Therefore, the purpose of this study was to determine the validity of force measurements acquired from WBB as compared to force measurements acquired from force plates in a motion analysis laboratory. We hypothesized that peak VGRF and inter-limb VGRF symmetry ratios would show absolute agreement between the WBB and force plates during a sit-to-stand and return-to-sit (STS-RTS) task in patients before and after total joint arthroplasty.

Methods

Participants

Individuals were recruited for this study before and after total joint arthroplasty. Subjects participated in the testing sessions 2-4 weeks prior to, or within 1 year of total hip arthroplasty (THA) or total knee arthroplasty (TKA). These subjects were recruited from a pool of participants enrolled in on-going observational studies evaluating functional performance and movement patterns before and after THA or TKA. Subjects were excluded if they had 1) neurological, vascular or other lower extremity musculoskeletal conditions that affected gait or functional performance, 2) self-reported lack of sensation in the foot or lower extremity, 3) uncontrolled hypertension, 4) history of cancer in the lower extremity, or 5) were unable to walk short distances (10 m) without an assistive device. All subjects included in this analysis were scheduled for or underwent unilateral THA or TKA. The study was approved by the Human Subjects Review Board of the University of Delaware and all subjects signed an informed consent prior to participation.

Procedures

Subjects performed the STS-RTS task in two conditions. In condition one, subjects performed the STS-RTS with each foot placed on an individual force plate (Bertec Corporation, Columbus, OH) (Figure 28A). In the second condition, subjects placed both feet on a single WBB (Nintendo of America Inc, Redmond, WA) (Figure 28B). In both conditions, subjects were seated on an armless and backless chair. The height of the chair was set to the subject's knee joint line to allow for 90 degrees of knee flexion when sitting. No restrictions were made on foot position when the task was performed on the force plates, but in the WBB condition foot placement was

standardized by asking the subject to place each foot on WBB an equal distance from the center line of WBB inside the rectangular borders defined imprinted on the board. The investigator also ensured that each foot was an equal distance from the front border of WBB. Before each trial on the WBB, foot position was visually checked to ensure appropriate foot placement. To account for the additional height of the WBB compared to the force plates that were embedded into the floor, the chair was secured to a wooden platform that was the same height as the WBB. Subjects were asked to stand from the chair at their self-selected pace. During each trial, subjects were asked to hold the arms in their lap and not to use their arms to assist with rising from the chair. Total of 6 trials were collected from each subject; 3 trials on the WBB and 3 trials on the force plate, preceded by two practices for each condition. The subjects were allowed to rest as needed between trials.

The force plates were calibrated in accordance with the manufacturer's recommendations. In the force plate condition the VGRF was collected for each limb independently from two separate force plates at 1080 Hz. VGRF were then low-pass filtered at 40 Hz using a second-order, phase-corrected Butterworth filter. The WBB was interfaced with a laptop computer using custom-written software (Labview 8.5 National Instruments, Austin, TX, U.S.A.) to collect vertical force data from the four individual strain-gauge type load cells of the WBB. Data were acquired through the standard Bluetooth connection on the laptop computer. The software acquisition rate for the force data was 100 Hz, although the actual output rate of the WBB has been shown to be variable, but on the order of 30-50 Hz¹⁰⁴. Force under each foot was measured by summing the force values from the two load cells under each foot (right and left sides of the WBB). No modifications were made to the WBB.

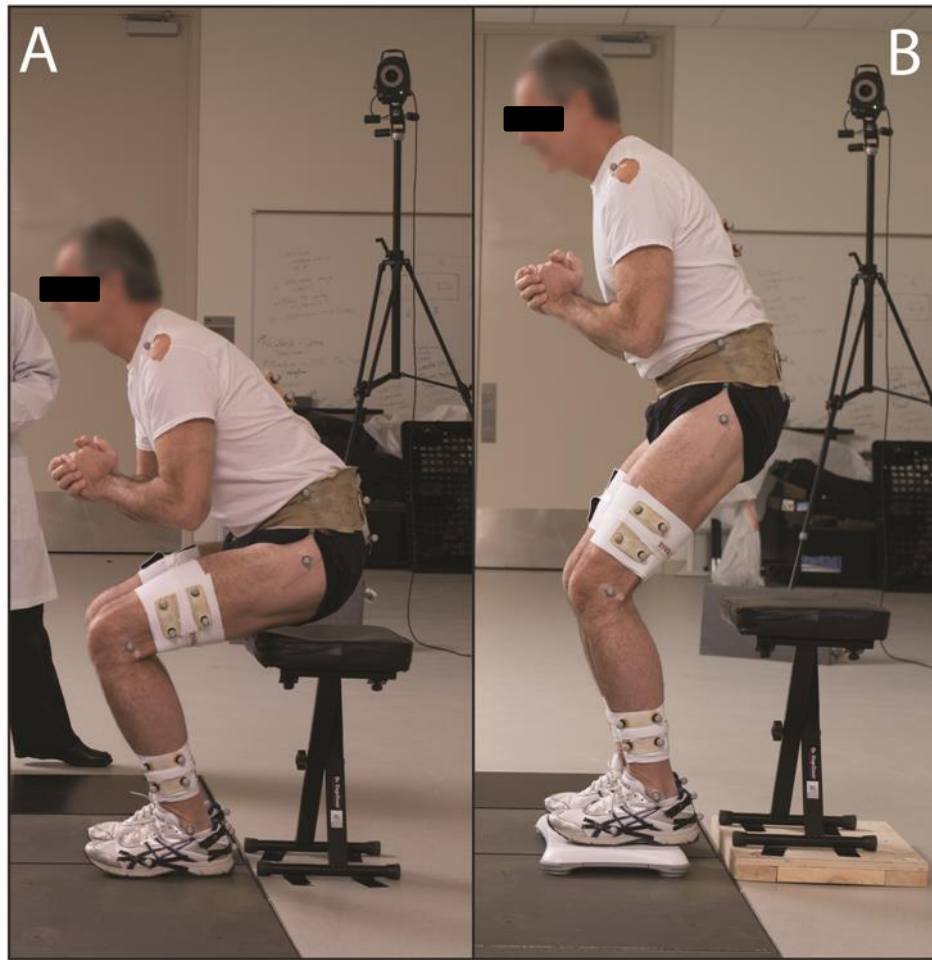


Figure 28 Subjects performed the STS-RTS task while data from each foot was acquired from the force plates (A) or from the Wii Balance Board (B).

