LOWER LIMB JOINT BIOMECHANICS DURING LOW- AND HIGH-DEMAND MOBILITY FOLLOWING TOTAL KNEE ARTHROPLASTY: IS LIMB SYMMETRY IMPORTANT AND AMENABLE TO CHANGE?

by

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ABSTRACT

Individuals recovering from total knee arthroplasty (TKA) perform compensatory strategies defined as interlimb asymmetries, resulting in lower functional performance and accelerated arthritic changes in other joints. This body of work focuses on factors related to the performance of the surgical limb by: 1) investigating how the demand of the mobility task influences compensation, 2) comparing the effectiveness of two biofeedback modes in correcting compensation, 3) evaluating if biofeedback can normalize compensation to similar levels as healthy matched pers (HMP), and 4) studying the relationship of modifiable risk factors to the compensations following TKA.

A total of 46 patients with TKA and 15 HMP were assessed in three separate clinical studies. In Study #1, compensation was compared between low- (level) and high- (decline) demand walking tasks in patients with TKA and HMP. In Study #2, we compared the efficacy of two modes of biofeedback on improving compensation and compared between groups. In Study #3, we tested whether risk factors considered modifiable (i.e., lower limb strength, power, residual knee pain, and/or balance confidence) help explain the level of compensation following TKA.

Study #1 showed greater total support moment (M_S), knee extensor moment (M_K), and vertical ground reaction force (vGRF) differences during decline walking compared to level walking in patients with TKA. Greater M_S, M_K, vGRF, and knee joint

angle differences were present in patients with TKA compared to HMP during decline walking. Study #2 showed patients with TKA exposed to internal knee extensor moment (IKEM) biofeedback demonstrated improvement in M_S and M_K symmetry compared to vGRF biofeedback. Additionally, IKEM biofeedback could normalize the level of compensation similar to HMP during decline walking. Study #3 concluded that knee extensor strength asymmetry showed a strong relationship on both M_S and M_K asymmetry following surgery. Lower limb power, residual knee pain, and balance confidence had no relationship on compensation.

These results suggest that compensation is amplified during more physically demanding mobility and can be normalized using knee kinetic biofeedback. Further, it seems intuitive to continue to focus on knee extensor strength and integrate into functional movement retraining with knee kinetic biofeedback to effectively correct compensatory movement strategies during rehabilitation.

This work is dedicated to my loving wife and my mother for without their unconditional support and patience this thesis would never have been possible.

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CHAPTER 1

INTRODUCTION

Total knee arthroplasty (TKA) is the standard surgical procedure for managing chronic pain and disability related to knee arthritis (Zeni, Abujaber, Flowers, Pozzi, & Snyder-Mackler, 2013). Greater than 700,000 TKA surgical procedures are performed annually in the United States at a cost of approximately $15,000 per procedure (Cram et al., 2012; Healy, Rana, & Iorio, 2011; Kurtz et al., 2005; Losina et al., 2009). Total knee arthroplasty is now among the most common major surgical procedures performed in the United States (Finks, Osborne, & Birkmeyer, 2011) and projected to increase 6-fold over the next 2 decades (Kurtz, Ong, Lau, & Manley, 2011). Studies have shown 70-90% of patients report improved health-related quality of life and functional status measures postoperatively (Baker, van der Meulen, Lewsey, & Gregg, 2007; Bourne, Chesworth, Davis, Mahomed, & Charron, 2010b; Wylde et al., 2009; Wylde, Dieppe, Hewlett, & Learmonth, 2007), however, persistent muscle (Schache, McClelland, & Webster, 2014) and gait deficits (McClelland, Webster, & Feller, 2007; Naal & Impellizzeri, 2010) exist years after surgery. These compensatory strategies are a resultant of interlimb asymmetry between the surgical and nonsurgical limbs, and commonly observed during low-demand tasks (Mizner & Snyder-Mackler, 2005; Yoshida, Mizner, Ramsey, & Snyder-Mackler, 2008). However, little is known on how these impairments relate to higher demand mobility tasks. Exploring this is important since more than 30% of patients with TKA report deficits in muscle and mobility function (Beswick, Wylde, Gooberman-Hill, Blom, & Dieppe, 2012; Bourne, Chesworth, Davis, Mahomed, & Charron, 2010a; Bourne et al., 2010b; Brander et al., 2003; Consensus, 2004; Dickstein, Heffes, Shabtai, & Markowitz, 1998; Franklin, Li, & Ayers, 2008; Jones, Voaklander, Johnston, & Suarez-Almazor, 2000; Wylde et al., 2007) with up to 55% reporting difficulty during more physically demanding activities (Noble et al., 2005; Wylde et al., 2007).

Compensatory motor strategies are a major contributor to interlimb asymmetry observed following TKA (Shakoor, Block, Shott, & Case, 2002; Shakoor et al., 2011; Smith, Christensen, Marcus, & LaStayo, 2014). These habitual strategies observed postoperatively have been developed by the arthritic process, the surgical intervention, reduced proprioceptive input from capsular/ligamentous tissues, lower limb weakness, and kinematic alternations induced by the implant design (Alnahdi, Zeni, & Snyder-Mackler, 2016; Bellemans, Banks, Victor, Vandenneucker, & Moemans, 2002; Massin & Gournay, 2006; Stiehl, Dennis, Komistek, & Crane, 1999; Victor et al., 2010). In spite of 80-90% of patients reporting a reduction in knee pain following TKA (Beswick et al., 2012; Bourne et al., 2010b), individuals commonly demonstrate a *knee stiffening strategy* (vertical ground reaction force [vGRF] loading, decreased knee flexion excursion, lower internal knee extension moments, and reduced quadriceps strength) of the surgical knee, which is observed years following surgery (Gaffney et al., 2016; McClelland et al., 2007; Milner, 2009). The lack of motor retraining during the postoperative recovery period is possibly a major contributor to the ongoing presence of interlimb asymmetry despite a resolution in knee pain.

Symmetry retraining using kinetic biofeedback during postoperative rehabilitation has demonstrated success with restoring joint mechanics to similar levels as healthy controls during low-demand mobility tasks (Zeni et al., 2013), however there have been no investigations to study if these changes are generalizable to high-demand mobility tasks, like navigating declines or stairs, which are required for community ambulation. These interlimb asymmetries can become chronic and lead to a lifetime of impaired mobility function and accelerated degenerative changes in the nonsurgical limb (Alnahdi, Zeni, & Snyder-Mackler, 2011; McMahon & Block, 2003; Shakoor et al., 2002). Relative to healthy peers, pronounced asymmetry is observed during more physically demanding tasks, especially eccentrically-biased activities like decline walking, which require a larger demand on the knee extensors (Finch, Walsh, Thomas, & Woodhouse, 1998; Mizner, Petterson, & Snyder-Mackler, 2005; Stevens-Lapsley, Balter, Kohrt, & Eckhoff, 2010; Walsh, Woodhouse, Thomas, & Finch, 1998). We do not know, however, if interlimb asymmetry during high-demand mobility tasks, like that needed while negotiating declines or descending stairs, can be mitigated by use of biofeedback.

To date, few investigators have explored using kinetic modes of vertical ground reaction force (vGRF) biofeedback to improve chronic interlimb asymmetry (Christiansen, Bade, Davidson, Dayton, & Stevens-Lapsley, 2015; McClelland, Zeni, Haley, & Snyder-Mackler, 2012; Zeni et al., 2013). The limited literature is also mixed when describing the effectiveness of using vGRF biofeedback in improving joint mechanics following TKA. Symmetry retraining interventions using vGRF have been described in a case report (McClelland et al., 2012) and a longitudinal cohort study (Zeni et al., 2013), both showing improved knee joint motion and sagittal knee moment symmetry compared to a standard-of-care model in sit-to-stand and level walking tasks. However, a recent randomized-control trial (Christiansen et al., 2015) comparing a vGRF biofeedback interventional group to a standard-of-care model concluded no improvement during sit-to-stand tasks that require a larger knee extensor demand. The limited evidence available pertaining to symmetry retraining has shown inconsistent findings of effective improvement of interlimb asymmetry during tasks that that are more physically demanding for the knee joint. This speaks to the gap in the literature pertaining to investigating more high-demand mobility tasks and how patients respond to these increased mechanical demands following TKA.

As high as 80% of patients show abnormal sagittal plane knee moment patterns relative to healthy peers (McClelland et al., 2007), indicating compensatory strategies continue to exist following surgery. This is the most consistent kinetic deficit reported in the literature and is well established as a major component to post-TKA chronic interlimb asymmetry (McClelland et al., 2007; Milner, 2009). Current modes of biofeedback lack joint-specific kinetic information to correct these persistent compensatory movement strategies, especially during tasks that require larger knee moment demands (i.e., decline walking, descending stairs, stand-sit). Providing a mode of biofeedback that delivers real-time internal knee extensor moment (IKEM) information might be a more effective mode of symmetry retraining in correcting compensatory movement patterns, especially during more physically demanding mobility tasks.

Interlimb asymmetry has been observed during level walking, though minimal mechanical demand is the knees is required, with primary emphasis placed largely on the other two major joints to propel the center of mass forward (Winter, 2005). Investigating a more physically demanding mobility task, especially a functional measure that requires larger mechanical demands at the knee, is needed to provide valuable information on movement strategies and potential compensatory behaviors that could be mitigated through biofeedback. During decline walking, the lower limb joints of the stance leg have to exert eccentric muscle control and utilize the necessary joint moments to maintain vertical support of the body, while balancing and supporting the body under gravitational force (Hong et al., 2014; Winter, 1980). Eccentrically-based tasks have been shown to be the most commonly reported impaired physical activities following a successful TKA (Gaffney et al., 2016). However, it is not well understood if vGRF is the most effective kinetic mode of biofeedback in improving interlimb asymmetry during high-demand tasks. Particularly in tasks that require increased knee extensor demands, in which a knee-specific biofeedback such as IKEM might provide superior results.

Compensatory strategies may also be related to modifiable risk factors that can be addressed during postoperative recovery. Interlimb asymmetries have been linked independently to discrepancies in lower limb strength, particularly the quadriceps femoris (Mizner & Snyder-Mackler, 2005; van der Krogt, Delp, & Schwartz, 2012). Strength deficits of 30-40% even years after surgery are not uncommon (Meier et al., 2008; Moutzouri et al., 2016; Silva et al., 2003; Valtonen, Poyhonen, Heinonen, & Sipila, 2009), with quadriceps weakness showing a substantial influence on interlimb asymmetry during gait (Mizner et al., 2011; Mizner & Snyder-Mackler, 2005; Vahtrik, Gapeyeva, Ereline, & Paasuke, 2014). However, it is important to investigate strength relationships of the entire lower limb as normal joint mechanics require a coordinated effort of all muscles, which may be challenging with individuals post-TKA. Muscle weakness alone, however, does not account for all the variability in interlimb asymmetry, and alternative factors need further investigation. As many as 20% of patients report residual knee pain following recovery from TKA (Beswick et al., 2012). Persistent knee pain could be a contributing factor to continual interlimb asymmetry in this population. Furthermore, low balance confidence has also been associated with inferior physical performance measures in patients following TKA (Webster, Feller, & Wittwer, 2006) and predictive of functional decline in older adults (Cumming, Salkeld, Thomas, & Szonyi, 2000; Mendes de Leon, Seeman, Baker, Richardson, & Tinetti, 1996; Vellas et al., 1997). Knowing compensatory strategies and sensory deficits are often associated with TKA (Milner, 2009; Skinner, Barrack, Cook, & Haddad, 1984; Slupik, Kowalski, & Bialoszewski, 2013), it is reasonable to hypothesize that these risk factors could be important in understanding interlimb asymmetry following surgery.

Our long-term research goal is to characterize the interlimb asymmetry of the total support moment (M_S) after primary unilateral TKA, which provides overall support to the body in stance. Assessing asymmetry in the M_S is a logical outcome measure in that it reliably evaluates intersegmental coordination between the lower limb joints (Winter, 2005), which can be challenging for individuals with abnormal learned motor behaviors and muscle dysfunction (Gaffney et al., 2016; Hong et al., 2014; Milner, 2008; Valtonen et al., 2009). The overall objectives of this body of work are four-fold: (1) To compare the interlimb asymmetry between low- (level) and high- (decline) demand walking tasks in patients with TKA at 6 months following surgery and healthy matched peers (HMP) and to compare interlimb asymmetry between TKA and HMP participants during the two walking tasks; (2) to compare the efficacy of two modes of biofeedback (vGRF vs. IKEM) on improving interlimb asymmetry in joint mechanics over time during decline walking following TKA; (3) to describe the gait characteristic differences between patients with TKA and HMP during both level and decline walking tasks and, if differences existed, we sought to determine if patients with TKA gait characteristics could be normalized, relative to HMP, with use of knee kinetic biofeedback; (4) to test whether the state of knee extensor strength, lower limb extensor power, residual knee pain, and/or balance confidence explained the level of interlimb joint mechanical asymmetry during a high-demand (decline walking) task at both 3 and 6 months following TKA.

1.1 Demand of Gait Task and Interlimb Joint Mechanical Asymmetry

Many patients report improved walking ability following TKA (Abbasi-Bafghi et al., 2012), though when systematically reviewing the literature there are numerous studies indicating abnormal joint mechanics that persist years after surgery (McClelland et al., 2007). Interlimb asymmetries are also commonly reported, subsequently leading to increased mechanical loading and accelerated degenerative changes in the nonsurgical limb (Alnahdi et al., 2011; Gaffney et al., 2016; McMahon & Block, 2003; Shakoor et al., 2002). Level walking is the most frequently studied functional activity found in the literature (Komnik, Weiss, Fantini Pagani, & Potthast, 2015), yet low mechanical demand is required at the knee during normal gait. However, during decline walking, a larger eccentric joint demand is required of the lower limb during stance, while balancing and supporting the body under gravitational force (Hong et al., 2014; Winter, 1980).

Implementation of these neuromuscular control strategies can be very challenging for individuals with muscle or joint impairments (Hong et al., 2014; Valtonen et al., 2009), however, evaluating the influence the task (high vs. low demand) has on interlimb asymmetry has been understudied and not exposed in the TKA population. To our knowledge, no study has compared interlimb asymmetry between participants 6 months following TKA to HMP during mechanically low-demand (0° slope walking) and high-demand (10° decline slope walking) mobility tasks.

1.2 Mode of Biofeedback on Correcting Interlimb Joint Mechanical Asymmetry During a High-Demand Gait Task

Patients who undergo a TKA continue to show chronic interlimb asymmetries that persist years following surgery (McClelland et al., 2007), despite significant improvements in their reported health-related quality of life measures (Ethgen, Bruyere, Richy, Dardennes, & Reginster, 2004). These compensatory movement strategies lead to over-loading of the nonsurgical limb and under-loading of the surgical limb. Interlimb asymmetry have been studied during multiple mobility tasks in patients following TKA (Worsley, Stokes, Barrett, & Taylor, 2013). However, eccentrically-based mobility tasks are considered the most physically demanding and commonly impaired movements following surgery (Gaffney et al., 2016). Investigators have concluded that during decline walking TKA patients demonstrate reduced speed, stride length, gait width, knee flexion excursion, and vGRF during weight acceptance compared to healthy adults (Myles, Rowe, Walker, & Nutton, 2002; Wiik, Aqil, Tankard, Amis, & Cobb, 2014). To date, however, no study has compared the symmetry of joint movement (kinematics) and loading (kinetics) during this high-demand decline walking task. Currently, kinetic modes of vGRF biofeedback have shown mixed results in improving knee joint motion and sagittal knee moment symmetry compared to a standard-of-care model in tasks that require larger knee extensor demands. Impairments in proper utilization of the surgical knee, however, continue to persist, especially with respect to knee moment contributions. Alternatively, a kinetic mode of IKEM biofeedback might provide a more immediate assessment of compensatory pattern correction that may not otherwise be detected, providing a potential means of attenuating interlimb asymmetry during a high-demand task. To date, no study has compared the effectiveness of two different modes of biofeedback (vGRF vs. IKEM) in correcting interlimb asymmetry during a high-demand mobility task such as decline walking.

1.3 Normalizing Abnormalities With Biofeedback During a High-Demand Gait Task

A recent systematic review (Komnik et al., 2015) comparing biomechanical parameters between TKA patients and healthy adults concluded significant gait pattern deficits between patient populations. Considering these chronic gait deficits have only been identified during low-demand tasks (i.e., level walking), concerns of larger mechanically demanding tasks (i.e., decline walking) could amplify the lower limb deficiencies. Decline walking has been shown to require a larger mechanical demand at the knee and present a greater risk of falling as a result of slipping or loss of balance relative to level walking (Hong et al., 2014; Sheehan & Gottschall, 2012). Considering the muscle and mobility deficits following TKA, these findings are not surprising, especially since decline walking is a highly demanding daily task controlled by the quadriceps muscle. Patients following TKA consistently demonstrate a *knee stiffening strategy*, characterized by reduced knee flexion and underutilization of the quadriceps muscle, as a motor strategy likely developed prior to surgery to avoid pain (Milner, 2009). This habitual strategy may be retained following surgery even though functional mobility is improved due to pain resolution. This evidence suggests that even though knee pain is diminished and patients are able to move through more knee motion, they do not necessarily spontaneously correct their gait to a more normal pattern (Milner, 2009). Knee-specific visual biofeedback using IKEM through computerized motion analysis could provide an immediate assessment of compensatory patterns that may not otherwise be detected, providing a potential means of attenuating asymmetrical movement strategies during a high-demand task (Segal et al., 2015). Currently, there are no peer-reviewed published studies that have investigated a knee-specific kinetic mode of biofeedback on a high-demand task such as decline walking and whether asymmetrical movement strategies can be normalized relative to HMP.