Data analysis

VGRF data was cropped manually for each trial to remove data before the start of stand and after the end of sit. VGRF data was then normalized to 100 points. Start and end of the STS-RTS task were determined by the minimum VGRF values. The sit-to-stand (STS) phase was defined as the first 25% of the task and the return-to-sit (RTS) phase was defined as the last 25% (Figure 29). Peak VGRF under each limb

and the symmetry ratio were calculated and used in this analysis. Peak VGRF during both the STS and RTS phases were calculated in Newtons (N). Interlimb force symmetry was calculated using the symmetry ratio, which was defined as the (peak force of the affected limb / peak force of the unaffected limb) * 100. This value was expressed as a percentage where a value of 100 implies perfect symmetry between limbs. Values less than 100 indicate greater force on the unaffected limb and values greater than 100 indicate greater force on the affected limb. These measures were computed during both conditions (force plate and WBB) for each trial. The average values from the 3 trials were used for the analysis. All outcome measures were collected and analyzed during STS and RTS phases, separately.

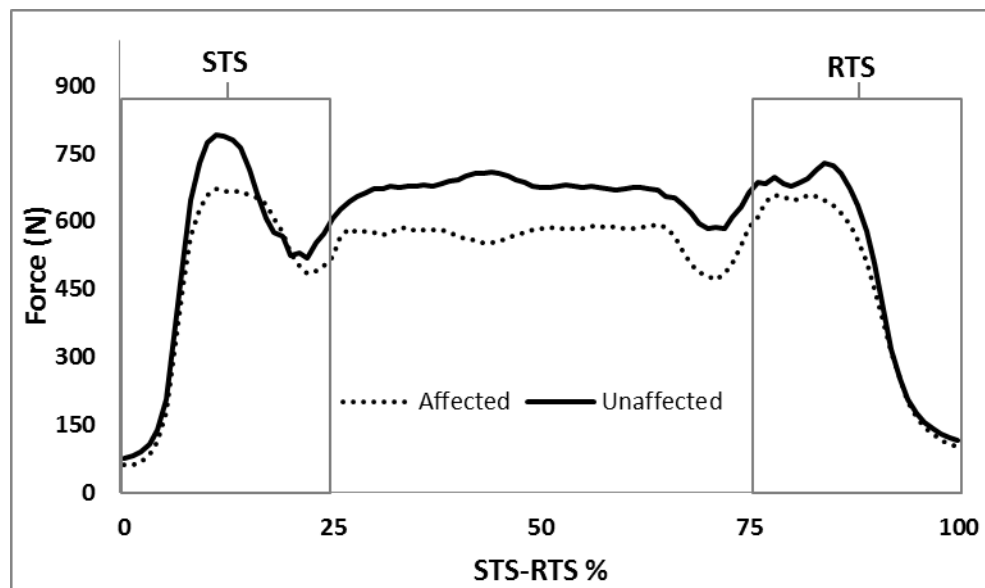


Figure 29 Example of vertical ground reaction force for both limbs throughout the sit to stand-return to sit (STS-RTS) task. Data were time-normalized to 100 points. The STS phase was defined as the first 25% of the task and RTS phase was defined as the last 25%.

Statistical analysis

Mean and standard deviation for all outcome variables were calculated. For concurrent validity, a two-way, mixed effects, average measure (mean of the three trials), Intraclass Correlation Coefficients ($ICC_{(3,3)}$) with 95% confidence intervals (CI) were used to measure the absolute agreement between the outcome measurements (i.e. peak force under each limb and symmetry ratio) obtained with the force plates and WBB. Univariate linear regression analysis was used to quantify the relationship between the force measurements from the force plates and WBB, as well as to develop equations that may account for the difference in force between the two methods. Agreement between the two devices for the peak force measurements were also examined by 95% limits of agreement. Bland-Altman plots were created to examine the spread of the error and to examine for systematic bias. Specifically, these plots were performed by plotting the difference in peak force measurements between the two methods against the mean of the two measurements, for each limb separately. All statistical analyses were conducted using the Statistical Package for the Social Sciences (IBM SPSS 21.0, Chicago, IL).

Results

Thirty-five subjects participated in this study. There were 16 men and 19 women with a mean (standard deviation) age of 66.4 (8.3) years, and mean body mass index of 29.1 (9.6) kg/m^2 . Eleven subjects participated prior to arthroplasty and twenty-four participated after arthroplasty. There were 27 subjects with hip osteoarthritis and 8 subjects with knee osteoarthritis. The left side was the affected side in 15 subjects (43%) and the right side was the affected side in 20 subjects (57%).

ICCs revealed excellent agreement between two methods for measuring the peak VGRF under the affected side ($ICC_{(3,3)} = 0.97-0.98$), under the unaffected side ($ICC_{(3,3)} = 0.99$), and for the symmetry ratio ($ICC_{(3,3)} = 0.83-0.88$), during the STS and RTS phases (Table 22). Regression analysis showed strong relationship between force plates and WBB measurements with R^2 values ranging from 0.64 to 0.97 (Figure 16). Regression equations that estimate the relationship between two methods are presented on each regression graph (Figure 30). Bland-Altman plots showed no obvious relationship between the difference and the mean for the peak VGRF under either affected or unaffected sides (Figure 31). There was evidence of fixed bias that favored less peak VGRF on the unaffected side (mean difference=14 N & 12 N during STS and RTS, respectively) on the WBB (Figure 31) & (Table 22). Similarly, there was a bias toward more force on the affected side (mean difference=21 N & 25 N during STS and RTS, respectively) when the task was performed on the WBB (Figure 31) & (Table 22). These differences between two methods showed a consistent trend across subjects; during STS phase there were 80% of subjects showed higher peak force on the affected side, while 69% of subjects had less peak force on the unaffected side when using the WBB. Higher SR was also found in 74% of subjects when performed the task on the WBB (Figure 32). Similar trend was observed during RTS phase, with 83% of subjects showed higher peak force on the affected side and 71% of subjects showed reduced peak force on the unaffected side, and 71% of subjects sit with higher SR when using WBB (Figure 33).