1.4 Modifiable Risk Factors Influence on Joint Mechanical Asymmetry During a High-Demand Gait Task

Interlimb joint mechanical asymmetry could be a product of modifiable risk factors that can be addressed in postoperative rehabilitation. Interlimb asymmetries have been linked to discrepancies in lower limb strength, particularly the quadriceps femoris (Mizner & Snyder-Mackler, 2005; van der Krogt et al., 2012). Muscle weakness is common following surgery and has been associated with poorer functional performance in older adults (Connelly & Vandervoort, 1997; Moxley Scarborough, Krebs, & Harris, 1999). Several studies have also shown strength deficits ranging from 30 to 40% even years after surgery (Meier et al., 2008; Moutzouri et al., 2016; Silva et al., 2003; Valtonen et al., 2009), with quadriceps weakness specifically showing a substantial influence on interlimb asymmetry during gait (Mizner & Snyder-Mackler, 2005). Muscle weakness alone, however, does not account for all of the variability in interlimb asymmetry. Studies have shown that a small, yet clinically substantial, subset of 6 to 30% of patients report continual knee pain following recovery from surgery (Elson & Brenkel, 2006; Insall & Scuderi, 1999). Persistent knee pain could be a prime factor to consider when addressing interlimb asymmetry in this population. Furthermore, low balance confidence has also been associated with inferior physical performance measures in patients following TKA (Webster et al., 2006) and predictive of activity avoidance and functional decline in older adults (Cumming et al., 2000; Mendes de Leon et al., 1996; Vellas et al., 1997). Knowing altered joint mechanics and sensory deficits are often associated with TKA (Milner, 2009; Skinner et al., 1984; Slupik et al., 2013), it is reasonable to hypothesize that these potential risk factors could be important in understanding interlimb asymmetry following surgery.

1.5 Specific Aims

The specific aims of the research described herein are as follows:

1) To compare the interlimb asymmetry between low- (level) and high- (decline) demand walking tasks in patients with TKA at 6 months following surgery and HMP and to compare interlimb asymmetry between TKA and HMP participants

during the two walking tasks.

2) To compare the efficacy of two modes of biofeedback (vGRF vs. IKEM) on improving interlimb asymmetry in joint mechanics over time during decline walking following TKA.
3) To describe the gait characteristic differences between patients with TKA and HMP during both level and decline walking tasks and, if differences existed, we sought to determine if patients with TKA gait characteristics could be normalized, relative to HMP, with the use of knee kinetic biofeedback.
4) To test whether the state of knee extensor strength, lower limb extensor power, residual knee pain, and/or balance confidence explained the level of interlimb joint mechanical asymmetry during a high-demand (decline walking) task at both 3 and 6 months following TKA.

1.6 Hypotheses

Based on the specific aims described above, it was hypothesized that:

1) Significantly greater interlimb asymmetry would be present during the decline walking task when compared to the level walking task. We further hypothesized that significantly greater interlimb asymmetry would be present during both tasks in patients with TKA when compared to HMP counterparts.
2) Significantly greater improvements in interlimb asymmetry would be made using IKEM biofeedback compared to vGRF biofeedback at both 3 and 6 months following surgery.
3) Patients with TKA with IKEM biofeedback will resemble significantly similar M_S

characteristics as HMP compared to participants without biofeedback at 6 months following surgery.

4) Each predictor variable would contribute to the variance explained by the interlimb asymmetry of the M_S and knee extensor moment (M_K) at each time point.

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CHAPTER 2

JOINT MECHANICAL ASYMMETRIES DURING LOW- AND HIGH-DEMAND MOBILITY TASKS: COMPARISON BETWEEN TOTAL KNEE ARTHROPLASTY AND HEALTHY MATCHED ADULTS

2.1 Abstract

Chronic interlimb joint mechanical asymmetry has been reported following TKA during low-demand mobility tasks such as level walking. However, no study has compared the interlimb asymmetry during a high-demand mobility task such as decline walking. The objective of this prospective cohort study was to compare interlimb asymmetry differences during both level and decline walking tasks at 6 months following TKA compared to asymmetry present in an age, gender, body mass index (BMI) and activity level matched healthy cohort. Kinetic and kinematic gait analysis was conducted on 42 patients with TKA and 15 HMP. Our results demonstrated significantly ($p \leq 0.05$) greater total support moment (M_S); (mean differences [*MD*] = 0.12; 95% CI = 0.06, 0.20), M_K (*MD* = 0.08; 95% CI=0.02, 0.14) and vGRF (*MD* = 0.03; 95% CI=0.01, 0.08) differences during decline walking compared to level walking in patients with TKA. Greater M_S (*MD* = 0.19; 95% CI = 0.09, 0.31), M_K (*MD* = 0.11; 95% CI = 0.03, 0.19), vGRF (*MD* = 0.04; 95% CI = 0.01, 0.08) and knee joint angle (*MD* = 2.4; 95% CI = 0.37,

3.67) differences were present in patients with TKA compared to HMP during decline walking. Greater M_S (*MD* = 0.14; 95% CI = 0.03, 0.23) and plantarflexor moment (M_A); (*MD* = 0.10; 95% CI = 0.03, 0.16) differences were present in patients with TKA compared to HMP during level walking. Post-TKA interlimb asymmetry during level walking worsens as the physical demands of the task are increased. Thus, even patients with good self-reported outcomes after TKA exhibit substantial deficits in their mobility reserves that could limit their independence and community mobility as they age.

2.2 Introduction

Total knee arthroplasty is one of the most common elective orthopaedic procedures performed in the United States. Projections estimate the number of procedures is expected to grow 673% to 3.48 million by 2030 (Kurtz, Ong, Lau, Mowat, & Halpern, 2007). This surge can be explained in part by the growing obesity epidemic, however rates of procedures in relatively younger patients that want to preserve an active lifestyle has dramatically increased (Witjes et al., 2016).

Although approximately 70-90% of patients report improved quality of life following surgery (Bourne, Chesworth, Davis, Mahomed, & Charron, 2010a), a significant percentage of patients report residual knee pain, weakness, functional deficits and dissatisfaction (Bourne, Chesworth, Davis, Mahomed, & Charron, 2010b; Meier et al., 2008). Interlimb asymmetry comparisons during gait further indicate continual presence of abnormal joint mechanics following TKA (McClelland, Webster, & Feller, 2007), despite self-reported outcomes indicating high perceived functional ability. Walking gait analysis reveals large disparities between patients with TKA and healthy peers (McClelland et al., 2007).

Abnormal joint mechanics that persist after TKA include reduced surgical limb loading, less knee flexion excursion, and lower knee moments relative to healthy peers during level walking (McClelland et al., 2007). Level walking is the most predominant human mobility task and one of the most essential activities to restore following surgery (Seedhom & Wallbridge, 1985). While many patients report improved walking ability, increased loading of the contralateral limb is associated with accelerated degenerative changes (Shakoor, Block, Shott, & Case, 2002). As a result, 35% of patients will undergo a second surgery to replace the contralateral knee (92%) or hip (8%) following the primary TKA procedure (Shakoor et al., 2002).

Although level walking is most frequently studied (Komnik, Weiss, Fantini Pagani, & Potthast, 2015), the mechanical demands placed on the knee during normal gait are relatively low (Winter, 2005). Investigating tasks that require low demand at the knee may not fully identify limitations in physical performance following surgery. During decline walking, a larger knee demand is required alongside a well-coordinated muscular response within the lower limbs (Hong et al., 2014; Winter, 1980). Implementation of these control strategies can be very challenging for individuals with muscle or joint impairments as commonly observed after TKA (Hong et al., 2014; Valtonen, Poyhonen, Heinonen, & Sipila, 2009). Evaluating interlimb asymmetry between tasks is clinically relevant as increased demand on the nonsurgical limb is a rate limiting factor on poorer physical performance (Mizner et al., 2011; Mizner & Snyder-Mackler, 2005).

The purpose of this study was to (1) compare the interlimb asymmetry between low- (level) and high- (decline) demand walking tasks in patients with TKA at 6 months following surgery and HMP and (2) compare interlimb asymmetry between TKA and HMP participants during the two walking tasks. We hypothesized that significantly greater interlimb asymmetry would be present during decline walking when compared to level walking, and that significantly greater interlimb asymmetry would be present during both tasks in patients with TKA relative to HMP.

2.3 Methods

2.3.1 Participants

A prospective cohort study was conducted with 42 participants who underwent primary unilateral TKA surgery between January 2015 and September 2016 and 15 healthy peers that were matched a priori on age, gender, BMI, and activity level (Table 2.1). All participants in this study met the following inclusion criteria: 45-75 years of age; BMI less than 40; University of California, Los Angeles (UCLA) activity scale of greater than 3; nonsurgical knee pain less than or equal to 4 out of 10 on a visual analog scale for walking or stair climbing; no comorbidities that would affect balance or walking ability; no prior knee joint replacement procedure and no plans of undergoing a TKA on the contralateral limb within 12 months after the initial procedure. The HMP had no confirmed diagnosis of knee arthritis or a history of joint replacement or other lower-limb joint surgery that would interfere with their walking ability. All TKA participants were evaluated at 6 months (mean, 6.4 ± 0.5 mo.) from surgery as physical function typically stabilizes at this time (Fortin et al., 2002; Mizner et al., 2011; Mizner, Petterson, & Snyder-Mackler, 2005). All surgical procedures were performed by one of three orthopaedic surgeons and participants were recruited from the University of Utah Orthopaedic Center (Salt Lake City, UT, USA). Healthy matched peers were recruited from the University of Utah, Center of Aging registry (Salt Lake City, UT, USA). The study was approved by the University of Utah Institutional Review Board and all subjects consented to participation prior to enrollment.

2.3.2 Procedures

Gait analysis was performed in the Motion Capture Core Facility at the University of Utah, using a dual-belt instrumented treadmill (Bertec Corp; Columbus, OH, USA). Participants were fitted with a safety harness, donned compressive clothing, and instrumented with 50 retro-reflective markers defining eight body segments based on a modified Plug-In-Gait marker set (Vicon, Oxford Metrics Ltd., London, UK; Figure 2.1).

First, a stationary trial was captured with each participant in a neutral standing position to align with the global laboratory coordinate system. Each participant's local joint coordinates were aligned to their standing position to control for intersubject variation in anatomical alignment during the static trial. Second, all participants were provided a warm-up period, approximately 3-5 minutes, to become accustomed to walking on the treadmill. Third, once participants verbally confirmed they felt comfortable with the task, they were instructed to "walk as normal as possible" as if ambulating on a flat surface and as if walking downhill. Treadmill velocities were constrained to 1.0 m/s (level) and 0.8 m/s (decline), respectively. Trials in which participants lost their balance, used their upper limbs for support on the surrounding bars or stepped onto the adjacent force platform were excluded. A trial was considered acceptable when all markers were visible and the participant's foot landed successfully on the force platforms without any disturbance to their gait. For each outcome variable, 10 successful steps were averaged and used for statistical analysis.

2.3.3 Clinical Metrics

All participants completed a battery of questionnaires to quantify perceived functional status. Participants completed the Patient Reported Outcomes Measurement Information System (PROMIS) computerized adaptive test (CAT) domains of physical function (PF-CAT), pain interference (PI-CAT), and depression (DEP-CAT; Table 2.1; Borg & Kaijser, 2006; Hawker, Mian, Kendzerska, & French, 2011; Naal, Impellizzeri, & Leunig, 2009). These instruments have been validated as a source for patient-reported outcome administration in orthopaedic specialties (Hart, Mioduski, & Stratford, 2005). Physical activity level was measured by the UCLA scale prior to testing. Rate of perceived exertion (RPE) and numeric knee pain rating scale (NPRS) were also recorded following completion of each session.

2.3.4 Data Processing

Marker trajectory was recorded using a 10-camera motion analysis system (Vicon, Oxford Metrics Ltd., London, UK) sampling at 200 Hz and analog data was collected on a treadmill instrumented with two force platforms sampling at 1000 Hz. Post processing and extraction of joint mechanical variables were accomplished using Visual3D software (C-motion, Inc., Germantown, MD, USA). Marker trajectory and analog data were low-pass filtered at 6 Hz and 25 Hz, respectively, using a fourth-order

Butterworth digital filter based on residual analysis (Winter, 2005). Each body segment was embedded with an orthogonal coordinate system with the positive x-axis directed to the right, the positive y-axis anteriorly, and the positive z-axis superiorly. To account for anatomical variations between participants, all data were normalized to body mass. Three-dimensional angular kinematics were calculated using a Visual3D model with a Cardan sequence (x, y, z), which defined the orientation coordinate system of the distal segment with respect to the proximal segment. The M_S of the lower limbs were computed as the summation of the net joint moments (M_H, M_K, M_A; Winter, 2005). All data were taken at the instant of peak knee flexion during the weight acceptance phase found during the first half of stance phase of the gait cycle. This event during gait was selected for observation in that it has shown to be the more mechanically demanding phase for the knee during these walking tasks (Hong et al., 2014).

2.3.5 Data Analysis

Participant demographics were evaluated using descriptive statistics. A two-way analysis of variance, with one between-group factor (TKA vs. HMA), one repeated-measures factor (task: level vs. decline) and their interaction term, was conducted to examine the effect of group and task on interlimb asymmetry. After fitting this model, a priori selected contrasts of clinical interest were performed using Wald post-tests. Two-sample *t* tests were conducted to examine differences between individual joint moment contributions of the surgical limb (TKA) compared to the dominant limb (HMP) during weight acceptance. Primary outcomes were interlimb asymmetry differences in peak sagittal plane joint moments. Secondary outcomes were vGRF and sagittal plane joint angles. Interlimb asymmetry was defined as a difference score by calculating the absolute value of the surgical limb minus the value of the nonsurgical limb for the TKA group (nondominant limb minus the dominant limb values for HMP group) during each gait task (Fu, Simpson, Kinsey, & Mahoney, 2013). A value equal to 0 signified perfect symmetry, values greater than 0 signified higher asymmetry. Effect sizes (ES) were computed as an indicator of the quantitative strength of the standardized mean differences (Cohen's d). Cohen's d equal to or greater than 0.20 presents a small effect, equal to or greater than 0.50 presents a medium effect, and equal to or greater than 0.80 presents a strong effect (Cohen, 1988). An a priori power analysis was conducted based on previous work (Hong et al., 2014), an ES of 1.2, indicated a minimum of 49 participants [14 HMP, 35 TKA) would be needed to detect between-subject differences at 95% power with a two-sided alpha 0.05. Due to the larger degree of variability observed in TKA joint mechanics compared to HMP (McClelland et al., 2007), a greater number of TKA participants were sampled to more precisely determine the within-subject differences if any existed. Data were analyzed using commercially available statistical software (Stata v14.1; Statacorp, LP, College Station, TX, USA).

2.4 Results

2.4.1 Participants

Forty-two TKA and 15 HMP participants were enrolled in this study (Table 2.1). Groups were similar in age, gender, BMI, PI-CAT, DEP-CAT, UCLA, and RPE (level) scores ($p > 0.05$). The TKA group reported lower PF-CAT scores compared to the HMP group ($MD = 5.15$; 95% CI = 1.96, 8.33; ES = 0.94; $p < 0.01$). The TKA group reported greater knee pain during decline ($MD = 1.26$; 95% CI = 0.42, 2.12; ES = 0.89; $p < 0.01$) and level ($MD = 0.66$; 95% CI = 0.08, 1.24; ES = 0.67; $p = 0.03$) tasks compared to the HMP group. Both TKA ($MD = 1.80$; 95% CI = 1.24, 2.40; ES = 1.53; $p < 0.01$) and HMP ($MD = 1.00$, 95% CI = 0.38, 1.62; ES = 1.20; $p < 0.01$) groups reported significantly greater RPE scores during the decline walking task compared to level walking tasks. The TKA group also reported greater RPE scores during the decline walking task ($MD = 0.90$; 95% CI = 0.18, 0.93; ES = 0.49; $p = 0.01$) compared to the HMP group.

2.4.2 Interlimb Asymmetry Between Task Analysis

Within TKA group comparisons revealed significantly greater interlimb asymmetry differences in peak M_S ($MD = 0.12$; 95% CI = 0.06, 0.20; ES = 0.60; $p < 0.01$), M_K ($MD = 0.08$; 95% CI = 0.02, 0.14; ES = 1.11; $p < 0.01$) and vGRF ($MD = 0.03$; 95% CI = 0.01, 0.08; ES = 0.48; $p < 0.01$) with decline walking compared to level walking during weight acceptance (Table 2.2). No interlimb differences were found within the HMP group comparisons between task.

2.4.3 Interlimb Asymmetry Between Group Analysis

Between group comparisons during decline walking revealed significantly greater interlimb asymmetry differences in peak M_S ($MD = 0.19$; 95% CI = 0.09, 0.31; ES = 1.07; $p = 0.02$), M_K ($MD = 0.11$; 95% CI = 0.03, 0.19; ES = 1.26; $p < 0.01$), vGRF ($MD = 0.04$; 95% CI = 0.01, 0.08; ES = 0.54; $p < 0.05$) and knee joint angle ($MD = 2.4$; 95% CI = 0.37, 3.67; ES = 0.74; $p < 0.05$) in the TKA group compared to the HMP group (Table 2.2). Between group comparisons during level walking revealed significantly greater interlimb asymmetry differences in peak M_S (*MD* = 0.14; 95% CI = 0.03, 0.23; ES = 0.79; *p* = 0.01) and M_A (*MD* = 0.10; 95% CI = 0.04, 0.16; ES = 0.92; *p* < 0.01) in the TKA group compared to the HMP group (Table 2.2).

2.4.4 Individual Joint Asymmetry Between Task and Group Analysis

The surgical limb (TKA) and dominant limb (HMP) to the M_S varied between task and group (Figure 2.2). For level walking, significantly greater M_H (*MD* = 0.07; 95% CI = 0.01, 0.14; ES = 0.68; *p* = 0.03) was found in the HMP group's dominant limb compared to the TKA group's surgical limb. For decline walking, significantly greater M_K (*MD* = 0.46; 95% CI = 0.33, 0.60; ES = 2.08; *p* = 0.02) was found in HMP group's dominant limb compared to the TKA group's surgical limb.

2.5 Discussion

The purpose of this prospective cohort study was to explore the performance and functional capacity of the surgical limb by comparing interlimb asymmetry during both a low- and high-demand walking task at 6 months following TKA and compare these differences to an HMP cohort. Our results indicate that patients with TKA demonstrated larger interlimb asymmetry during decline walking compared to level walking. Greater joint moment, vGRF, and joint angle differences were also seen in the TKA group compared to the HMP group during both walking tasks. Further findings indicate participants perceived greater physical exertion during decline walking compared to level waking, while no clinically meaningful difference in knee pain was observed between groups (Hawker et al., 2011).