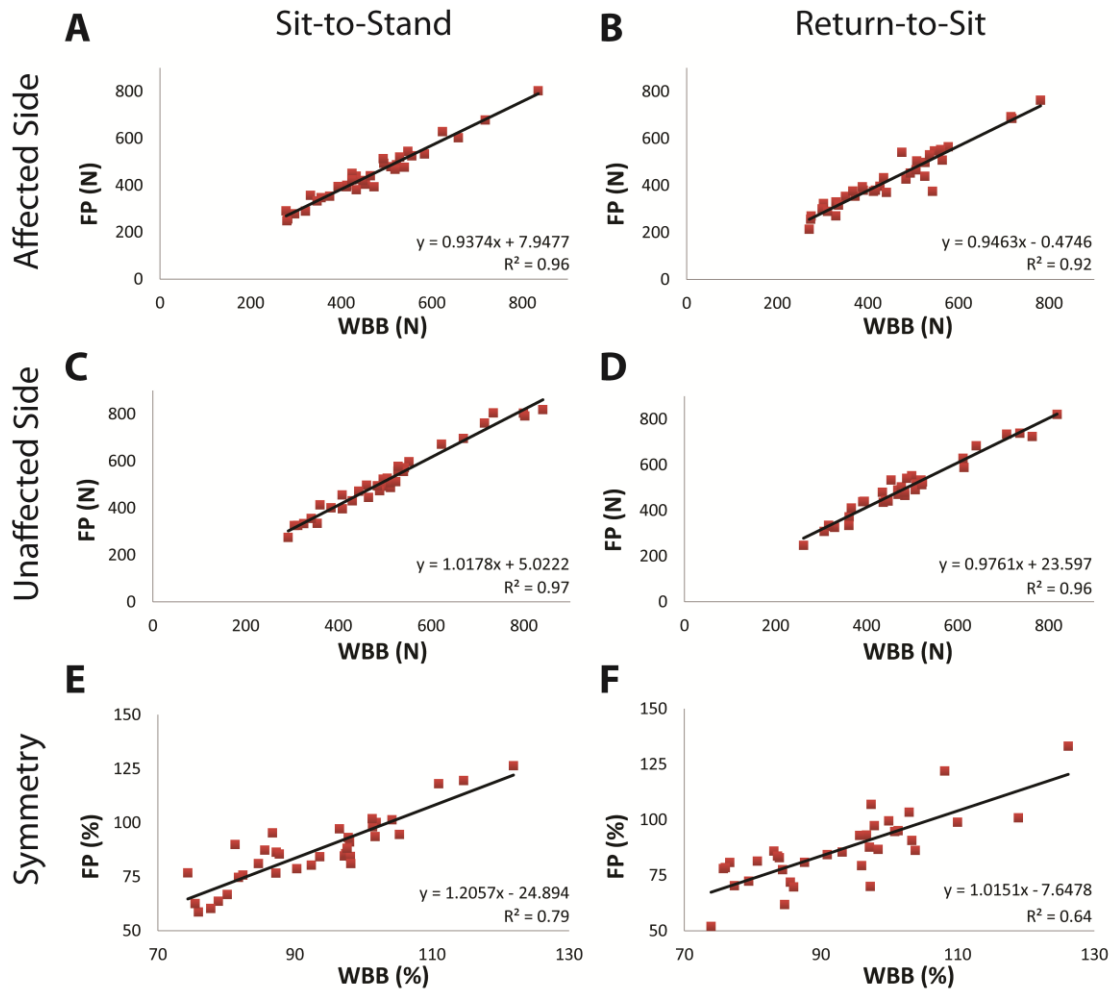


Figure 30 Scatter plot illustrating the relationship between the VGRF measured using the Wii balance board (WBB) and force plates (FP) for the affected and unaffected sides (A,B and C,D), as well as for the Symmetry Ratio of VGRF (E and F) during Sit-to-Stand and Return-to-Sit phases.

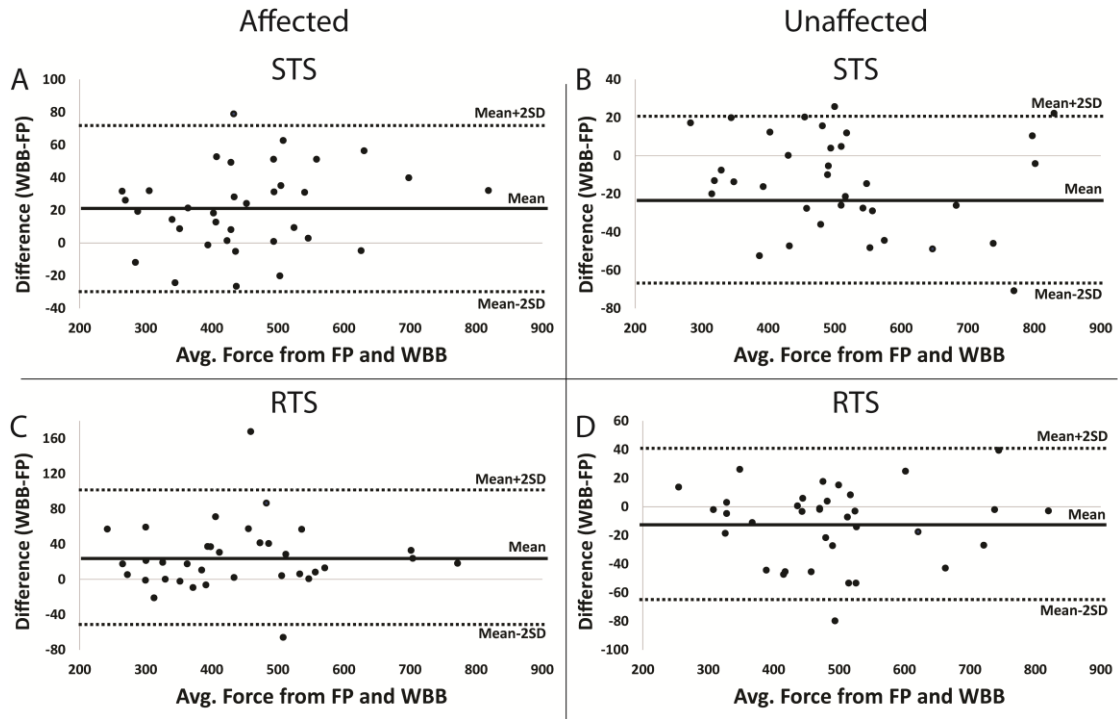


Figure 31 Bland–Altman plots representing comparisons between the laboratory-grade force platform (FP) and the Wii Balance Board (WBB) during STS phase: (A) for the affected side; (B) for the unaffected side; and during RTS phase (C) for the affected side; (D) for the unaffected side. The mean line represents the mean difference between the devices, with the upper and lower lines representing the limits of agreement (two standard deviations).

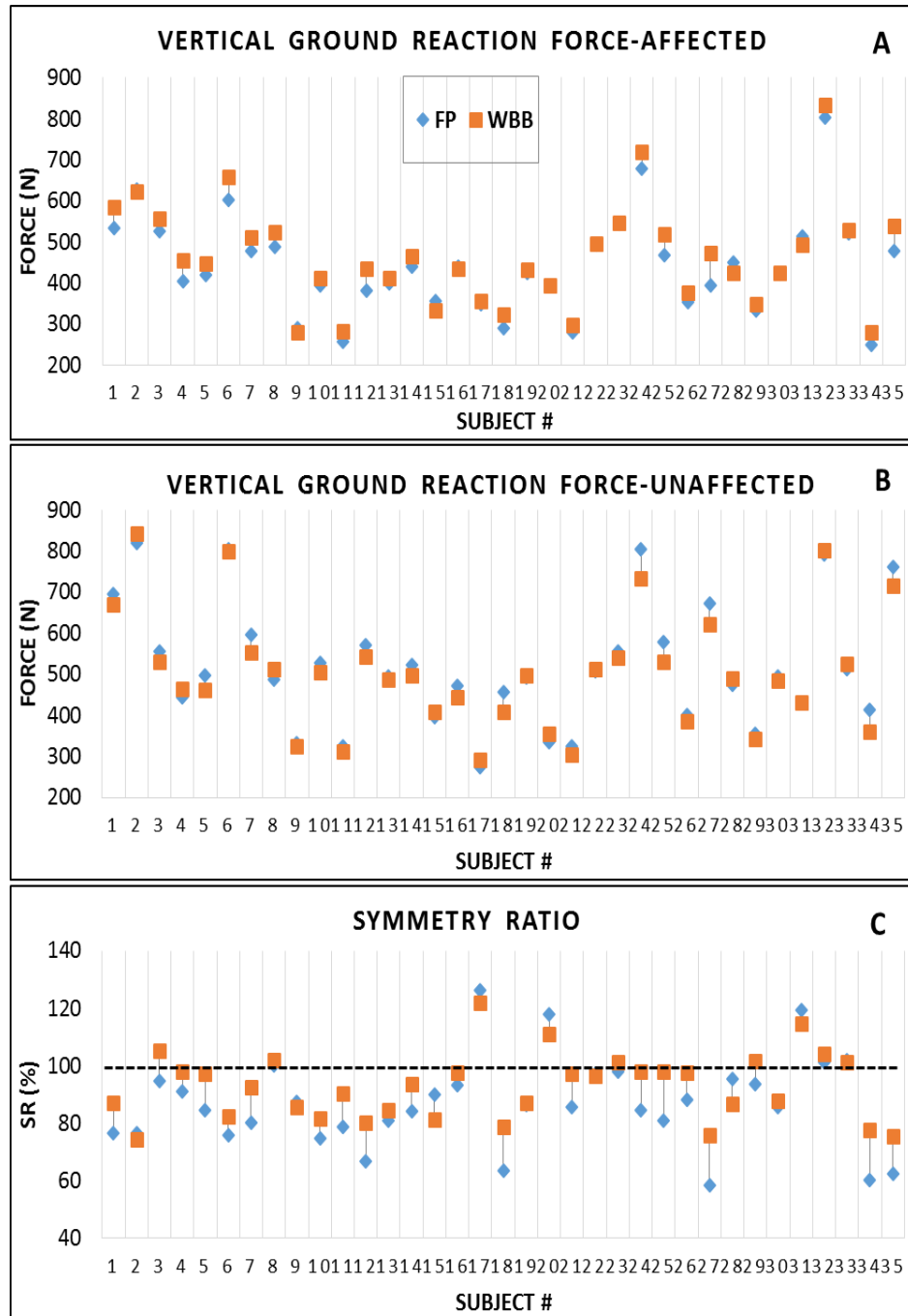


Figure 32 Plots of VGRF (A&B) and force symmetry ratio (C) measured by Wii Balance Board (WBB) and by force plate (FP) during sit to stand phase (STS). Plots show the consistent trend of more VGRF on the affected side (A), lower VGRF on the unaffected side (B), and higher symmetry ratio (C) when using Wii Balance Board (WBB).