As the number of TKA procedures continues to increase, it is important to evaluate functional tasks that require larger knee extensor demands, as patients encounter these obstacles regularly following surgery. No study has compared interlimb kinetic asymmetry between these mobility tasks, however residual interlimb deficits are not uncommon after surgery and compensatory strategies have been shown to amplify as the knee demand is increased. Large effects in kinetic interlimb asymmetries were observed during tasks within both groups. However, the TKA group displayed a greater than three-fold magnitude difference in asymmetry compared to the HMP group, indicating compensatory strategies of the surgical limb continue to exist following surgery. Interlimb asymmetries appear to be amplified as the extensor demand of the task is increased, providing evidence that despite good perceived functional ability and pain resolution, compromised functional performance is observed during higher demand mobility.

Investigators have shown similar findings in patients with TKA displaying no differences in knee extension moment asymmetry during level walking, however greater between limb moment disparities observed during a sit-to-stand task (Mizner & Snyder-Mackler, 2005). Our findings were comparable, as patients with TKA displayed greater M_S interlimb asymmetry between tasks, with lower M_K contributions on the surgical limb relative to the nonsurgical limb. Other studies have shown asymmetry of the surgical limb with smaller moment and lower power absorption and generation output compared to the nonsurgical limb during step up and down tasks (Pozzi, Marmon, Snyder-Mackler, & Zeni, 2016; Pozzi, Snyder-Mackler, & Zeni, 2015). Similar findings have also been shown during ascending and descending stairs (Mandeville, Osternig, & Chou, 2007;

McClelland, Feller, Menz, & Webster, 2014), providing compelling evidence that patients with TKA continue to rely on the nonsurgical limb as the demand of the task is increased. These interlimb asymmetries may be a product of abnormal learned motor behaviors, muscle weakness or residual knee pain deficits that have shown to persist following surgery (Meier et al., 2008; Yoshida, Zeni, & Snyder-Mackler, 2012). It is important to note that approximately 10% of interlimb asymmetry is related to normal variability in healthy adults (Lugade, Wu, Jewett, Collis, & Chou, 2010), which explains some of variability between tasks. However, further research is needed to understand to what extent interlimb asymmetry becomes a deterrent to functional performance. Though this study cannot confirm the cause of the interlimb asymmetry between tasks, it does indicate that increasing demand on the lower limb joints leads to larger compensatory strategies in the TKA population.

Normalizing proper joint mechanics to allow for adequate return to both low- and high-demand mobility tasks is an essential expectation following TKA. Tasks that require eccentric muscle control and larger extensor moments are frequently encountered in daily function and amplified during more physically demanding recreational activities. Restoring interlimb asymmetry to comparable levels as HMP could provide further insight on why negligible improvement in physical activity is observed following TKA (Witjes et al., 2016). Our findings indicate larger rates of asymmetry in vGRF loading and knee flexion motion during weight acceptance were observed in comparison to HMP. Comparable trends in greater M_K asymmetry were also observed, as both the interlimb discrepancy and magnitude of the moment output were different between groups. Expectations in postoperative performance of the surgical knee vary greatly between patients. However, promoting an avenue to improved physical activity in older more medically compromised patients, while also providing a means of returning relatively younger patients back to higher demanding recreational activities are important goals to the medical community.

Several studies have shown interlimb asymmetry during level walking, concluding patients with TKA demonstrate reduced M_K and knee flexion excursion compared to HMP (McClelland et al., 2007). Our findings showed that patients with TKA displayed significantly greater peak M_S interlimb asymmetry, with observed differences seen largely in the M_A contribution. Discrepancy with the existing evidence could be explained by the mode of data collection as our results were based on a treadmill, which may yield different results than an over-ground environment. Additionally, marginal differences could also be explained by inconsistencies in gait speed across studies and status of the contralateral knee as potential bias could be introduced if comparisons are made to an unhealthy joint reference.

Significantly lower M_K of the surgical knee was also observed in patients with TKA compared to HMP counterparts during decline walking. Patients with TKA have shown to display significantly less weight acceptance loading and lower knee flexion excursion during decline walking when compared to healthy adults (Myles, Rowe, Walker, & Nutton, 2002; Wiik, Aqil, Tankard, Amis, & Cobb, 2014). Patients with TKAs' surgical knee displayed approximately 30% less M_K output compared to HMP dominant limb, suggesting an adoption of a *knee stiffening strategy*, likely related to abnormal learned motor behaviors or muscle dysfunction. The HMP group demonstrated greater knee absorption ability during the decline task, while patients with TKA displayed a reduced knee extensor strategy during weight acceptance. Larger magnitude of M_K differences between group may also be related to the constrained velocity of the treadmill and motor strategy to overcome the eccentric decelerative demands required during the decline task. These deficits may be amenable to change, therefore further study to examine the potential of a retraining intervention appears warranted from these data.

Several limitations of the present study should be noted when interpreting the results. Our data were comprised of relatively healthy and active patients with TKA, which may bias the results toward this more homogeneous patient population. We did not control for rehabilitation experience (inpatient or outpatient) or follow a rehabilitation protocol. We constrained the treadmill velocity to provide a more standard gait analysis, however this may have biased the results based on the physical stature, limb length, and functional ability of the participants to walk at the constrained speeds. Alternative influential variables (i.e., lower limb strength, surgical implant design, etc.) were not accounted for and could have influenced the results. Data collection was limited to predominantly sagittal plane joint mechanics and focused on the weight acceptance phase of gait.

2.6 Conclusions

Patients with TKA demonstrate greater interlimb asymmetry during a high-demand decline walking task compared to a low-demand level walking task. Patients with TKA display different joint mechanics compared to HMP during both mobility tasks. These findings are clinically relevant as the number of TKA procedures is rapidly increasing annually, with younger and more active individuals undergoing surgery that are eager to return to higher level of physical function following surgery. Further, the interlimb asymmetries are amplified as the task demands increase, suggesting decline walking results in compensatory strategies of the surgical limb and overutilization of the nonsurgical limb. Unrealized recovery of the surgical limb potentially means reduced longevity of independent community mobility or limited recreational opportunities in younger patients.

2.7 Contributions

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Table 2.1 Descriptive and patient-reported outcome scores

Characteristics	TKA (n = 42)	HMP (n = 15)	P Value
Age, y	62.3 (8.1)	65.3 (5.6)	0.19
Sex, % male	52.4	60.0	0.61
Weight, kg	84.5 (17.0)	81.2 (15.4)	0.51
Height, m	1.73 (0.1)	1.75 (0.1)	0.47
BMI (kg/m^2)	26.2 (8.6)	26.4 (3.5)	0.93
PF-CAT *T* Score	47.6 (5.4)	52.8 (5.5)	0.00
PI-CAT *T* Score	50.6 (8.5)	46.1 (8.0)	0.08
DEP-CAT *T* Score	47.2 (7.1)	48.7 (5.3)	0.48
UCLA Activity Scale	6.2 (5-7)	7.2 (6-8)	0.06
RPE Scale (level)	1.7 (0.7)	1.6 (0.7)	0.67
RPE Scale (decline)	3.5 (0.9)	2.6 (0.9)	0.01
NPRS Score (level)	0.6 (1.1)	0.0 (0.0)	0.03
NPRS Score (decline)	1.2 (1.6)	0.0 (0.0)	0.00

Note: Values represented as mean (SD). TKA, total knee arthroplasty; HMP, healthy matched peers; BMI, body mass index; PF-CAT, physical function computerized adaptive testing; PI-CAT, pain interference computerized adaptive testing; DEP-CAT, depression computerized adaptive testing; UCLA, University of California Los Angles; RPE, rate of perceived exertion; NPRS, numeric knee pain rating scale.

Table 2.2 Interlimb total support moment (M_S), individual joint moments (units: Nm/kg), vertical ground reaction force (unit-less), and the joint angles (units: degrees) occurring during weight acceptance with level (0°) and decline (10°) slope walking.

Parameters	Level			Decline		
TKA	Surg^[†]	Nonsurg^[†]	Diff[†]	Surgl^[†]	Nonsurg^[†]	Diff[†]
Kinetics						
Peak M_S	0.71 (0.18)	0.87 (0.22)	0.16 (0.03)[b]	1.46 (0.24)	1.74 (0.20)	0.28 (0.03)[a,b]
Hip	0.20 (0.12)	0.26 (0.11)	0.06 (0.01)	–0.34 (0.22)	–0.44 (0.22)	0.10 (0.02)
Knee	0.23 (0.14)	0.31 (0.14)	0.08 (0.01)	0.52 (0.21)	0.68 (0.20)	0.16 (0.02)[a,b]
Ankle	0.18 (0.17)	0.31 (0.15)	0.13 (0.02)[b]	0.46 (0.13)	0.56 (0.12)	0.10 (0.01)
GRF	0.89 (0.07)	0.95 (0.08)	0.06 (0.01)	0.95 (0.13)	1.04 (0.12)	0.09 (0.01)[a,b]
Kinematics						
Hip	17.3 (10.9)	19.7 (8.8)	2.4 (0.3)	10.5 (9.6)	12.8 (9.3)	2.3 (0.3)
Knee	–10.3 (6.2)	–13.4 (5.7)	3.1 (0.4)	–17.0 (6.0)	–21.3 (6.5)	4.3 (0.5)[b]
Ankle	1.2 (3.5)	3.6 (3.2)	2.4 (0.3)	5.6 (3.0)	7.6 (3.0)	2.0 (0.3)
HMP	NonDom^[†]	Dom^[†]	Diff[†]	NonDom^[†]	Dom^[†]	Diff[†]
Kinetics						
Peak M_S	0.65 (0.23)	0.67 (0.24)	0.02 (0.01)	1.91 (0.31)	2.00 (0.34)	0.09 (0.04)
Hip	0.11 (0.04)	0.15 (0.07)	0.04 (0.01)	–0.40 (0.19)	–0.46 (0.18)	0.06 (0.01)
Knee	0.28 (0.17)	0.31 (0.17)	0.03 (0.01)	0.99 (0.22)	1.04 (0.24)	0.05 (0.03)
Ankle	0.23 (0.12)	0.19 (0.10)	0.04 (0.01)	0.57 (0.19)	0.67 (0.24)	0.10 (0.02)
GRF	0.90 (0.11)	0.97 (0.11)	0.07 (0.01)	1.20 (0.13)	1.15 (0.12)	0.05 (0.01)
Kinematics						
Hip	15.6 (5.3)	16.8 (5.1)	1.2 (0.3)	13.9 (5.3)	15.9 (5.7)	2.0 (0.2)
Knee	–11.0 (5.1)	–12.6 (5.2)	1.6 (0.3)	–23.9 (4.8)	–25.8 (4.9)	1.9 (0.3)
Ankle	1.3 (1.3)	2.8 (1.9)	1.5 (0.3)	5.3 (2.2)	7.0 (2.3)	1.7 (0.3)

Abbreviations: Surg, Surgical, Nonsurg, Nonsurgical; Diff, Difference; NonDom, Nondominant; Dom, Dominant

[a] Indicates significant within-group difference for task ($P < 0.05$).

[b] Indicates significant between-group difference for group ($P < 0.05$).

[†] Values are mean differences (standard error) from ANOVA model. Each table row represents a separate model.

^ Values are means (standard deviations) from raw data.

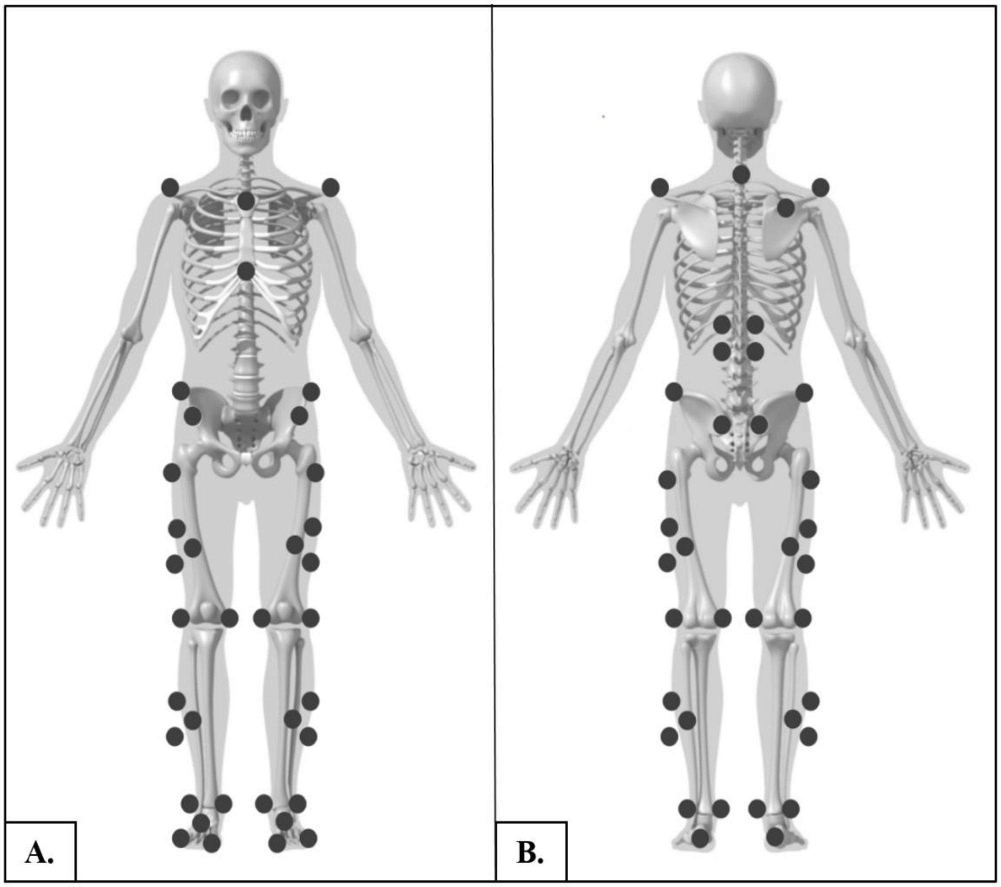
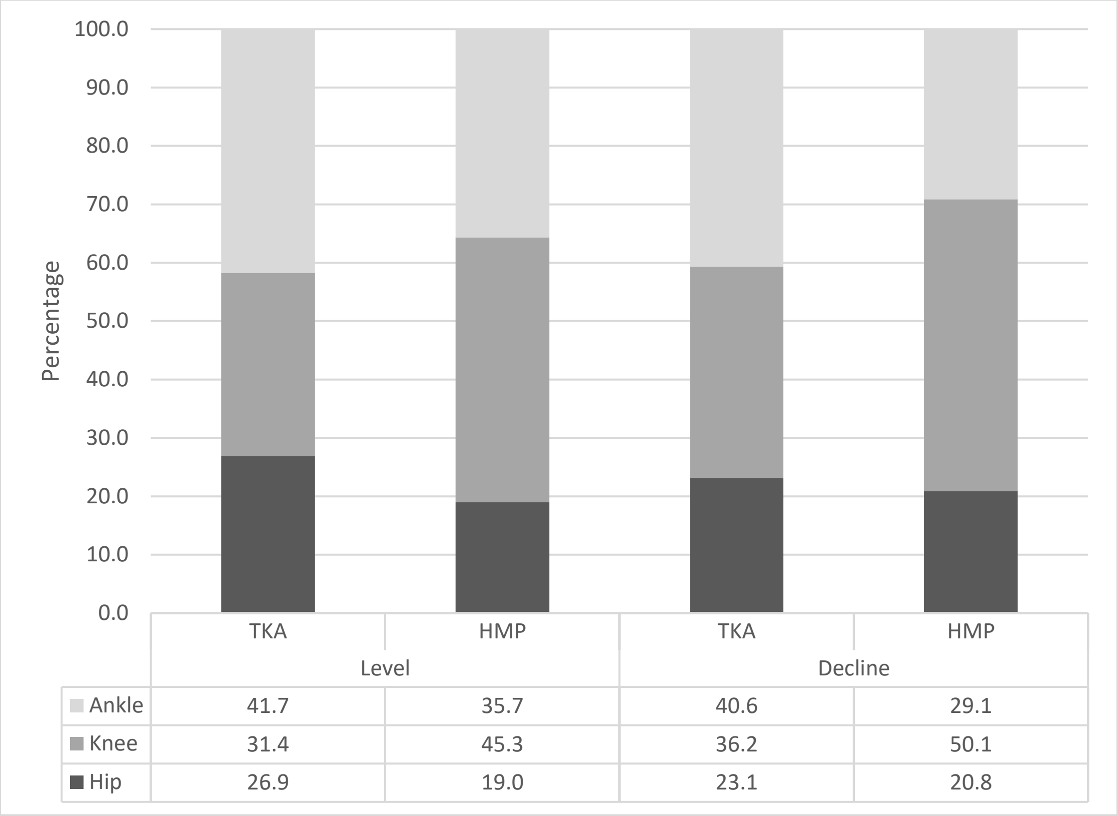


Figure 2.1 Marker placement for modified Plug-In-Gait marker set (A., anterior, B., posterior).
Image supplied by C-Motion, Inc., used by permission.



	TKA	HMP	TKA	HMP
	Level		Decline	
▨ Ankle	41.7	35.7	40.6	29.1
▨ Knee	31.4	45.3	36.2	50.1
■ Hip	26.9	19.0	23.1	20.8

Figure 2.2 Individual joint contributions of the total support moment (%) during weight acceptance between walking tasks for the total knee arthroplasty (TKA) and healthy matched peer (HMP) groups.

CHAPTER 3

COMPARISON OF TWO MODES OF BIOFEEDBACK IN CORRECTING JOINT MECHANICAL ASYMMETRY FOLLOWING TOTAL KNEE ARTHROPLASTY DURING A HIGH-DEMAND MOBILITY TASK

3.1 Abstract

Individuals with TKA persistently display interlimb asymmetry in joint mechanics during level walking that is exacerbated as task demands are increased. Biofeedback to correct aberrant movement behaviors after TKA has had mixed results. There are little data to help guide selection of treatment variables used for biofeedback in gait retraining efforts. This study compared the efficacy of two modes of biofeedback (vGRF or IKEM) to improving limb symmetry for joint kinetics during the weight acceptance phase of decline walking. We examined the effectiveness of both training styles at 3 and 6 months following surgery. Decline gait analysis was completed with 30 participants (17 men; 61.9 ± 8.5 years old; BMI 28.4 ± 3.7 kg/m^2) who were equally allocated to receive either vGRF or IKEM biofeedback. Participants exposed to IKEM biofeedback demonstrated significant improvement in M_S ($p = 0.01$; $p = 0.05$) and M_K ($p = 0.01$; $p = 0.03$) symmetry compared to vGRF biofeedback at 3 and 6 months. Participants exposed to IKEM biofeedback demonstrated significant improvements in

knee flexion ($p < 0.01$; 3 months) and hip flexion ($p = 0.03$; 6 months) motion symmetry compared to vGRF biofeedback. Interlimb asymmetry in joint mechanics persisted over time between 3 and 6 months following surgery. The vGRF biofeedback did not effectively correct interlimb asymmetry at either time point, while the IKEM biofeedback was effective at both time points. These findings indicate patients with TKA can undergo effective means of interlimb asymmetry corrective training during a higher demand mobility task earlier in the recovery process.