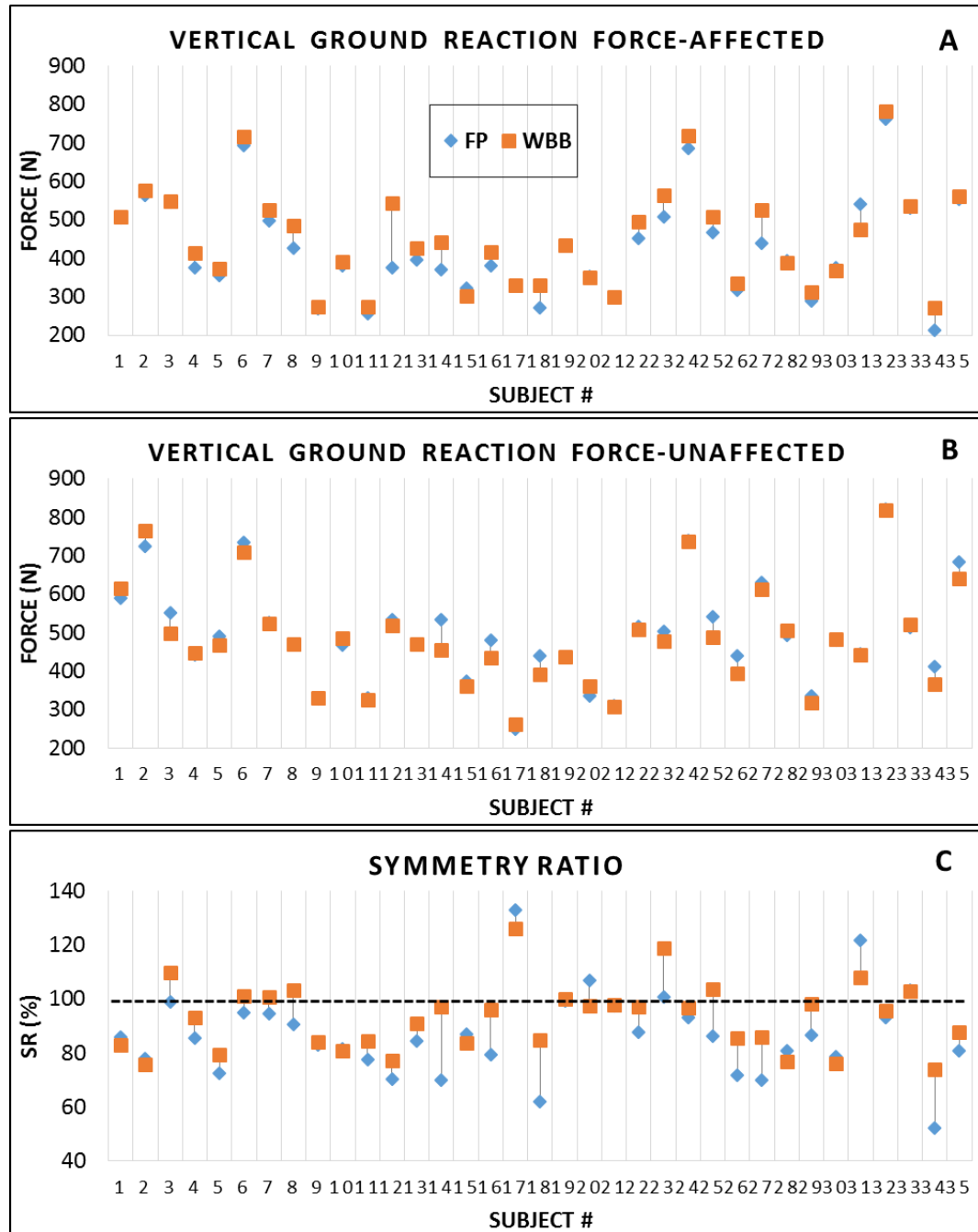


Figure 33 Plots of VGRF (A&B) and force symmetry ratio (C) measured by Wii Balance Board (WBB) and by force plate (FP) during return-to-sit phase (RTS). Plots show the consistent trend of more VGRF on the affected side (A), lower VGRF on the unaffected side (B), and higher symmetry ratio (C) when using Wii Balance Board (WBB)

Table 22 Peak VGRF (Newtons) and Symmetry Ratio (affected/unaffected) during STS and RTS

	Force Plate Mean (SD)	WBB Mean (SD)	Mean diff. (95% CI)	ICC3,3 (95% CI)
STS phase				
Affected (N)	441.9 (119.7)	463.9 (125.1)	21 (12.6, 29.4)	0.98 (0.91,0.99)
Unaffected (N)	519.1 (148.5)	505.1 (143.8)	-14 (-5.6, -22,3)	0.99 (0.97,0.99)
Symmetry Ratio (%)	86.9 (15.7)	92.7 (11.5)	5.8 (3.2, 8.3)	0.88 (0.57,0.95)
RTS phase				
Affected (N)	426.4 (128.6)	451.1 (130.1)	25 (12.1, 37.3)	0.97 (0.90,0.99)
Unaffected (N)	496.1 (131.7)	484.1 (132.3)	-12 (-3.2, -20.7)	0.99 (0.97,0.99)
Symmetry Ratio (%)	86.8 (15.75)	92.9 (12.45)	6.1 (2.9, 9.3)	0.83 (0.52,0.93)
WBB: Wii Balance Board; CI: confidence interval; Mean diff.: mean difference between two methods; STS: sit to stand; RTS: return to sit; SR: symmetry ratio				

Discussion

Previous studies have used the WBB to measure the force under each foot and the inter-limb symmetry ratio^{55,96,102}; however none of these studies assessed the accuracy of WBB force measurements compared to laboratory force plates during dynamic tasks. The ability to use a portable, low-cost and valid tool to assess weight bearing asymmetry is of substantial clinical importance, but the utility of this tool is dependent on its accuracy. We hypothesized that force magnitude and symmetry ratios obtained through the WBB would be comparable to the same metrics obtained through research grade force plates. The exceptionally high ICC values and high R^2 values show the excellent agreement and strong relationships of WBB measurements with force plates, and indicate that using the WBB may be appropriate for clinical applications. Importantly, the Bland-Altman plots revealed a random spread in error, suggesting differences between measurement devices do not depend on the magnitude of the force under foot where the scatter around the bias line didn't show any proportional bias. This finding indicates that our results can likely be extrapolated to individuals with high and low degrees of asymmetry between limbs. However, there was evidence of greater symmetry on the WBB than on the force plates (Table 1). This discrepancy between devices is likely attributed to two factors: 1) the method in which left and right force data is acquired from a single WBB and 2) the need to place the feet in a symmetrical and standardized position during the WBB trials.