3.2 Introduction

Individuals recovering from unilateral TKA show interlimb asymmetries characterized by higher dynamic knee stiffness, decreased limb loading, and reduced internal knee extensor moments (Hatfield, Hubley-Kozey, Astephen Wilson, & Dunbar, 2011; Mizner & Snyder-Mackler, 2005; Worsley, Stokes, Barrett, & Taylor, 2013; Yoshida, Zeni, & Snyder-Mackler, 2012), despite improvements in knee pain and perceived functional performance (Baker, van der Meulen, Lewsey, & Gregg, 2007). These altered biomechanical patterns and resultant compensatory strategies between the surgical and nonsurgical limb can persist for years following a successful postoperative recovery (McClelland, Webster, & Feller, 2007; Mizner et al., 2011; Yoshida et al., 2012). Chronic interlimb asymmetry has shown to lead to muscle disuse in the surgical limb and abnormal overloading onto the nonsurgical limb (Alnahdi, Zeni, & Snyder-Mackler, 2011; McMahon & Block, 2003; Shakoor, Block, Shott, & Case, 2002).

These movement asymmetries have further shown to predispose patients to pain in other joints, functional limitations and arthritic changes over time (Alnahdi et al., 2011; Ritter, Carr, Keating, & Faris, 1994). Interlimb faulty asymmetry has been studied through combined motion analysis and inverse dynamic methods to show asymmetries in sit-to-stand (Christiansen, Bade, Davidson, Dayton, & Stevens-Lapsley, 2015; Farquhar, Reisman, & Snyder-Mackler, 2008; Zeni, Abujaber, Flowers, Pozzi, & Snyder-Mackler, 2013), level walking (Alnahdi et al., 2011; Christiansen et al., 2015; Zeni et al., 2013), and stair climbing (Mandeville, Osternig, & Chou, 2007; McClelland, Feller, Menz, & Webster, 2014). However, the magnitude of interlimb asymmetry has shown to vary between tasks, as more physically demanding activities result in greater compensatory strategies (Mizner & Snyder-Mackler, 2005). Several clinical factors (i.e., pain, swelling, muscle weakness, etc.) are rate-limiting metrics in restoring functional mobility, and early recovery is necessary prior to normalizing joint mechanics. However, the timing in which patients have the physical capacity to effectively complete higher demanding tasks is not well understood.

Eccentrically-biased mobility tasks have shown to be the most physically demanding and commonly reported impairment following surgery (Gaffney et al., 2016), however, the degree of interlimb asymmetry during a more physically demanding mobility task such as decline walking has been understudied in this population. Decline walking is a commonly performed mobility task that requires larger knee extensor moment demands to decelerate the joint compared to other activities of daily living (Hong et al., 2014; Komnik, Weiss, Fantini Pagani, & Potthast, 2015; Myles, Rowe, Walker, & Nutton, 2002). Performing this task can be challenging for individuals with muscle and joint dysfunction; however, it is clinically important to understand the degree of interlimb asymmetry and how modes of motor retraining can assist in correcting compensatory strategies during short-term recovery. Furthermore, it is necessary to identify if interlimb asymmetry is amenable to change over time and if prolonged recovery may be prohibitive of adapting compensatory strategies if implemented early in the recovery process.

Real-time biofeedback using vGRF modes of symmetry retraining have been studied as a means of correcting compensatory strategies following surgery (Christiansen et al., 2015; McClelland, Zeni, Haley, & Snyder-Mackler, 2012; Zeni et al., 2013). These studies have shown biofeedback to be effective in correcting interlimb knee extensor moment asymmetry during level walking, indicating promising results for a task that requires low mechanical demand at the knee. Mixed results in correcting interlimb asymmetry during tasks that require a larger knee extensor demand, such as a sit-to-stand task, have shown to be ineffective at correcting persistent compensatory strategies. Chronic knee extensor moment asymmetry is one of the most common kinetic deficits reported in the literature (McClelland et al., 2007) and shown to be a surrogate of poorer functional performance (Mizner et al., 2011; Mizner & Snyder-Mackler, 2005). Alternatively, a kinetic mode of IKEM biofeedback might provide a more immediate assessment of compensatory strategy correction that may not otherwise be detected, providing a potential means of attenuating interlimb asymmetry during a high-demand task. To date, no study has compared the effectiveness of two different modes of biofeedback (vGRF vs. IKEM) in correcting interlimb asymmetry over time during a high-demand task such as decline walking.

To address the current gaps in the literature we proposed to compare the efficacy of two modes of biofeedback (vGRF vs. IKEM) on improving interlimb asymmetry in joint mechanics over time during decline walking following TKA. We hypothesized that significantly greater improvements in interlimb asymmetry would be made using IKEM biofeedback compared to vGRF biofeedback at both 3 and 6 months following surgery.

3.3 Methods

3.3.1 Participants

A prospective cohort study was conducted with 30 participants (17 men; mean ± SD age, 61.9 ± 8.5 years; BMI, 28.4 ± 3.7 kg/m^2) who underwent a primary unilateral TKA surgery between January 2015 and September 2016. Fifteen participants underwent gait symmetry training using vGRF biofeedback and were compared to those of an age, gender, body mass index (BMI), and activity level matched TKA group of 15 participants that underwent training using IKEM biofeedback (Table 3.1). All participants underwent a primary unilateral TKA and met the following inclusion criteria: between 45-75 years of age; BMI less than 40; UCLA activity scale of greater than 3; nonsurgical knee pain less than or equal to 4 out of 10 on a visual analog scale; no comorbidities that would have influenced the balance or walking ability; no current diagnosis or treatment of neurological conditions; no prior knee joint replacement procedure to either limb and no plans of undergoing a TKA on the contralateral limb within 12 months after the initial procedure. All surgical procedures were performed by one of three orthopaedic surgeons and were recruited from a single medical center (Salt Lake City, UT, USA). The study was approved by the University of Utah Institutional Review Board and all subjects consented to participation prior to enrollment.

3.3.2 Procedures

All testing was completed in two single sessions at the Motion Capture Core Facility at the University of Utah, Department of Physical Therapy and Athletic Training. Participants underwent two separate sessions of gait symmetry training at both 3 (3.3 ± 0.5 mo.) and 6 (6.2 ± 0.6 mo.) months following surgery. These timepoints were selected as most patients have recovered from acute knee pain, retained peak knee range of motion and been discharged from formal physical therapy at 3 months, while physical performance recovery has shown to normalize at 6 months following surgery with marginal functional improvements observed beyond this time point (Fortin et al., 2002; Mizner et al., 2011; Mizner, Petterson, & Snyder-Mackler, 2005). Nonrandomized matched assignment was conducted with the first 15 participants enrolled allocated into the vGRF group and matched to 15 participants that were allocated into the IKEM group.

Prior to the participant’s entry into the laboratory, the system was calibrated and a standing calibration trial was obtained to determine joint centers to create a segment coordinate system. Demographics and anthropometrics were collected from the participant. Each participant was fitted with compressive clothing and safety harness, and then instrumented with 50 retro-reflective markers (14 millimeters), allowing for tracking of eight body segments. The modified Plug-In-Gait marker set (Vicon, Oxford Metrics Ltd., Oxford, UK) defined one HAT segment (combined head, arms, and trunk), one pelvis segment, two thigh segments, two shank segments and two foot segments. The marker locations were used for attributing coordinate systems for each segment and were positioned on the seventh cervical spinous process, manubrium of the sternum, inferior body of the sternum, bilaterally on the anterior/posterior superior iliac spines, right spine of scapula, iliac crests, greater trochanters, acromions, medial and lateral epicondyles of the femurs, medial and lateral malleoli, 1st and 5th heads of the metatarsals, dorsum of the feet, and calcaneal tuberosities (Figure 2.1). One rigid cluster with 4 noncollinear markers was placed at the base of the lumbar spine and 2 nonrigid clusters with 4 noncollinear markers were placed at the lateral side of each thigh and shank. Kinematic joint angles were computed using the Euler *x-y-z* sequence corresponding to flexion/extension (x-axis), abduction/adduction (y-axis), and rotation (z-axis) sequences. Kinetic joint moments were computed with inverse dynamic methods and normalized to BM (kg).

3.3.3 Gait Symmetry Training

All participants walked on a 10° decline sloped instrumented treadmill in shoes at a constrained velocity of 0.8 m/s. The constrained velocity was implemented to fix the task demands across conditions (nonbiofeedback and biofeedback) and time points (3 and 6 months). The inclination angle of 10° has been shown to require greater knee joint demand then level walking and is a common grade of mobility within the community (Hong et al., 2014; Sheehan & Gottschall, 2012). Participants decline gait analysis was conducted under two conditions: (1) nonbiofeedback trials in which they were instructed to walk “as normal as possible as if walking downhill” without exposure to any form of visual biofeedback, and (2) biofeedback trials in which they were instructed to use the visual kinetic biofeedback provided to assist in correcting interlimb asymmetries. Half the participants received vGRF biofeedback (z-axis) via real-time tracing of both lower limb signals through commercial software (Vicon, Oxford Metrics Ltd., Oxford, UK).

The other half of the participants received IKEM biofeedback (x-axis) via real-time kinetic computation of the signal through Visual3D software (C-motion, Inc., Germantown, MD, USA). Visual biofeedback was displayed to participants on a 40.0-inch monitor positioned approximately 1.0 meter anterior to the treadmill along with verbal instructions (Figure 3.1).

Initially, a 3-5 minute warm-up period was provided to allow the participants to become comfortable walking on the instrumented treadmill. Once participants verbally confirmed they felt comfortable with the task, they were asked to walk at the constrained speed as the nonbiofeedback trials were collected followed by 3-5 minutes of data collection. Participants were provided a rest period, approximately 5-10 minutes, prior to beginning the biofeedback trials. As the participants began the second round of testing, they were instructed to maintain symmetry between the surgical and nonsurgical limbs by using the visual kinetic biofeedback of each limb provided on the monitor. Trials in which participants lost their balance, used their upper limbs for support on the surrounding bars or stepped onto the adjacent force platform were excluded. A trial was considered acceptable if all markers were visible and the participants foot landed successfully on the force platforms without any disturbance to their gait. For each outcome variable, 10 successful steps were averaged and used for statistical analysis.

3.3.4 Data Processing

All motion capture testing and analysis were captured using a 10-camera motion analysis system sampling at 200 Hz (Vicon Motion Systems; Oxford, UK), synchronized with a dual-belt instrumented treadmill mounted on two force platforms (Bertec;

Columbus, OH, USA) sampling at 1000 Hz. Data were recorded and synchronized using Nexus 2.1.1 software (Vicon, Oxford Metrics Ltd., Oxford, UK). Post processing and extraction of biomechanical variables were acquired using Visual3D v6.00.27 (C-motion, Inc., Germantown, MD, USA). The raw marker and force platform data were filtered using a 4th-order low pass Butterworth digital filter at a cut-off frequency of 6 Hz (trajectory) and 25 Hz (analog). The cut-off frequency was determined by residual analysis and visual inspection (Winter, 2005).

3.3.5 Clinical Metrics

The National Institute of Health supported Patient Reported Outcomes Measurement Information System (PROMIS) was also collected to evaluate participants' perception of physical function, mental health, and pain interference. These instruments have been validated as a source for patient-reported outcome administration in medical, surgical, and orthopaedic specialties (Hart, Mioduski, & Stratford, 2005; Hung, Clegg, Greene, & Saltzman, 2011; McHorney, 2003; Wyrwich, Norquist, Lenderking, & Acaster, 2013). The PF-CAT item bank v1.2 includes a total of 124 physical function items across 5 domains of physical performance: upper extremity, lower extremity, axial, central, and instrumental activities of daily living. The PI-CAT item bank v1.1 includes 41 items evaluating the extent to which pain hinders participants' engagement with social, cognitive, emotional, physical and recreational activities. The DEP-CAT item bank v1.0 includes a total of 28 items across 4 categories of mental health: self-reported negative mood (sadness, guilt), views of self (self-criticism, worthlessness), and social cognition (loneliness, interpersonal alienation), as well as decreased positive affect and engagement (loss of interest, meaning, and purpose). The participant's pattern of responses to the PROMIS measures were computed as a standardized *T* score, with a mean of 50 based on the United States general population, and a standard deviation (SD) of 10 (Hung et al., 2011). For example, a participant who scores a *T* score of 40 is one SD below the U.S. mean. These PROMIS domains were selected from broadly accepted outcome instruments and have demonstrated appropriate psychometric properties (Hung et al., 2011; Rose, Bjorner, Becker, Fries, & Ware, 2008). The UCLA activity rating scale was also recorded. The UCLA scale is an 11-point numeric scale where participants indicate the most appropriate activity level, with 1 defined as *no physical activity, dependent on others* and 10 defined as *regular participation in impact sports*. This scale is a validated instrument and frequently used in the TKA population (Naal, Impellizzeri, & Leunig, 2009).

3.3.6 Data Analysis

Participant demographics were evaluated using descriptive statistics. To compare the efficacy of the two modes of real-time biofeedback (vGRF vs. IKEM), a linear correction model on rate of interlimb asymmetry was conducted after controlling for nonbiofeedback asymmetry in an analysis of covariance fashion. Two-sample *t* tests were used to assess change in nonbiofeedback interlimb asymmetry between 3 and 6 months for all outcome variables. Outcome variables were computed as a difference score, calculated as the absolute value of the surgical limb minus the value of the nonsurgical limb during gait analysis (Fu, Simpson, Kinsey, & Mahoney, 2013). A value equal to 0 signified perfect symmetry, values greater than 0 signified higher asymmetry. Primary outcomes were difference scores in peak sagittal plane M_S and individual joint moment contributions (x-axis). Secondary outcomes were difference scores in peak vGRF (z-axis) and sagittal plane joint angles (x-axis). The M_S of the lower limbs was defined as the summation of the net joint moments. All kinetic and kinematic data was computed during peak knee flexion within the weight acceptance phase (heel strike to midstance) of the gait cycle. This phase of gait was identified for observation as it has shown to be more mechanically demanding for the knee and an appropriate phase to identify asymmetry of joint mechanics (Hong et al., 2014; Wiik, Aqil, Tankard, Amis, & Cobb, 2014; Winter, 1980).

Effect sizes were computed as partial correlations (Cohen's f^2) and paired mean differences (Cohen's d) for all outcome variables. Cohen's f^2 equal to or greater than 0.02 presents a small effect, equal to or greater than 0.15 presents a medium effect, and equal to or greater than 0.35 presents a strong effect (Cohen, 1988). Cohen's d equal to or greater than 0.20 presents a small effect, equal to or greater than 0.50 presents a medium effect, and equal to or greater than 0.80 presents a strong effect (Cohen, 1988). An a priori power analysis was conducted based on previous work (Christiansen et al., 2015). An ES of 1.1 indicated a minimum of 15 participants would be needed to detect between-subject differences, providing 80% power with a two-sided alpha 0.05. Data were analyzed using commercially available statistical software (Stata v14.1; Statacorp, LP, College Station, TX, USA).

3.4 Results

3.4.1 Participants

Thirty patients with TKA were enrolled in this study and match allocated into each biofeedback group (Table 3.1). Descriptive statistics revealed groups were comparable in age, gender, BMI, UCLA, PF-CAT, PI-CAT, and DEP-CAT scores ($p >$ 0.05).

3.4.2 Gait Biomechanics

Analysis of covariance adjusted for the baseline nonbiofeedback condition revealed the vGRF group displayed greater interlimb asymmetry in peak M_S ($p = 0.01$; Cohen $f^2 = 0.29$), M_K ($p = 0.01$; Cohen $f^2 = 0.35$) and knee flexion joint motion ($p < 0.01$; Cohen $f^2 = 0.54$) outcomes when compared to the IKEM group at 3 months following gait symmetry training (Table 3.2, Figure 3.2-3.3). Partial correlations indicated a small to medium effect sizes, in favor of the IKEM group, in correcting interlimb asymmetry after accounting for the baseline nonbiofeedback condition at 3 months. The vGRF group displayed similar findings of greater interlimb asymmetry in peak M_S ($p = 0.05$; Cohen $f^2 = 0.14$), M_K ($p = 0.03$; Cohen $f^2 = 0.21$) and hip flexion joint motion ($p = 0.03$; Cohen $f^2 = 0.18$) outcomes in comparison to the IKEM group at 6 months following gait symmetry training (Table 3.2, Figure 3.2-3.3). Partial correlations further indicated small effect sizes, in favor of the IKEM group, in correcting interlimb asymmetry after accounting for the baseline nonbiofeedback condition at 6 months. Two-sample *t* tests revealed significantly less interlimb asymmetry in vGRF ($p < 0.01$; Cohen d = 0.78) at 6 months compared to 3 months. All other variables demonstrated similar asymmetry at both time points ($p > 0.05$), indicating no change was observed over time.

Between-group differences revealed participants in the IKEM group were able to demonstrate improved interlimb symmetry in peak M_K during weight acceptance following gait symmetry retraining (Figure 3.4). Between-group differences further revealed participants in the vGRF group displayed significantly lower peak M_K during weight acceptance in the surgical limb compared to the nonsurgical limb (Figure 3.5). There were no statistically significant between-group differences in primary outcomes of interlimb asymmetry of M_H and M_A at either time point. Additionally, no statistically significant between-group differences in secondary outcomes of interlimb asymmetry of vGRF (3 and 6 month), hip flexion motion (3 months), knee flexion motion (6 months) and ankle dorsiflexion motion (3 or 6 months) were observed.