The primary difference between how the WBB and force plates can be used to acquire force data is that the force plates measure the force under each limb separately, while the forces obtained from the WBB must be calculated as the relative weight on the load cells from the right and left sides. Because the two sides of the WBB are not

independent, some force from the left foot may be captured by the load cells on the right side and vice versa. This phenomenon contributes to the fixed bias when measuring the magnitude on the affected and unaffected limbs, even though the WBB was designed for bilateral use during game play on the Nintendo console.

When using the WBB there was a 12 to 14 N decrease of force magnitude on the unaffected side and 21 to 25 N increase of force on the affected side; however these differences were consistent across the majority of subjects as shown in Figures 5&6. The transfer of force between sides and load cells in the WBB likely contributes to the higher symmetry ratios observed when using this device. However, these consistent biases can be adjusted for by using the regression equations that estimate the force plate values based on the magnitude of the WBB force. Previous studies have used two WBBs at the same time (one under each foot) to independently measure the vertical force from each foot and avoid the error associated with side-to-side transfer of force^{54-56,96}.

The small and systematic differences in force measurement between the force plates and WBB may also be attributed to the necessary constraints in foot position using the WBB. The force plates in the laboratory measured 60 by 90 cm for each plate, while the space on top of the WBB measured only 52 by 33.5 cm and subjects on the WBB were constrained to placing the feet equidistant from the center of the device. These positional constraints were necessary because a shift in the foot placement towards one side increases the resultant force that is recorded under that limb when using the WBB, which is not a problem when using two forceplates. The symmetrical foot placement may also have forced the subjects to adopt a more symmetrical loading pattern when performing the STS-RTS task when compared to

the force plates. Our current findings suggest that while only one WBB can be used to measure force asymmetry, clinicians using the WBB in a clinical setting should be aware that the measures of asymmetry during an unconstrained STS-RTS task may be slightly greater than those calculated from the WBB. It has been shown that initial foot position has an influence on the STS biomechanics including the loading symmetry¹⁰⁵.

Recent studies have shown that WBB is a reliable and valid tool, in comparison to laboratory-grade force plates as “gold-standard”, for measuring center of pressure path during standing task^{56,102,103}. WBB has also excellent test-retest reliability for assessing weight bearing asymmetry⁵⁶. Our study adds to the building base of literature supporting the clinical utility of the WBB as a tool to evaluate weight bearing asymmetry during dynamic activities. Clinicians should use the average of three trials to reproduce the same validated outcomes from this study. The use of the average trials is important during the acquisition of movement data, which has some degree of inherent and normal variability between trials. It is also recommended that the same WBB should be used to longitudinally track changes in weight bearing asymmetry for the same individuals, rather than using different WBBs, as using the same WBB provides better repeatability of a single force measurement compared to force repeatability across different boards¹⁰⁶.

A recent study by Bartlett et al reported measurement error of the WBB force to be within ± 9.1 N when compared to a laboratory force plate¹⁰⁶, which is smaller than the current study. However, Bartlett’s study quantified the accuracy of WBB measurements by applying static loads to each of the four cell loads of the WBB independently then estimated the total error, while the current study evaluated the

accuracy of the force under each limb computed by summing the forces of left or right load cells during a dynamic task performance. Given that the WBB will likely be used to capture dynamic activities in the clinic, the current study provides insight into the utility of the WBB in clinical environment.

The WBB is a valid method to measure peak VGRF under each limb and the inter-limb symmetry ratio during STS and RTS tasks in subjects prior to or after joint arthroplasty. The WBB may serve as a suitable, low-cost alternative to expensive, laboratory force plates for measuring weight bearing asymmetry in a clinical or home-based setting. WBB may also be incorporated in different rehabilitation options such as providing real-time force biofeedback to help maximize movement symmetry, and for measuring reaction forces on a leg press machine, in patient populations who characterized with weight bearing asymmetry during functional activities. Clinicians utilizing this device must be aware that additional movement constraints that are required during the WBB task may inflate measures of movement symmetry. Clinicians interested in the absolute force values that occur in unconstrained conditions can utilize regression equations to improve accuracy of the measures.

Chapter 6

CONCLUSION: FUNCTIONAL LIMITATIONS, INTER-LIMB MOVEMENT ASYMMETRIES AND THE UNDERLYING FACTORS IN SUBJECTS WITH UNILATERAL THA

The overall goal of this dissertation was two-fold. The first fold was to identify the primary physical impairments contribute to functional limitations and abnormal movement patterns before and after THA. The second fold was to evaluate the potential utility of using the real-time visual feedback for reducing asymmetrical movement in THA population. The results from this work will allow to better design rehabilitation programs that may maximize functional and biomechanical recovery after THA.

Findings of Aim 1

Aim 1: To characterize functional recovery 3 months after THA using performance-based and self-reported measures, and identify how physical impairments are related to the patient's perceptions and performance of functional tasks after THA.

- Hypothesis 1.1: Compared to pre-operative levels; patients will demonstrate a significant reduction in pain, increase in hip motion, and increase in hip and knee strength in the operated limb, as well as improvements in performance-based and self-reported function at three months following THA.
- Hypothesis 1.2: Patients at 3 month post-surgery will show weaker muscle strength and worse function compared to healthy individuals.

- Hypothesis 1.3: The operated hip joint pain would be the primary contributor to self-reported outcomes, while operated hip and knee strength would be the main contributors to performance-based outcomes three months following THA.
- Hypothesis 1.4: the reduction of hip pain would be the primary contributor to improvement in self-reported outcomes, while improvements in hip and knee strength would be the be the main contributors to changes in performance-based outcomes three months following THA.

The longitudinal evaluation in this study provides evidence of the positive impacts of THA on subject's functional and clinical outcomes 3 months post-surgery. Individuals at 3 months following the surgery have marked pain reduction, and better functional ability compared to the pre-operative timepoint. Despite improvements, the results also highlight persistent deficits in strength and function at 3 months after THA, when compared to those in healthy control group. Physical impairments contribute to functional limitations at 3 months post-surgery. Specifically, the results provide evidence that self-reported and performance-based measures capture different aspects of disabilities that are influenced differently by pain and strength 3 months after THA. The results suggest that both methods should be utilized to evaluate functional recovery when the purpose of the intervention is to reduce disability. Change in strength is not a determinant to change in function after THA, and this is likely attributed to the fact that there was no change in hip abductor strength by 3 months after THA. Because strength was related to functional performance after THA, rehabilitation protocols that address the residual strength deficits may enhance function after THA.

Findings of Aim 2

Aim 2: To evaluate the sit to stand movement strategies before and after THA, and to identify how physical impairments influence these movement strategies before and after THA.

- Hypothesis 2.1: Before THA, patients will demonstrate inter-limb movement asymmetries with lower vertical ground reaction force, and smaller hip and knee moments in the operated limb compared to non-operated limb, and lateral trunk movement towards the operated side.
- Hypothesis 2.2: Three months after THA, patients will show improvements in movement symmetry that is driven by the increase in vertical ground reaction force, and hip and knee moments in the operated limb.
- Hypothesis 2.3: Despite improvements, patients 3 months after THA will still demonstrate some residual movement asymmetries.
- Hypothesis 2.4: Surgical hip pain and muscle weakness will be related to less VGRF, smaller joint moments, and greater trunk lean on the operated side before and after THA.
- Hypothesis 2.5: Pre- to post-operative improvements in hip pain and strength will be positively related to increases in VGRF, joint moments and trunk lean on the operated side.

In this study, we prospectively evaluated the sit to stand movement strategy in patients before and after THA. Subjects prior to THA rise from the chair with asymmetrical movement patterns that presented with lower VGRF, frontal and sagittal moments on the operated limb compared to the non-operated limb. After surgery, there were significant improvements in biomechanical symmetry compared to pre-operative values that driven by greater loads through the operated limb. However,

significant differences still exist between limbs and subjects continue to move with compensatory patterns that overload the non-operated limb. Less strength on the operated limb was related to greater unloading of the operated limb. Similarly, increased strength after THA was related to increased loading of the operated limb. This study suggests that improving the hip and knee strength may improve movement symmetry during STS.

Findings of Aim 3

Aim 3: To evaluate the immediate influence of real-time visual feedback of weight bearing on lower extremity kinematics and kinetics during a STS task in patients before and after THA.

- Hypothesis 3.1: During receiving visual feedback, patients would exhibit increased symmetry in weight bearing and joint kinematics and kinetics, before and after THA.
- Hypothesis 3.2: Visual feedback would lead to larger increase in sagittal plane hip and knee moment symmetry in patients 3 months after THA compared to pre-operative session.
- Hypothesis 3.3: Operated limb strength and pain will influence the magnitude of improvements in VGRF and joint moment symmetry during receiving the visual feedback, before and 3 months following THA.

This study highlighted the positive influences of real-time visual feedback of weight distribution on movement symmetry during STS. With feedback of only VGRF under each limb, subjects moved with less inter-limb asymmetry in the joint sagittal and frontal moments. Subjects before and after THA showed similar response to visual feedback and the magnitude of change was not related to the subject's strength. These

results suggest that weight bearing feedback could have beneficial effect on movement symmetry in THA population, and structured pre-operative and/or post-operative feedback program can potentially be utilized in the clinical setting. However, developing such feedback program should be preceded by longitudinal research to assess the learning effect and the long-term benefits for using the visual feedback on function and movement symmetry in THA population.

Findings of Aim 4

Aim 4: To determine the validity of force measurements acquired from a single WBB as compared to force measurements acquired from force plates in a motion analysis laboratory.

- Hypothesis 4.1: Peak VGRF and inter-limb VGRF symmetry ratios would show absolute agreement between the WBB and force plates during a sit-to-stand and return-to-sit task (STS-RTS) in patients before and after total joint arthroplasty.

In this “agreement” study, we examined whether the WBB can be used as a portable, low-cost tool to accurately assess weight bearing asymmetry in comparison to laboratory-grade force plates as “gold-standard”. The WBB and laboratory force plates showed excellent agreement for measuring peak VGRF under each limb and the inter-limb symmetry ratio during rising from, and returning to a chair, in subjects prior to or after joint arthroplasty. It is important to note there was a consistent trend in which VGRF on the unaffected side was lower and VGRF on the affected side was higher when using the WBB. These differences can be adjusted for by utilizing regression equations that estimate the force plate values based on the WBB force. The results of this aim indicate that the WBB may serve as a valid, suitable, and low-cost

alternative to expensive, laboratory force plates for measuring weight bearing asymmetry in a clinical or home-based setting.

Summary of Findings

Overall, this dissertation provides evidence for the post-operative improvements in functional abilities and movement symmetry; however the results highlight the persistence of physical impairments, functional limitations and asymmetrical movement strategies in patients 3 months after THA. Literature revealed that similar findings continue to persist even in the long term after THA. The results show that physical impairments presented in our sample are linked to lower functionality and altered movement pattern.

Addressing functional limitations and loading asymmetry is imperative during rehabilitation for THA population. This dissertation lays down the foundation of using the real time visual feedback to reduce interlimb asymmetries. Albeit feedback did not immediately eliminate movement asymmetries, higher intensity and duration of visual feedback, combined with addressing underlying physical impairments, may have beneficial effects on mitigating movement asymmetries and subsequently improving functional abilities.

Future Work

Given the relationship between strength measures and functional and biomechanical outcomes in this cohort of study, future work is needed to evaluate the effect of improving the knee extensors and hip abductors of the operated limb on functional and biomechanical outcomes in older adults undergoing THA. Despite the positive response to visual feedback that found in our subjects, further research should

first assess the training effect of real-time weight bearing visual feedback on movement symmetry, and to determine whether the improved movement symmetry through the feedback can be reflected on physical function. This future work may lead to construct a structured feedback program that can be employed in the clinical settings. Moreover, it is possible that physical, psychological and perioperative factors that were not assessed in this study may also influence recovery after THA. Future studies should evaluate the effect of fear of movement, joint stability, balance, endurance, hip flexion and extension strength and surgical approach on functional and movement symmetry recovery following the surgery.