3.5 Discussion

In this prospective study, we evaluated the presence of interlimb asymmetry in joint mechanics during decline walking and compared the efficacy of two modes of real-time biofeedback over time on symmetry retraining following a primary unilateral TKA. The principal findings were: (1) participants exposed to the IKEM biofeedback demonstrated significantly greater improvements in M_S and M_K symmetry compared to those exposed to vGRF biofeedback at both 3 and 6 months following surgery; (2) participants exposed to the IKEM biofeedback also demonstrated significantly greater improvements in knee flexion (3 months) and hip flexion (6 months) motion symmetry when compared to those exposed to vGRF biofeedback following surgery.

Attenuating interlimb asymmetry is an important component to address in postoperative rehabilitation following unilateral TKA, as faulty movement strategies have shown to related to accelerated arthritic changes, muscle weakness and lower functional performance (Christiansen et al., 2015; McMahon & Block, 2003; Mizner & Snyder-Mackler, 2005; Shakoor et al., 2002; Zeni et al., 2013). Our findings indicate that during a higher demand task such as decline walking, patients continue to demonstrate interlimb asymmetry in joint mechanics during weight acceptance that remains over the first 6 months postoperatively. These findings coincide with existing evidence showing patients with TKA demonstrate reduced speed, single leg stance time, knee flexion excursion, and weight acceptance loading on the surgical limb compared to the dominant limb of healthy adults during decline walking greater than 12 months following surgery (Myles et al., 2002; Wiik et al., 2014). This evidence provides further support that interlimb asymmetry does not simply resolve over time and residual deficits continue to persist despite favorable patient-reported outcomes. Our baseline nonbiofeedback data indicate consistent interlimb knee extensor moment asymmetry patterns were observed under constrained environments at both 3 and 6 months following surgery. Similar evidence has further shown during lower physically demanding tasks such as level walking, as patients with TKA show reduced joint excursion, higher dynamic stiffness, and inferior knee extensor moments of the surgical knee and increased loading onto the nonsurgical knee at various time-points following surgery (Alnahdi et al., 2011; Debbi et al., 2015; McClelland et al., 2007; McGinnis, Snyder-Mackler, Flowers, & Zeni, 2013; Yoshida et al., 2012).

Motor pattern retraining could be an important addition to post-TKA rehabilitation protocols to correct compensatory strategies often disregarded, as priority is placed on other components of recovery (i.e., restoring joint motion, lower limb strength, and mobility). Studies utilizing symmetry retraining with visual, auditory, and tactile biofeedback have shown mixed results in correcting interlimb asymmetry and improving functional performance (Christiansen et al., 2015; McClelland et al., 2012; Zeni et al., 2013). One potential explanation for these findings is that the vGRF or equivalent mode of biofeedback studied lacks joint-specific kinetic information that could more precisely assist in correcting compensatory strategies, especially during tasks that require larger M_K demands (i.e., decline walking, descending stairs, stand-sit). Initial findings indicate that gait retraining using IKEM biofeedback can be effective at correcting interlimb asymmetry during a higher demand task such as decline walking. Participants exposed to IKEM biofeedback revealed greater improvement in interlimb M_K and joint kinematic (knee and hip) symmetry when compared to vGRF biofeedback under the same environmental constraints within the first 6 months following surgery.

These findings are clinically relevant in that just providing biofeedback does not appear to result in attenuation of interlimb asymmetry during tasks that require higher knee demands (Christiansen et al., 2015; Zeni et al., 2013). However, providing a more precise measure of biofeedback that offers knee-specific kinetic information to the patient was shown to be more effective. Investigating IKEM biofeedback has not been studied has an effective mode of motor retraining due to the complexity of computation of the real-time moment signal. To date, achieving accurate IKEM biofeedback requires a sophisticated gait laboratory, robust marker set model, synced communication between software, and patient comprehension, which can be challenging for most rehabilitation clinics. However, as high as 80% of patients with TKA show an abnormal sagittal knee moment pattern following surgery compared to healthy peers (McClelland et al., 2007). Additionally, asymmetry in knee extensor moments have been linked to quadriceps weakness, degradation of the contralateral limb, and poorer functional performance (Mizner et al., 2005; Mizner & Snyder-Mackler, 2005; Worsley et al., 2013; Yoshida, Mizner, Ramsey, & Snyder-Mackler, 2008). Exposure to IKEM biofeedback as a novel method of motor retraining was able to provide a more effective means of correcting interlimb asymmetry, providing an optimal mechanism in amending compensatory strategies. Our data shows preliminary findings that resolution of interlimb knee extensor moment asymmetry was possible and achievable as early as 3 months following surgery during a higher demand task. No patients experienced adverse events that were related to the gait symmetry training and likely this protocol could be implemented earlier in the rehabilitation process. However, a more pragmatic mode of IKEM biofeedback is clinically needed and further research is required to assist in developing this technology within the rehabilitation setting.

Investigating more physically challenging mobility tasks with TKA patients is necessary to detect potential compensation strategies that may not be detectable during lower demand tasks (Komnik et al., 2015), despite interlimb differences observed during over-ground walking. Potentially higher rates of compensation could demonstrate greater negative outcomes than we anticipate as little research has been conducted in this area. Studies generally show patients are able to demonstrate similar unilateral sagittal and frontal plane knee moment strategies during stair descent comparative to controls (Standifird, Cates, & Zhang, 2014), however interlimb differences have not been studied. As the number of joint arthroplasty procedures continue to increase in younger and more active individuals (Hawker, 2006; Williams et al., 2013), investigating more physically demanding mobility tasks is needed to provide valuable information on movement strategies and potential compensatory behaviors that could be mitigated through postoperative rehabilitation.

Data from this study cannot determine the cause of the interlimb asymmetry and it is important to note that these compensatory strategies can be multifactorial in nature. However, similar trends of asymmetry were observed over time, despite participants in this study being generally healthy, physically active and reporting good patient-reported outcomes. These initial findings support the notion that compensatory motor strategies remain even after a successful recovery following TKA. Although more effective improvements in interlimb asymmetry were observed using IKEM biofeedback, these changes were a result of motor adaptations during single sessions of gait retraining and not observed to be retained over time. Further research is needed to determine if motor retraining using IKEM biofeedback can be effective at long-term retention and ultimately lead to improved functional performance through a longitudinal cohort study.

Several limitations of our study are worth noting: No long-term follow-up measures were obtained greater than 6 months following surgery, although we were able to draw conclusions regarding change over time in the short-term. If significant changes over time were to occur, likely this would have been observed during the short-term, however, future studies should assess asymmetry in joint mechanics at longer follow-ups. Importantly, despite the improvements in interlimb symmetry seen using the IKEM biofeedback technique, these findings were observed during single sessions of training and further research is needed to determine if longitudinal training can lead to long-term retention. Although we studied the effectiveness of two modes of biofeedback in correcting interlimb asymmetry during a more physically demanding mobility task, there are many modifiable risk factors that could influence compensatory strategies. Further research should also explore how interlimb strength deficits, residual joint pain, or perceived confidence of the surgical limb influence interlimb asymmetry during higher demand tasks. Participants in this study were generally healthy and active, which may be a concern of nonrepresentative bias in that more medically compromised patients could potentially have demonstrated different findings. Furthermore, no randomization of treatment allocation was performed, inherently leading to potential bias in the results, despite extensive matching on potential confounding variables. Limited interpretability of the results could be a concern in that we focused solely on the peak joint mechanic outcomes during the weight acceptance phase of the decline walking task. Lastly, the clinical relevance of using a laboratory-based biofeedback option is a concern as most rehabilitation clinics do not have access to this mode of equipment. However, determining the influence a joint-specific kinetic form of biofeedback is a necessary first step before more pragmatic modes of retraining can be implemented.

3.6 Conclusion

Interlimb asymmetry in joint mechanics persisted over time between 3 and 6 months following surgery, despite improved perceived physical function and knee pain. The vGRF biofeedback did not effectively correct interlimb asymmetry at either time point, while the IKEM biofeedback was effective at both time points. These findings indicate patients with TKA can undergo effective means of interlimb asymmetry corrective training during a higher demand mobility task earlier in the recovery process. Patients did not have to wait for more recovery to occur at 6 months in order to attempt a prolonged training intervention as the patients had adequate physical resources to correct the aberrant mobility patterns with IKEM feedback as early as 3 months following surgery.

3.7 Contributions

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Table 3.1 Descriptive characteristics of patients by group

Variable	vGRF (*n* =15)	IKEM (*n* =15)	*P* Value
Age, y	61.6 (8.9)	62.1 (8.2)	0.90
Sex, % male	53.3	60.0	0.14
Weight, kg	88.9 (19.5)	82.7 (14.4)	0.33
Height, m	1.73 (0.1)	1.71 (0.1)	0.67
BMI (kg/m^2)	29.5 (3.7)	28.2 (4.7)	0.42
UCLA Activity Scale	5.9 (4-9)	5.8 (3-9)	0.93
PF-CAT T-Score	48.5 (5.6)	47.8 (5.9)	0.76
PI-CAT T-Score	48.2 (6.7)	47.9 (8.5)	0.92
DEP-CAT T-Score	49.8 (6.1)	45.6 (8.9)	0.14

Note: Values represented as mean (SD), unless otherwise stated. Values for UCLA activity scale represented as mean (range). vGRF, vertical ground reaction force; IKEM, internal knee extensor moment; BMI, body mass index; UCLA, University of California Los Angeles; PF-CAT, physical function computerized adaptive testing; PI-CAT, pain interference computerized adaptive testing; DEP-CAT, depression computerized adaptive testing.

Table 3.2 Between-group comparison of interlimb asymmetry improvement on joint mechanics during weight acceptance of decline walking for each time point, after controlling for asymmetry during the nonbiofeedback condition.

Variable/Time Point	vGRF Group (*n* = 15)		IKEM Group (*n* = 15)			
	M	SE	M	SE	Effect Size, Cohen f^2§	*P* Value
M_S, Nm/kg						
3 month	0.24	0.03	0.11	0.03	0.29	0.01
6 month	0.26	0.04	0.15	0.04	0.14	0.05
M_H, Nm/kg						
3 month	0.12	0.02	0.12	0.02	0.00	0.88
6 month	0.12	0.02	0.11	0.02	0.02	0.45
M_K, Nm/kg						
3 month	0.17	0.02	0.08	0.02	0.24	0.01
6 month	0.18	0.02	0.10	0.02	0.21	0.03
M_A, Nm/kg						
3 month	0.14	0.02	0.12	0.02	0.02	0.44
6 month	0.16	0.02	0.11	0.02	0.14	0.06
vGRF, BM						
3 month	0.10	0.02	0.09	0.02	0.01	0.55
6 month	0.08	0.01	0.09	0.01	0.02	0.51
Hip Angle, deg.						
3 month	4.40	0.45	3.21	0.45	0.13	0.07
6 month	2.75	0.45	4.19	0.45	0.18	0.03
Knee Angle, deg.						
3 month	6.11	0.51	3.31	0.51	0.54	0.00
6 month	5.21	0.74	3.95	0.74	0.05	0.24
Ankle Angle, deg.						
3 month	3.22	0.39	2.45	0.39	0.07	0.18
6 month	3.78	0.46	2.58	0.46	0.11	0.08

Values were expressed as adjusted means (standard error). *Abbreviations:* vGRF, vertical ground reaction force; IKEM, internal knee extensor moment; M_S, total support moment; M_H, hip moment; M_K, knee moment; M_A, ankle moment; BM, body mass; deg., degrees.

§*Effect size categories (0.20 = small, 0.50 = medium, 0.80 = large).*

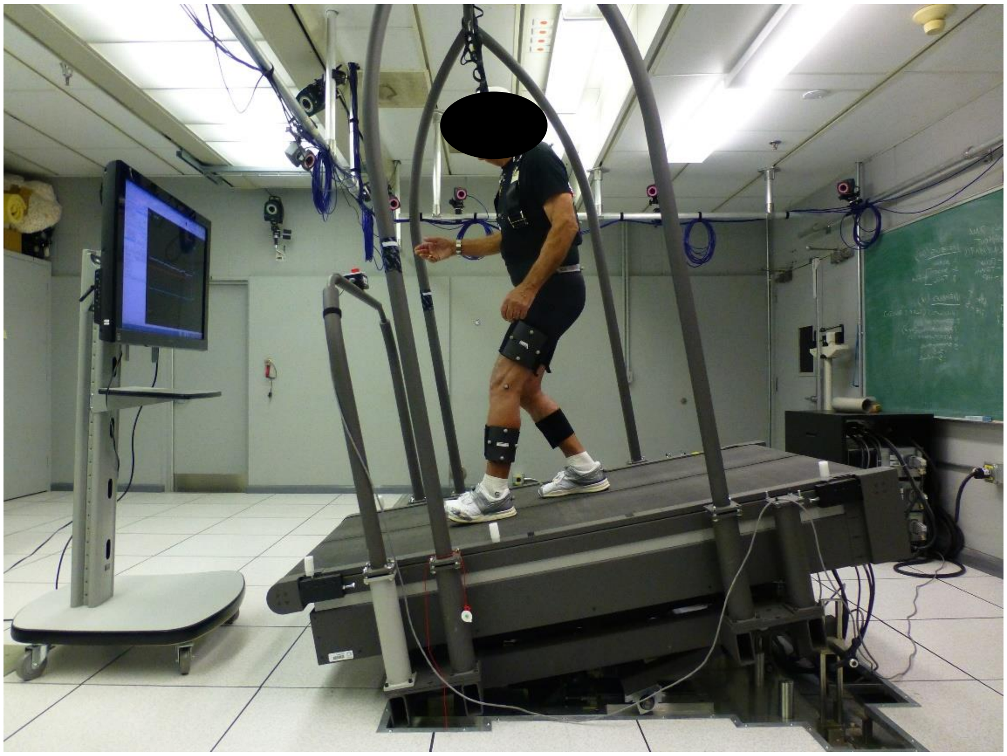
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Figure 3.1 Real-time biofeedback training during decline walking.

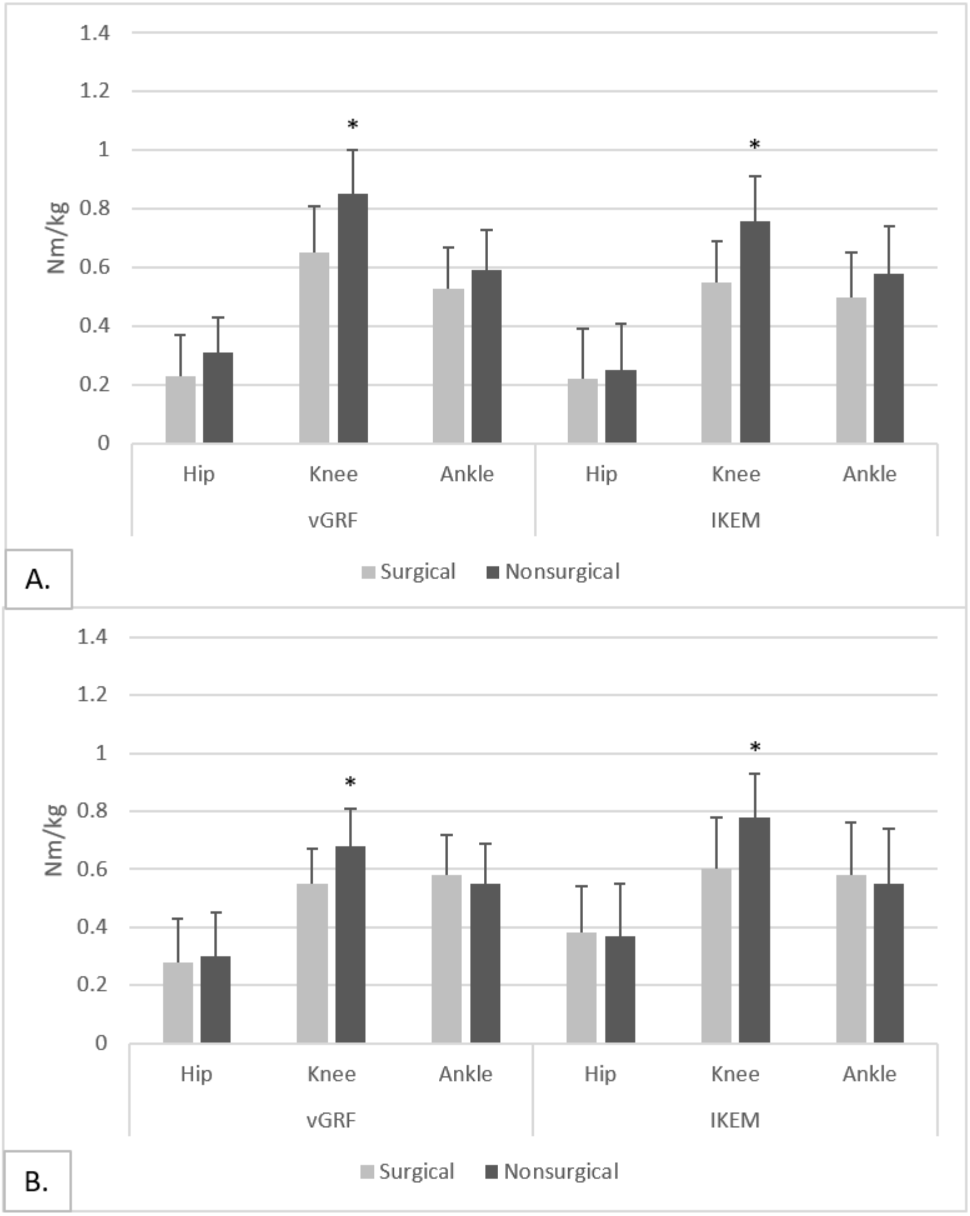

Figure 3.2 Mean (SE) of interlimb peak sagittal plane internal joint moments during nonbiofeedback condition between modes of biofeedback (vGRF vs. IKEM) during weight acceptance of decline walking for 3 months (A) and 6 months (B). Abbreviations: vGRF, vertical ground reaction force; IKEM, internal knee extensor moment.