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Appendix

**INSTITUTIONAL REVIEW BOARD APPROVAL INFORMED CONSENT
FORM**

Institutional Review Board Approval



RESEARCH OFFICE

210 Hulliher Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE: January 3, 2012

TO: Joseph Zeni, PT PhD
FROM: University of Delaware IRB

STUDY TITLE: [291881-1] Biomechanical and Functional Outcomes after Total Hip Arthroplasty

SUBMISSION TYPE: New Project

ACTION: APPROVED
APPROVAL DATE: January 3, 2012
EXPIRATION DATE: December 13, 2012
REVIEW TYPE: Full Committee Review

Thank you for your submission of New Project materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Full Committee Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

If you have any questions, please contact Jody-Lynn Berg at (302) 831-1119 or jlberg@udel.edu. Please include your study title and reference number in all correspondence with this office.

Informed Consent Form

Project title: Biomechanical and Functional Outcomes after Total Hip Arthroplasty

Principal Investigator: Joseph Zeni PT, PhD

Additional Investigators: Leo Raisis, MD
Gregory Dominick, PhD
Adam Marmon, PhD

Graduate Students: Federico Pozzi
Sumayah Abujaber
Kathleen Madara, PT

You are being asked to participate in a research study that will help describe differences in how people perform functional activities like walking and climbing stairs after having hip replacement surgery. Participation is voluntary. You may withdraw at any time without consequence. A total of 200 subjects will participate in this study. Testing will be completed 2-4 weeks before your surgery, 3 months after your surgery and 1 year after your surgery. All of the testing will take place in the Department of Physical Therapy at the University of Delaware. The research coordinator at the University of Delaware will contact you by phone or mail to schedule your follow-up evaluations.

Testing Procedures

Testing consists of several activities. First, we ask you to complete questionnaires about your ability to perform activities of daily living and exercise. This is followed by strength testing of the muscles of your hip and thigh. We will also evaluate your ability to perform tasks like walking and stair-climbing. This information will help to determine abnormal movement patterns that may lead to problems in other normal activities of daily living. It will teach us about the strength differences between your two legs. Total testing time will take approximately 1.5 hours.

Questionnaires:

You will complete three questionnaires about how your hips are working and your general health. The health history questionnaire is a standard questionnaire that includes questions about your overall physical health. The Hip Outcome Score is a questionnaire that describes how your hip, stiffness and weakness may affect your ability to perform everyday activities. You will also be asked to fill out a questionnaire that asks about your emotional well-being because your emotional state is related to pain. If you have low back pain, you may also be asked to fill out the Oswestry Low Back Disability Index. This asks 10 questions about how the back pain affects your ability to perform daily activities. You will also be asked to complete one questionnaire that asks about your participation in sports and other physical activities. Some of these questions may not apply to you. You can skip any question if it makes you feel uncomfortable or anxious or can skip questions for any other reason without penalty.

Functional Tests:

How far you can bend and straighten both hips will be measured. Functional testing will include four parts. These are a timed walking test, a timed stair-climbing test, a chair

Subject's Initials _____

rising test, and a six minute walk test. The timed walking test times how long it takes you to stand up from a chair, walk three meters, turn around and return a seated position in the chair. The chair rising test assesses how many times you can stand up out of a chair in 30 seconds. The stair-climbing test times how long it takes you to walk up and down one flight of stairs. The six minute walk test assesses how far you can walk in 6 minutes.

Strength Testing:

The strength of the muscles on the outside of your thigh will be tested with a hand held device. You will lie on a padded table and asked to push into the device as hard as you can. A second strength test will assess the strength of the muscles on the front of your thigh. You will be seated in a device that will measure the amount of force you can produce. You will be asked to kick as hard as you can. If at any time, discomfort becomes more than you care to tolerate, let us know and we will stop further testing.

Risks

The procedures to which you will be exposed are safe, but you may experience some muscle soreness a day or two following strength testing. This soreness is similar to the muscle soreness that you may feel if you lift weights or vigorously exercise. It is often a sign that you are increasing your muscle strength. Although the force levels used in this study pose very little risk for injury, it is possible that a muscle strain could occur. Because we will be evaluating the way you move during a variety of activities, tripping and falling are risks for the functional evaluations.

Compensation

You will receive a \$25 gift card to a local retailer at each testing session. Because there are 3 testing sessions, you will receive 3 gift cards if you complete all of the testing sessions.

Benefits:

The benefits of this study include functional analyses by a licensed physical therapist. This provides you with detailed information about your legs and how you perform the functional tasks. The information that we obtain with our testing will be used to guide future physical therapy treatments. It will also provide doctors and therapists with information about changes in your legs affect your ability to perform everyday activities after surgery.

Confidentiality

Data will be entered from the record to a computerized database where all patients will be identified by a case number. Neither your name nor any identifying information will be used in any publication or presentation resulting from this study. Only you and the investigators will have access to the data. Data will be stored indefinitely. You may reach the investigator at any time, if you have questions or problems associated with the study. The telephone numbers are listed at the end of this form.

What if you are injured during your participation in the study?

If you are injured during research procedures, you will be offered first aid at no cost to you. If you need additional medical treatment, the cost of this treatment will be your responsibility or that of your third-party payer (for example, your health insurance). By signing this document you are not waiving any rights that you may have if injury was the result of negligence of the university or its investigators.

Subject Statement

The functional and strength testing session will last up to 90 minutes. I am between the ages of 35 and 85 and do not have:

Hypertension (high blood pressure) that is not controlled by medication

Neurologic impairments (for example, stroke, or head injury)

I am not currently receiving treatment for active cancer

Your signature below indicates that you are voluntarily agreeing to take part in this research study. You have been informed about the study's purpose, procedures, possible risks and benefits. You have been given the opportunity to ask questions about the research and those questions have been answered. You will be given a copy of this consent form to keep.

If you have any questions about this study, please contact the Principal Investigator, Joseph Zeni at 302-831-4263.

If you have any questions or concerns about your rights as a research participant, you may contact the University of Delaware Institutional Review Board at 302-831-2137.

Subject' s Signature

Date

Witness (Signature)

Subject' s Name (Printed)