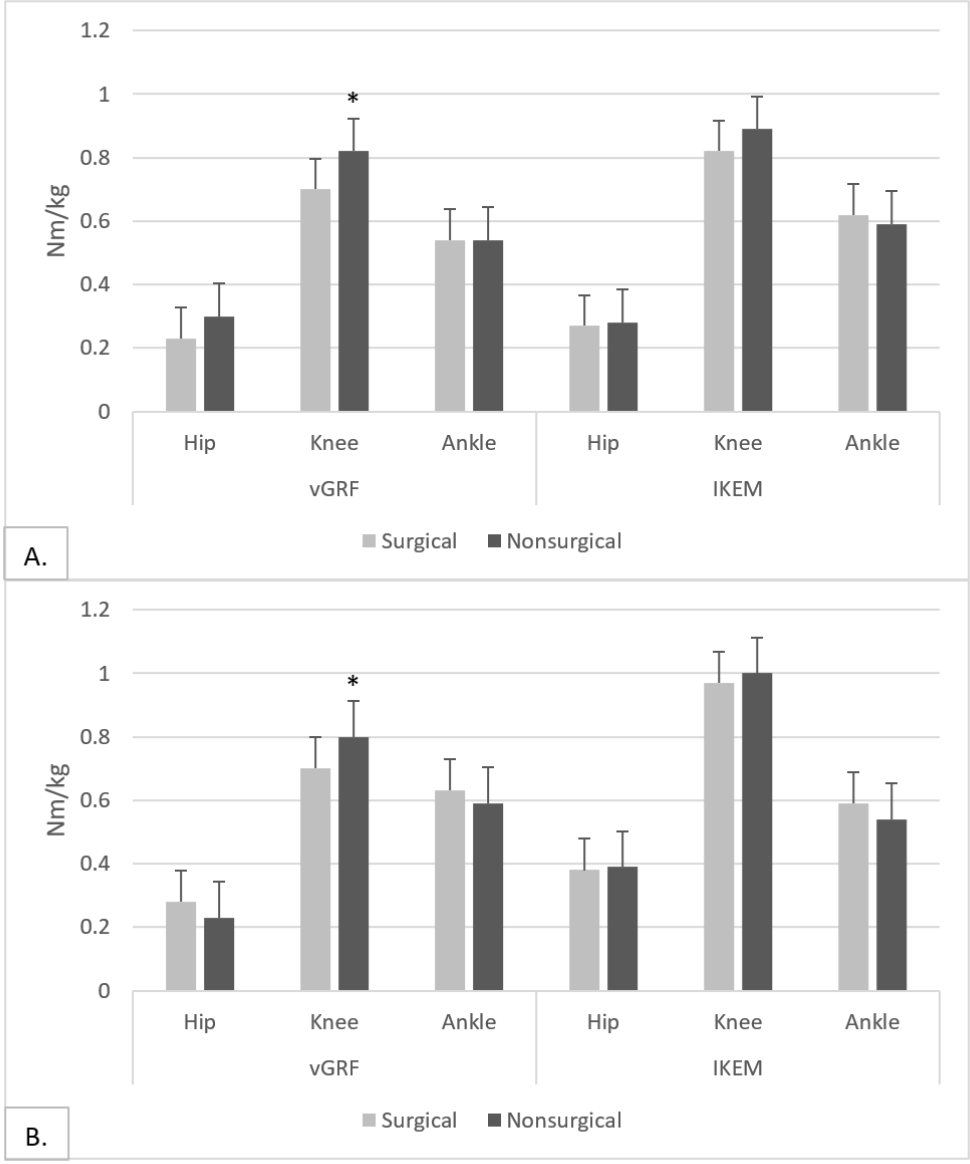

Figure 3.3 Mean (SE) of interlimb peak sagittal plane internal joint moments during biofeedback condition between modes of biofeedback (vGRF vs. IKEM) during weight acceptance of decline walking for 3 months (A) and 6 months (B). Abbreviations: vGRF, vertical ground reaction force; IKEM, internal knee extensor moment.

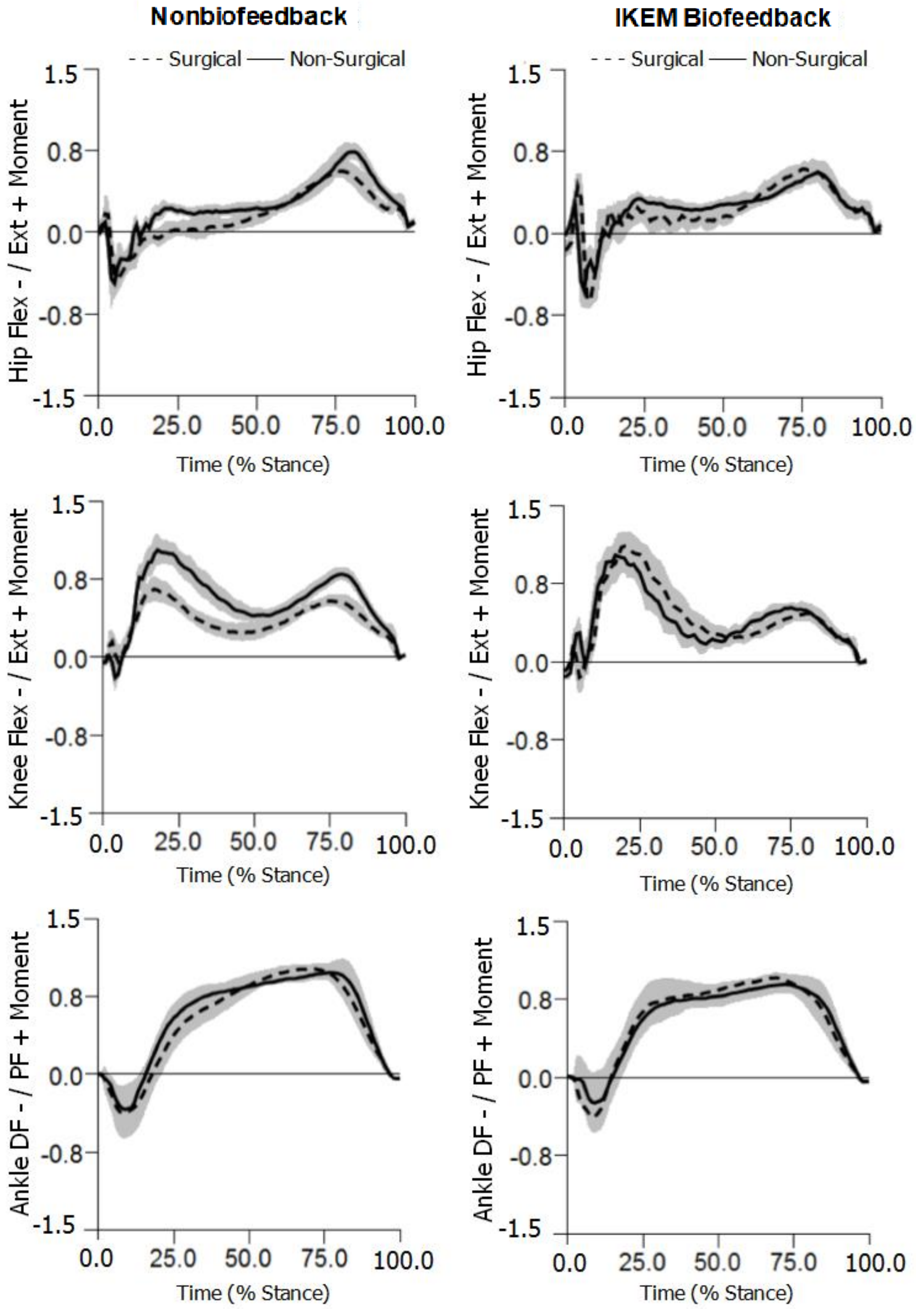

Figure 3.4 Representative example of joint moment (Nm/kg) changes between nonbiofeedback and internal knee extensor moment biofeedback during decline walking. Abbreviations: IKEM, internal knee extensor moment; Flex, flexion; Ext, extension; DF, dorsiflexion; PF, plantarflexion.

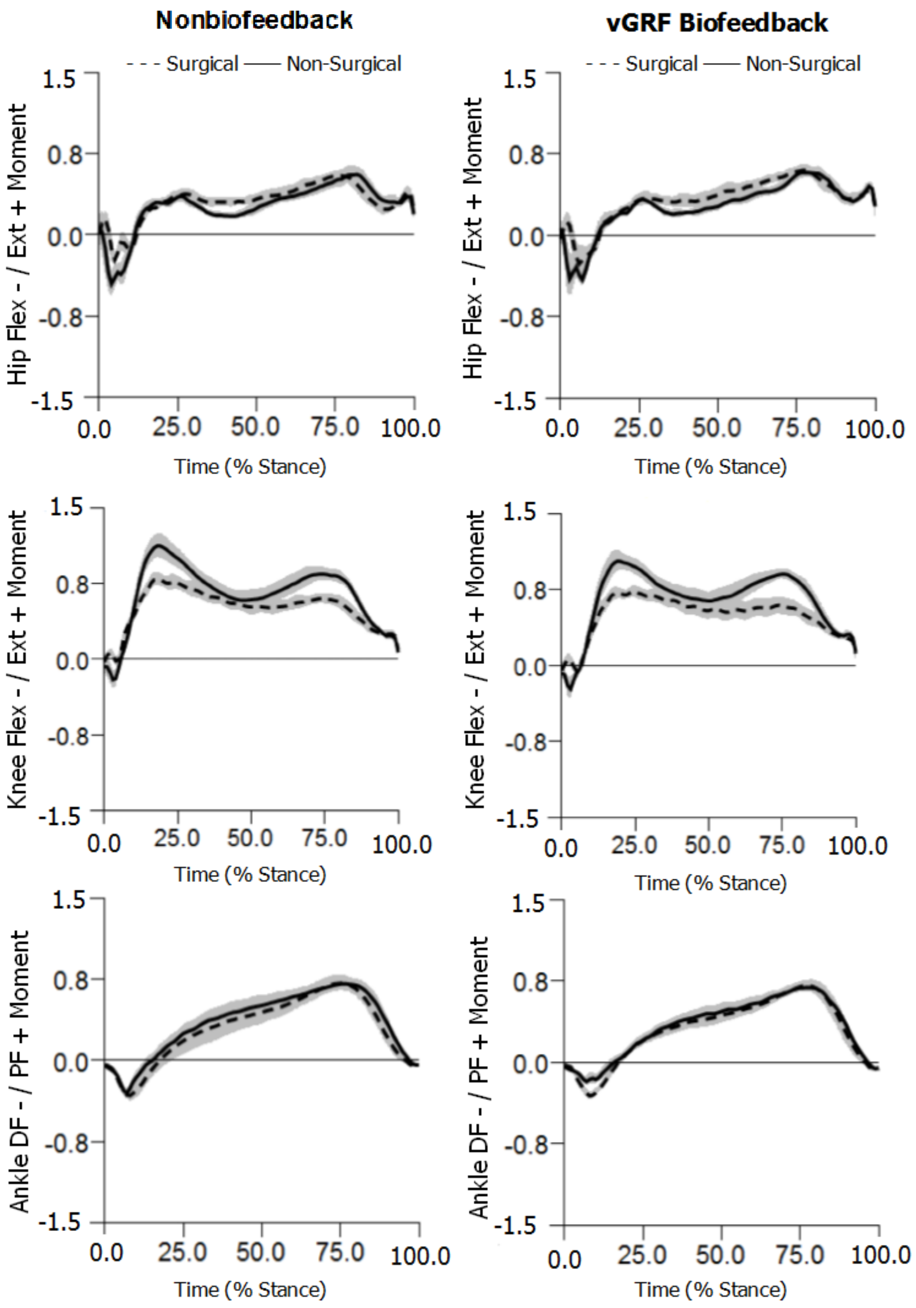

Figure 3.5 Representative example of joint moment (Nm/kg) changes between nonbiofeedback and vertical ground reaction force biofeedback during decline walking. Abbreviations: vGRF, vertical ground reaction force; Flex, flexion; Ext, extension; DF, dorsiflexion; PF, plantarflexion.

CHAPTER 4

NOVEL BIOFEEDBACK TECHNIQUE NORMALIZES GAIT ABNORMALITIES DURING HIGH-DEMAND MOBILITY AFTER TOTAL KNEE ARTRHOPLASTY

4.1 Abstract

Knee mechanics following TKA varies significantly from normal joint function and are exacerbated as task demands are increased, leading to gait abnormalities. Knee kinetic biofeedback could provide an immediate assessment of compensatory patterns and could provide a means of attenuating these deficits. The purpose of this study was (1) to describe the gait characteristic differences between TKA recipients and HMP during both level (low-demand) and decline (high-demand) walking tasks; and (2) where differences existed, to determine the impact of knee kinetic biofeedback on normalizing these gait characteristics. Twenty participants 6 months following a primary unilateral TKA (13 men; mean ± SD age, 63.5 ± 7.9 years; BMI, 27.3 ± 4.7 kg/m^2) and 15 HMP (9 men; mean ± SD age, 65.3 ± 5.5 years; BMI, 26.3 ± 3.5 kg/m^2) underwent three-dimensional gait analysis testing during level and decline walking. Variables of interest included (1) sagittal plane angular impulse during weight acceptance, (2) impulse during the stance phase, and (3) vGRF and sagittal plane angular motion at peak knee flexion. Knee kinetic biofeedback was implemented to patients with TKA to correct abnormal

gait characteristics if observed. Patients with TKA had lower knee extensor angular impulse (*MD*, 0.12; CI, 0.58, 0.83; $p < 0.001$), vGRF (*MD*, 0.17; CI, 0.79, 0.93; $p < 0.001$), and knee flexion motion (*MD*, 6.6; CI, 0.65, 0.92; $p = 0.005$) compared to the non-TKA group during decline walking without biofeedback. Patients with TKA normalized their knee extensor angular impulse (*MD*, 0.01; CI, 0.82, 1.20; $p = 0.991$) and peak vGRF (*MD*, 0.05; CI, 0.87, 1.04; $p = 0.299$) during decline walking when exposed to biofeedback. No between-group differences were observed during level walking. Groups were similar in age, gender, body mass index, physical activity level, pain interference, and depression scores ($p > 0.05$). Between-group differences were observed in patient-reported physical function as the non-TKA group reported higher *T* scores with a mean (SD) of 52.8 (5.4) compared with a mean of 47.6 (5.4) in the TKA group ($p = 0.009$). Short-term findings suggest patients with TKA demonstrate compensatory gait characteristics during a high-demand mobility task when compared to HMP. Our findings indicate that knee kinetic biofeedback can induce immediate improvements in gait characteristics during a high-demand mobility task. There may be a potential role for the use of novel biofeedback techniques to improve patient gait and mechanics following TKA.

4.2 Introduction

Individuals who have undergone TKA continue to report and display functional performance deficits, particularly during more physically demanding mobility tasks, despite resolution in knee pain and improved patient-reported outcomes (Milner, 2009; Noble et al., 2005; Paxton, Melanson, Stevens-Lapsley, & Christiansen, 2015). Thus, advancements in surgical technique and alternative implant designs have been proposed to improve joint mechanics to ultimately resolve these functional impairments. Despite current efforts in improving modern TKA, in vivo analyses demonstrate surgical knee kinematics vary significantly from normal knee mechanics (Victor et al., 2010). These findings have been supported through fluoroscopy and marker-based motion analysis testing (Andriacchi, 1993; Banks, Markovich, & Hodge, 1997; Bertin et al., 2002; Dennis, Komistek, Mahfouz, Haas, & Stiehl, 2003; Insall et al., 2002; Komistek, Dennis, & Mahfouz, 2003; McClelland, Zeni, Haley, & Snyder-Mackler, 2012; McClelland, Webster, & Feller, 2007; Milner, 2009; Stiehl, Komistek, & Dennis, 1999). Challenges in restoring normal physiologic function of the knee are multifaceted and largely related to compensatory strategies developed by the arthritic process, the surgical intervention, reduced proprioceptive input from capsular/ligamentous tissues, lower limb weakness, and kinematic alternations induced by the implant design (Alnahdi, Zeni, & Snyder-Mackler, 2016; Bellemans, Banks, Victor, Vandenneucker, & Moemans, 2002; Massin & Gournay, 2006; Stiehl, Dennis, Komistek, & Crane, 1999; Victor et al., 2010).

Aberrant joint mechanics may be amenable to change through advancements in motor retraining techniques. Biofeedback retraining has been studied in many patient populations in correcting walking, running, and jumping mechanics. Biofeedback modes include visual (Crowell, Milner, Hamill, & Davis, 2010; Davis & Futrell, 2016; Dingwell, Davis, & Frazier, 1996; Messier & Cirillo, 1989; White & Lifeso, 2005) or auditory (Cronin, Bressel, & Fkinn, 2008; McNair, Prapavessis, & Callender, 2000; Petrofsky, 2001; Seeger, Caudrey, & Scholes, 1981) information to the patient that would otherwise be undetectable without the necessary technology. In the majority of these studies, patients with TKA that received biofeedback could correct faulty movement mechanics and improve functional performance (Christiansen, Bade, Davidson, Dayton, & Stevens-Lapsley, 2015; McClelland et al., 2012; Zeni, Abujaber, Flowers, Pozzi, & Snyder-Mackler, 2013). Recent studies incorporating motor retraining into postoperative TKA rehabilitation have shown encouraging results in improving gait mechanics to levels commensurate with HMP (Christiansen et al., 2015; Zeni et al., 2013). However, as high as 80% of patients show an absence of normal sagittal plane knee extensor moments during gait (McClelland et al., 2007). This is the most consistent movement analysis deficit reported in the literature and is a major contributor to functional limitations following surgery (McClelland et al., 2007; Milner, 2009). Visual biofeedback using internal knee extensor moments through computerized motion analysis could provide an immediate assessment of compensatory patterns that may not otherwise be detected, providing a potential means of attenuating gait characteristic deficits during both low- (level walking) and high-demand (decline walking) mobility tasks (Segal et al., 2015). To our knowledge, there are no peer-reviewed publications that have investigated knee specific kinetic biofeedback during walking tasks and its impact on normalizing joint mechanical strategies.

The purpose of this study was (1) to describe the gait characteristic differences between patients with TKA and HMP during both level and decline walking tasks; and (2) where differences existed, to determine the impact of knee kinetic biofeedback on normalizing these gait characteristics.

4.3 Methods

After approval from the institutional review board, a prospective cohort study of convenient sampling was conducted identifying 20 participants (13 men; mean ± SD age, 63.5 ± 7.9 years; BMI, 27.3 ± 4.7 kg/m^2) who underwent a primary unilateral TKA surgery between June 2015 and July 2017 and 15 healthy peers (9 men; mean ± SD age, 65.3 ± 5.5 years; BMI, 26.3 ± 3.5 kg/m^2) matched a priori on age, gender, BMI, and physical activity level (Table 4.1). All surgical procedures were performed by one of three fellowship trained joint reconstruction surgeons through a medial parapatellar approach. Implants included seven (35%) with a cruciate retaining design (Vanguard, Zimmer Biomet, Warsaw, IN, USA), 7 (35%) with bicruciate retaining implant (Vanguard XP, Zimmer Biomet, Warsaw, IN, USA), and 6 (30%) with posterior-cruciate substituting implant (Triathalon PS, Stryker, Kalamazoo, MI, USA). All participants in this study met the following inclusion criteria: between 45-75 years of age, BMI less than 40, UCLA activity scale of greater than 3, nonsurgical knee pain less than or equal to 4 out of 10 on a visual analog scale for walking or stair climbing, no comorbidities that would have influenced balance or walking ability, no prior knee joint replacement procedure to either limb, and no plans of undergoing a TKA on the contralateral limb within 12 months after the initial procedure. The healthy matched non-TKA group had neither confirmed diagnosis of knee arthritis nor history of joint replacement or other lower-limb joint surgery that would interfere with their normal gait pattern. All TKA participants were recruited from the University of Utah, Orthopaedic Center (Salt Lake City, UT, USA) and non-TKA peers were recruited from the University of Utah, Center of Aging registry (Salt Lake City, UT, USA).

The trajectory data were captured using a 10-camera motion analysis system (Vicon Motion Systems; Oxford, UK) and analog data were collected using a dual-belt instrumented treadmill (Bertec; Columbus, OH, USA). Data were recorded and synchronized using Nexus 2.1.1 (Vicon, Oxford Metrics Ltd., Oxford, UK). Post processing and the extraction of gait characteristics were performed using Visual3D v6.00.27 (C-motion, Inc., Germantown, MD, USA). Trajectory and analog data were filtered using a 4th-order low pass Butterworth digital filter at cut-off frequencies of 6 Hz and 25 Hz, respectively, based on residual analysis (Winter, 2005).

Each participant donned compressive clothing and was fitted with a safety harness prior to testing. Fifty retro-reflective markers (14 mm diameter) were instrumented on specific anatomical locations based on a modified Plug-In-Gait marker set (Vicon, Oxford Metrics Ltd., Oxford, UK) (Figure 4.1). The marker set defined one HAT segment (combined head, arms and trunk), one pelvis segment, two thigh segments, two shank segments, and two foot segments. Marker locations were used for attributing coordinate systems for each segment. A standing static calibration was first obtained to identify joint centers and to create a segment coordinate system. Each participant's local joint coordinates were aligned to their standing position to control for intersubject variation in anatomical alignment during the static trial.

Gait analysis on TKA participants was conducted under two conditions: (1) nonbiofeedback trials where participants were instructed to walk "as normal as possible" without any visual biofeedback, and (2) biofeedback trials where they were instructed to use the visual kinetic biofeedback provided to assist in correcting abnormal knee mechanics (Figure 4.2). The gait analysis in the non-TKA group was conducted under only the nonbiofeedback condition. Level walking was evaluated as it is the most common functional task performed by most adults (Komnik, Weiss, Fantini Pagani, & Potthast, 2015). Because minimal mechanical demand is required at the knee to accomplish level walking (Winter, 2005), decline walking was chosen as a high-demand mobility task. Decline walking is a commonly performed mobility task that requires large decelerative mechanical demands at the knee and has been understudied in this patient population. The inclination angle of 10° has been shown to require greater lower limb joint demand than level walking and represents a common grade of mobility within the community (Hong et al., 2014; Sheehan & Gottschall, 2012).

Prior to data collection, participants were provided a 3-5 minute warm-up period to become accustomed to walking on the instrumented treadmill. Treadmill velocities were constrained at 1.0 m/s (level) and 0.8 m/s (decline), respectively. Primary outcomes were angular impulse (area under the moment-time curve) of the limb during the weight acceptance phase (heel strike to midstance) of gait within both conditions. Secondary outcomes were impulse (area under the force-time curve), vGRF, and peak angular motion. All kinetic metrics were normalized to participants' BM (kg). The TKA participants were evaluated at 6 months (mean, 6.2 ± 0.6 mo.) from surgery as physical function typically stabilizes at this time (Fortin et al., 2002; Mizner et al., 2011; Mizner, Petterson, & Snyder-Mackler, 2005). For each outcome variable, 10 successful steps were averaged. A successful step was one in which all markers were visible, and the participant maintained a consistent gait cycle and could ambulate successfully without crossing over onto the adjacent force platform.

Patient-reported outcomes were measured using the National Institute of Health's

PROMIS CAT domains of PF-CAT, PI-CAT and depression DEP-CAT scores. These PROMIS domains have demonstrated appropriate psychometric properties (Hung, Clegg, Greene, & Saltzman, 2011; Rose, Bjorner, Becker, Fries, & Ware, 2008). The TKA group was defined as having a good PF-CAT score if they scored in less than one standard deviation away from the mean score for the United States general population (mean *T* score, 50.0 [10.0]), while the non-TKA group was defined as higher functioning if they scored above the national average. The UCLA activity rating scale was also collected as a 11-point numeric scale range as participants indicated the most appropriate activity level, with 1 defined as *no physical activity, dependent on others* and 10 defined as *regular participation in impact sports*. This scale is a validated instrument and frequently used in the TKA population (Naal, Impellizzeri, & Leunig, 2009).

The normalized mean of all gait characteristics was computed by dividing the TKA group mean by the non-TKA group mean and reported with a 95% CI. This was computed using generalized gamma regression, a general linear model with a log link, and gamma family. In generalized gamma regression, back-transforming the absolute value regression coefficient providing the ordinary arithmetic normalized mean, and back-transforming the 95% CI for the coefficient providing the 95% CI for the arithmetic normalized mean (Chow & Liu, 2000; Fleiss, 1986). A percent difference from normal [(TKA surgical limb – non-TKA dominant limb) / non-TKA dominant limb] was computed through the general linear model to provide a clinical measure of effect representing the relative interlimb symmetry comparison between groups. Interlimb symmetry was defined as the comparison of the TKA participants' surgical limb to the dominant limb of the non-TKA participants for each gait analysis. Effect sizes were computed for the mean differences as Cohen's d. Cohen's d equal to or greater than 0.20 presents a small effect, equal to or greater than 0.50 presents a medium effect, and equal to or greater than 0.80 presents a strong effect (Cohen, 1988). An a priori power analysis was conducted based on previous work (Christiansen et al., 2015). An effect size of 1.1 indicated a minimum of 15 participants would be needed to detect between-subject differences, providing 80% power with a two-sided alpha 0.05. Data were analyzed using commercially available statistical software (Stata v14.1; Statacorp, LP, College Station, TX, USA).

4.4 Results

Groups were similar in age, gender, BMI, UCLA, PI-CAT, and DEP-CAT scores ($p > 0.05$; Table 4.1). Between-group differences were observed in patient-reported PF-CAT as the non-TKA group reported higher *T* scores with a mean (SD) of 52.8 (5.4) compared with a mean of 47.6 (5.4) in the TKA group ($p = 0.009$; Table 4.1).

Without biofeedback, those in the TKA group demonstrated lower knee extensor angular impulse compared to those in the non-TKA group during decline walking (*MD*, 0.12; CI, 0.58, 0.83; $p < 0.001$; Table 4.2; Figure 4.3). The clinical measure of effect showed the TKA group displayed a 30% deficit in knee extensor output during the weight acceptance phase compared to the non-TKA group, resulting in a large effect size (Cohen's d, 1.34). The surgical limb of the TKA group, without biofeedback, had lower peak vGRF output compared to the limb of the non-TKA group (*MD*, 0.17; CI, 0.79, 0.93; $p < 0.001$; Table 4.2; Figure 4.3). The clinical measure of effect indicated the TKA group displayed a 14% deficit in limb loading compared to the non-TKA group, resulting in a large effect size (Cohen's d, 1.23). The surgical limb of the TKA group, without biofeedback, also displayed lower knee flexion joint angle (*MD*, 6.6; CI, 0.65, 0.92; *p* = 0.005; Table 4.2; Figure 4.3) compared to the non-TKA group, resulting in a large effect size (Cohen's d, 1.00).

With biofeedback, those in the TKA group demonstrated relatively comparable measures of knee extensor angular impulse (*MD*, 0.01; CI, 0.82, 1.20; *p* = 0.991; Table 4.2; Figure 4.3) and peak vGRF (*MD*, 0.05; CI, 0.87, 1.04; *p* = 0.299; Table 4.2; Figure 4.3) compared to the non-TKA group during decline walking. Biofeedback exposure improved the clinical measure of effect of the TKA group by 29% (30% to 1%) and 10% (14% to 4%) relative to the non-TKA group for the knee extensor angular impulse and peak vGRF outcomes, respectively. Knees in the TKA group, with biofeedback, displayed higher knee flexion joint angle (*MD*, -3.7; CI, 1.01, 1.31; *p* = 0.028; Table 4.2; Figure 4.3) compared to the non-TKA group, indicating a large effect size (Cohen's d, 0.74). No between-group differences were observed during level walking (*p* > 0.05; Table 4.3). Therefore, no biofeedback testing was conducted.

4.5 Discussion

Advancements in surgical technique and implant design efforts have revolutionized joint arthroplasty in recent decades, resulting in improved survivorship and clinical outcomes (Baker, van der Meulen, Lewsey, & Gregg, 2007; Bourne, Chesworth, Davis, Mahomed, & Charron, 2010; Wylde et al., 2009; Wylde, Dieppe, Hewlett, & Learmonth, 2007). However, studies indicate abnormal gait characteristics continue to exist relative to normal knee function, despite these advancements in surgical practice (Victor et al., 2010). Restoring normal joint function of the knee is challenging and the etiology of abnormal mechanics can be multifactorial in nature. Furthermore, younger, more active individuals are undergoing joint arthroplasty at higher rates, and returning to higher-demand tasks is becoming a common expectation. Surgical approaches designed to restore normal joint mechanics have been thoroughly studied (Andriacchi, 1993; Banks et al., 1997; Bertin et al., 2002; Dennis et al., 2003; Insall et al., 2002; Komistek et al., 2003; McClelland et al., 2012; McClelland et al., 2007; Milner, 2009; Stiehl, Komistek, et al., 1999), however, aberrant joint mechanics continue to exist. Normalizing gait characteristics may require a collaborative effort of both surgical and motor retraining measures in returning patients to higher levels of physical function. Motor retraining through novel kinetic biofeedback may provide a mechanism of improving gait characteristics, particularly during higher demand mobility tasks.

The study had several limitations. First, no long-term follow-up assessment was conducted, so observations can only be interpreted during the short-term. It is unclear at this point if the intervention of the biofeedback training leads to long lasting improvements in gait characteristics. Second, participants in this study were generally healthy and active, which may be a concern of nonrepresentative bias in that more medically compromised patients could potentially have demonstrated different findings. Third, results were based on data collected on an instrumented treadmill, which could yield different results than an over-ground environment. Fourth, marker-based motion analysis has certain limitations in the ability to accurately assess lower limb gait characteristics. Although marker-based limitations are acknowledged, we chose this method given its widespread use in the literature and because it is the recommended standard for motion analysis. Fifth, significant effort was taken to match the groups based upon important confounding variables, however alternative confounding variables were not accounted for within this analysis.

Patients with TKA demonstrated abnormal gait characteristics during high-demand mobility, but not during a low-demand walking task when compared to non-TKA counterparts. These findings suggest that as the demand of the task increases, patients with TKA display inferior kinematic and kinetic output of the surgical limb, and compensatory strategies continue to exist despite favorable patient-reported outcomes and pain resolution. Recent systematic reviews reveal most studies evaluate normalizing gait characteristics to healthy controls during level walking (Komnik et al., 2015; McClelland et al., 2007), however, a growing number of joint arthroplasty patients are interested in returning to more physically demanding functional and recreational activities (Bourne et al., 2010). Decline walking requires a larger mechanical demand at the knee compared to other activities of daily living and presents a greater risk of falling as a result of slipping or loss of balance relative to level walking (Hong et al., 2014; Sheehan & Gottschall, 2012). Considering the muscle and mobility deficits following TKA, these findings are not surprising, especially since decline walking is a demanding task largely controlled by the quadriceps muscle. Similarly, Wiik, Aqil, Tankard, Amis, and Cobb (2014) compared gait characteristics during decline walking at a minimum of 12 months following surgery, concluding patients with TKA displayed inferior impulse and vGRF output during weight acceptance compared to both unicompartmental joint arthroplasty patients and healthy adults. Current findings indicate patients following TKA demonstrate a *knee stiffening strategy*, characterized by reduced knee flexion and limb loading, as a motor strategy likely developed prior to surgery to avoid pain (Milner, 2009). This habitual strategy may be retained following surgery even though functional mobility is improved due to pain resolution. It has been shown that the same gait characteristics observed in patients with preoperative end-stage knee arthritis are retained greater than a year following TKA (Smith, Lloyd, & Wood, 2006). Studies also indicate that marginal physical performance improvements are made beyond the first 6 months following surgery (Fortin et al., 2002; Kennedy, Stratford, Hanna, Wessel, & Gollish, 2006; Mizner et al., 2005), suggesting that these compensatory strategies could be observed years later (McClelland et al., 2007). Further, even though knee pain is diminished and patients are able to move through more knee motion, this may not equate to correction of gait to a more normal pattern (Milner, 2009). With recent evidence indicating statistically predictable joint deterioration of the nonsurgical limb following a unilateral TKA (Shakoor, Block, Shott, & Case, 2002), retention or development of these abnormal movement strategies following TKA may have significant consequences over time (Milner, 2009).

This study is the first to demonstrate that patients with TKA display relatively similar gait characteristics as their non-TKA matched peers after being exposed to knee-specific biofeedback retraining during high-demand decline walking. This suggests that patients 6 months following TKA can make immediate corrections of joint kinetics to achieve relatively normal gait. These findings are important because incorporating knee-specific biofeedback into the postoperative recovery could be a viable option to improve gait compensation and its sequelae following TKA. Motor retraining with knee-specific kinetic biofeedback can be an effective modality in resolving chronic gait compensation once successful surgical management of the diseased joint has been performed. Contrary to the existing literature (McClelland et al., 2007), our findings found patients with TKA displayed similar gait characteristics as non-TKA counterparts during low-demand level walking. McClelland et al. (2007) reported the majority of studies have shown that patients with TKA display reduced knee flexion motion and inferior angular loading of the surgical limb during level walking when compared to healthy controls at various time points postoperatively. Investigators have attempted to attenuate these abnormal movement patterns through alternative modes of biofeedback as a means of correcting movement pattern abnormalities (Christiansen et al., 2015; McClelland et al., 2012; Zeni et al., 2013). These studies have shown mixed results in improving gait characteristics, particularly in restoring normal knee kinetics to normative levels during task that require greater knee extensor demand (i.e., sit-to-stand). Our findings show compelling evidence that knee kinetic biofeedback can make immediate corrections of gait characteristics to relatively normal levels. These results need to be interpreted with caution as potential confounding variables could have influenced the gait characteristic changes. It is important to note that large effect changes in gait characteristics during decline walking were observed, despite not adjusting for variance explained by potential confounders. Further study is needed to determine if the improvement seen with the use of biofeedback during high-demand decline walking could lead to lasting improvements in gait characteristics and functional recovery.

4.6 Conclusion

Total knee arthroplasty patients continue to compensate with faulty gait characteristics during a high-demand mobility task postoperatively, despite good patient-reported outcomes and minimal knee pain. Biofeedback using knee kinetics under high-demand mobility can induce immediate improvements in gait characteristics. Further research should explore gait characteristics observed during even more physically demanding tasks and randomized study designs comparing use of knee kinetic biofeedback in restoring gait characteristics with longer follow-up to determine sustainability over time.

4.7 Contributions

We thank the financial support from the National Institutes of Health (NIH-S10RR026565) and the LS Peery Discovery Program in Musculoskeletal Restoration.

4.8 References

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Table 4.1 Descriptive characteristics of patients by group

Variable	TKA (*n* = 20)	CON (*n* = 15)	*P* Value
Age, y	63.5 (7.9)	65.3 (5.5)	0.452
Sex, % male	65.0	60.0	0.762
Weight, kg	81.1 (13.7)	81.2 (15.3)	0.986
Height, m	1.72 (0.1)	1.74 (0.1)	0.399
BMI (kg/m^2)	29.5 (3.7)	28.2 (4.7)	0.424
UCLA Activity Scale	6.1 (4-9)	7.2 (5-9)	0.935
PF-CAT *T* Score	47.6 (5.4)	52.8 (5.4)	0.009
PI-CAT *T* Score	50.2 (8.6)	46.1 (7.9)	0.164
DEP-CAT *T* Score	45.8 (8.3)	48.7 (5.2)	0.252

Note: Values represented as mean (SD), unless otherwise stated. Values for UCLA activity scale represented as mean (range). BMI, body mass index; UCLA, University of California Los Angles; PF-CAT, physical function computerized adaptive testing; PI-CAT, pain interference computerized adaptive testing; DEP-CAT, depression computerized adaptive testing.

Table 4.2 Between-group comparison of gait characteristics during decline walking

Variable/Time Point	TKA Group[*] (*n* = 20)	CON Group[*] (*n* = 15)	Effect Size, Cohen d[§]	% Difference of Normal^	*P* Value
ΔL_H Ext (+), Nms/kg					
NFB	0.21 (0.02)	0.23 (0.03)	0.23	10%	0.506
FB	0.21 (0.02)	0.22 (0.03)	0.13	6%	0.707
ΔL_K Ext (+), Nms/kg					
NFB	0.27 (0.01)	0.39 (0.02)	1.34	30%	<0.001
FB	0.39 (0.02)	0.40 (0.02)	0.00	1%	0.991
ΔL_A PF (+), Nms/kg					
NFB	0.29 (0.02)	0.34 (0.02)	0.54	12%	0.122
FB	0.31 (0.01)	0.34 (0.02)	0.37	8%	0.271
Imp, Ns/kg					
NFB	0.51 (0.01)	0.55 (0.02)	0.51	7%	0.075
FB	0.54 (0.01)	0.55 (0.02)	0.17	2%	0.601
vGRF, BM					
NFB	1.04 (0.03)	1.21 (0.03)	1.23	14%	<0.001
FB	1.16 (0.03)	1.21 (0.03)	0.35	4%	0.299
Hip Flex Angle (+), deg					
NFB	12.9 (1.37)	14.9 (1.83)	0.32	14%	0.366
FB	17.8 (1.54)	15.6 (1.56)	0.34	-14%	0.294
Knee Flex Angle (+), deg					
NFB	18.6 (1.10)	24.0 (1.65)	1.00	23%	0.005
FB	27.7 (1.21)	24.0 (1.20)	0.74	-16%	0.028
Ankle DF Angle (+), deg					
NFB	1.9 (0.31)	2.4 (0.44)	0.27	18%	0.430
FB	3.5 (0.55)	2.4 (0.41)	0.58	-24%	0.072

Abbreviations: ΔL_H, hip angular impulse; ΔL_K, knee angular impulse; ΔL_A, ankle angular impulse; NFB, nonbiofeedback; FB, biofeedback; Imp, impulse; vGRF, peak vertical ground reaction force; BM, body mass; Ext, extension; Flex, flexion; PF, plantarflexion; DF, dorsiflexion; deg, degrees.

[*] *Values are mean (standard errors).*

[†] *Values are mean (95% confidence interval) difference between groups (TKA group – CON group).*

[§] *Effect size categories (0.20 = small, 0.50 = medium, 0.80 = large).*

^*Percent difference relative to the control group computed through general linear model.*

Table 4.3 Between-group comparison of gait characteristics during level walking

Variable/Time Point	TKA Group[*] (*n* = 20)	CON Group[*] (*n* = 15)	Effect Size, Cohen d[§]	% Difference of Normal^	*P* Value
ΔL_H Ext (+), Nms/kg					
NFB	0.11 (0.02)	0.12 (0.02)	0.13	10%	0.712
FB	–	–	–	–	–
ΔL_K Ext (+), Nms/kg					
NFB	0.07 (0.01)	0.08 (0.01)	0.18	15%	0.579
FB	–	–	–	–	–
ΔL_A PF (+), Nms/kg					
NFB	0.49 (0.01)	0.50 (0.02)	0.16	3%	0.640
FB	–	–	–	–	–
Imp, Ns/kg					
NFB	0.57 (0.01)	0.57 (0.01)	0.11	0%	0.733
FB	–	–	–	–	–
vGRF, BM					
NFB	0.93 (0.02)	0.93 (0.02)	0.03	0%	0.937
FB	–	–	–	–	–
Hip Flex Angle (+)					
NFB	17.3 (1.95)	15.6 (2.02)	0.21	-11%	0.528
FB	–	–	–	–	–
Knee Flex Angle (+)					
NFB	10.0 (1.16)	11.0 (1.48)	0.19	10%	0.581
FB	–	–	–	–	–
Ankle DF Angle (+)					
NFB	-2.5 (0.42)	-1.5 (0.29)	0.35	-18%	0.101
FB	–	–	–	–	–

Abbreviations: ΔL_H, hip angular impulse; ΔL_K, knee angular impulse; ΔL_A, ankle angular impulse; NFB, nonbiofeedback; FB, biofeedback; Imp, impulse; vGRF, peak vertical ground reaction force; BM, body mass; Ext, extension; Flex, flexion; PF, plantarflexion; DF, dorsiflexion; deg, degrees.

[*] *Values are mean (standard errors).*

[†] *Values are mean (95% confidence interval) difference between groups (TKA group – CON group).*

[§] *Effect size categories (0.20 = small, 0.50 = medium, 0.80 = large).*

^*Percent difference relative to the control group computed through general linear model.*

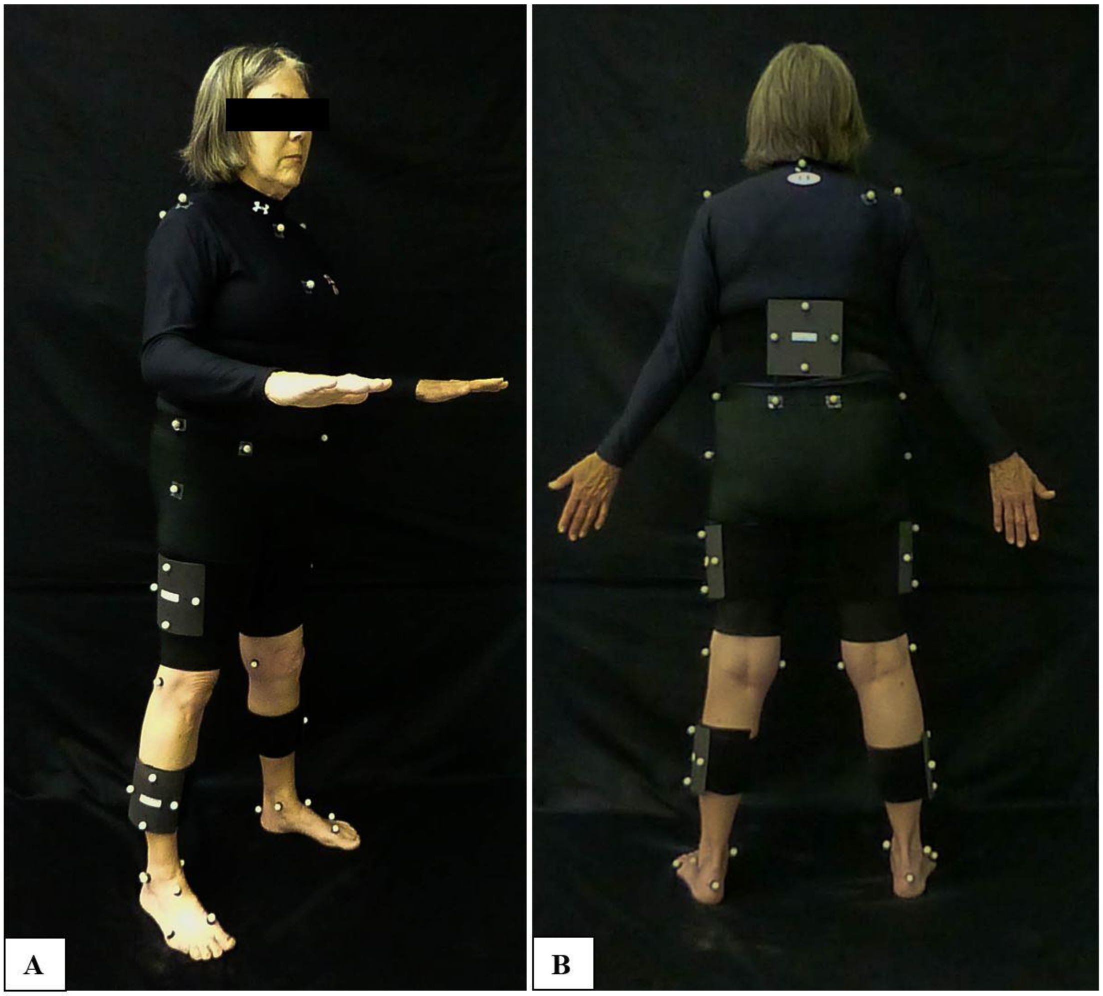

[redacted]

Figure 4.1 Marker placement for modified Plug-In-Gait marker set (A., anterolateral, B., posterior).

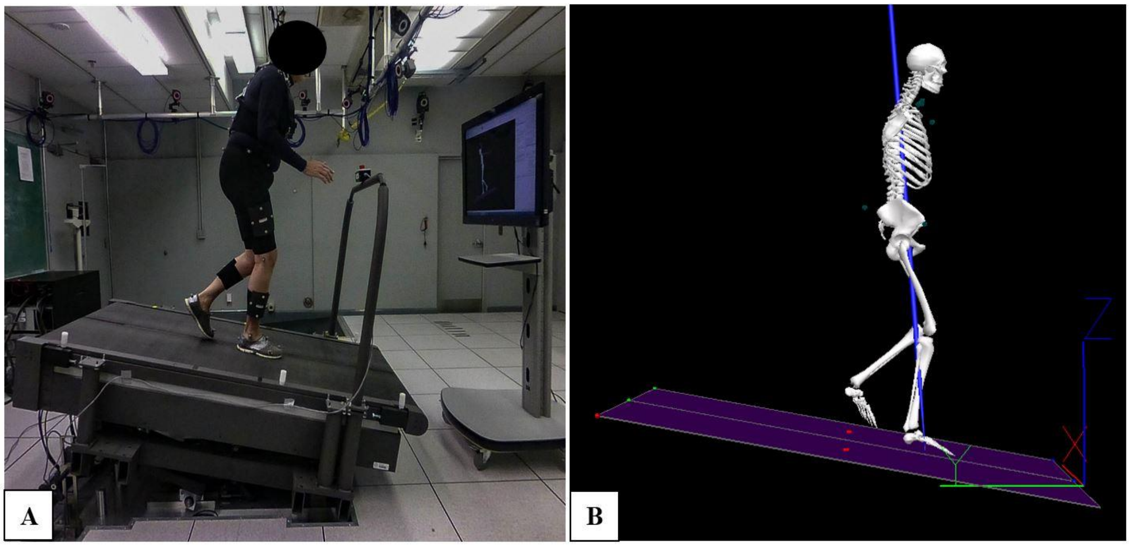
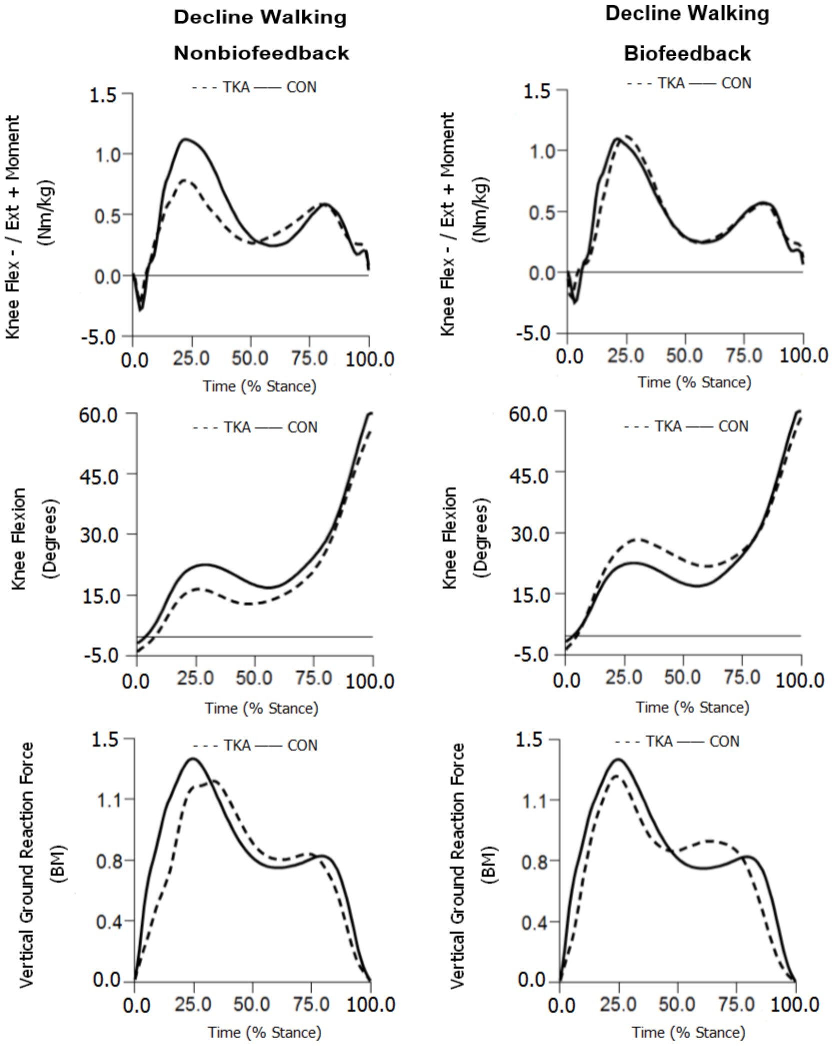


Figure 4.2 Participant performing real-time kinetic biofeedback gait training (A) and 3D motion capture model illustration (B) during decline walking.


Decline Walking Nonbiofeedback

Decline Walking Biofeedback

Figure 4.3 Representative example of gait characteristic changes between nonbiofeedback and knee kinetic biofeedback during decline walking. Abbreviations: Flex, flexion; Ext, extension; BM, body mass.

CHAPTER 5

MODIFIABLE RISK FACTORS AND JOINT MECHANICAL ASYMMETRY DURING HIGH-DEMAND MOBILITY AFTER TOTAL KNEE ARTRHOPLASTY

5.1 Abstract

Compensatory strategies identified as interlimb joint mechanical asymmetries are common following TKA. Modifiable factors that can be addressed in rehabilitation might help explain interlimb asymmetries during a physically demanding mobility task, though this has not been quantified. Therefore, the purpose of this study was to test whether knee extensor strength, lower limb power, residual knee pain, and/or balance confidence explain the level of interlimb asymmetry during the weight acceptance phase of decline walking. Forty-6 patients with TKA underwent testing of leg strength, power, and self-reported knee pain, and balance confidence, while interlimb joint mechanics was assessed during decline walking at 3 and 6 months postoperatively. Knee extensor strength asymmetry showed a significant positive relationship on both total support moment and knee extensor moment asymmetry at both 3 and 6 months following surgery. Lower limb power, residual knee pain, and balance confidence had no relationship with interlimb asymmetry at either timepoint. Statement of Clinical Relevance: This study quantifies how modifiable risk factors that can be reversed in

rehabilitation are linked to interlimb asymmetries during a physically demanding task following TKA. Asymmetry in knee extensor strength, indicated as quadriceps weakness in the surgical knee, is linked to the compensatory joint mechanic strategies and performance of the knee during the functionally important task of walking down an incline. It is likely there are alternative risk factors that influence interlimb asymmetry though it may useful to focus on reversing knee weakness. This may then address the chronic mechanical compensatory strategies post-TKA.

5.2 Introduction

Projections have estimated 4.5 million people in the United States are currently living with a TKA and the number of knee replacement surgeries will be growing exponentially in the coming decades since it is widely accepted as an effective surgical procedure (Kurtz, Ong, Lau, & Manley, 2011; Wylde, Dieppe, Hewlett, & Learmonth, 2007). Up to 30% of patients report dissatisfaction in their physical function, despite marked improvement in knee pain and improving health-related quality of life (Dickstein, Heffes, Shabtai, & Markowitz, 1998; Wylde et al., 2007). Further, 1 year following surgery patients still demonstrate knee extensor muscle weakness (50%; Mizner et al., 2011), slower walking speed (18%; Walsh, Woodhouse, Thomas, & Finch, 1998), slower abilities negotiating stairs (51%; Walsh et al., 1998) and a higher fall-risk (14%; Matsumoto, Okuno, Nakamura, Yamamoto, & Hagino, 2012) compared to HMP.

Abnormal interlimb joint mechanical asymmetry also exists following TKA (Mizner & Snyder-Mackler, 2005), as patients adopt compensatory strategies that distribute mechanical load away from the surgical limb resulting in higher loading onto the nonsurgical limb (Ouellet & Moffet, 2002). These interlimb asymmetry deficits are not uncommon and can persist for years following surgery (McClelland, Webster, & Feller, 2007). It is not clear, however, if these interlimb asymmetries worsen during high-demand mobility tasks that require controlled eccentric muscle activity, like that needed while negotiating declines and stairs. This is important since asymmetries, if present, can lead to chronic joint overloading and accelerated degenerative changes in the nonsurgical limb (Alnahdi, Zeni, & Snyder-Mackler, 2011; Ritter, Carr, Keating, & Faris, 1994).

Interlimb asymmetry is likely a product of several modifiable risk factors that can be addressed during postoperative recovery and rehabilitation. Interlimb asymmetries have been linked independently to discrepancies in lower limb strength, particularly the quadriceps femoris musculature (Mizner & Snyder-Mackler, 2005; van der Krogt, Delp, & Schwartz, 2012). Muscle weakness is common following surgery and has been associated with poorer functional performance in older adults (Connelly & Vandervoort, 1997; Moxley Scarborough, Krebs, & Harris, 1999). Chronic strength deficits of 30-40% have been observed years after surgery (Meier et al., 2008; Moutzouri et al., 2016; Silva et al., 2003; Valtonen, Poyhonen, Heinonen, & Sipila, 2009), with quadriceps femoris weakness showing a substantial influence on interlimb asymmetry during gait (Mizner et al., 2011; Mizner & Snyder-Mackler, 2005; Vahtrik, Gapeyeva, Ereline, & Paasuke, 2014). However, it is important to investigate strength relationships of the entire lower limb as normal joint mechanics require a coordinated effort of all muscles, which may be challenging with individuals post-TKA. Lower limb extensor power has shown to be a surrogate of entire leg strength with deficits showing to be a relevant measurement on physical performance and fall risk in older adults (Perry, Carville, Smith, Rutherford, & Newham, 2007).

Muscle weakness alone, however, does not account for all the variability in interlimb asymmetry and additional factors need further investigation. As high as 20% of patients report residual knee pain following recovery from TKA (Beswick, Wylde, Gooberman-Hill, Blom, & Dieppe, 2012). Persistent knee pain could be a contributing factor to continual interlimb asymmetry in this population. Furthermore, low balance confidence has also been associated with inferior physical performance measures in patients following TKA (Webster, Feller, & Wittwer, 2006) and is predictive of functional decline in older adults (Cumming, Salkeld, Thomas, & Szonyi, 2000; Mendes de Leon, Seeman, Baker, Richardson, & Tinetti, 1996; Vellas et al., 1997). Knowing compensatory strategies and sensory deficits are often associated with TKA (Milner, 2009; Skinner, Barrack, Cook, & Haddad, 1984; Slupik, Kowalski, & Bialoszewski, 2013), it is reasonable to hypothesize that these risk factors could be important in understanding interlimb asymmetry following surgery.

The influence modifiable risk factors have on interlimb asymmetry has largely been studied during tasks that require relatively low mechanical demand at the knee (Benedetti et al., 2003; Mizner & Snyder-Mackler, 2005; Vahtrik et al., 2014; Yoshida, Mizner, & Snyder-Mackler, 2013), however, patients must negotiate functional challenges that require greater knee demand in daily and recreational environments. It is important to understand how risk factors, considered modifiable over time and reversible with rehabilitation, affect interlimb asymmetry to improve functional recovery following surgery. During a physically demanding task such as decline walking, internal extensor moments of the hip, knee, and ankle must provide intersegmental coordination between limbs to stabilize the mechanical loads in supporting the center of mass during stance (Hong et al., 2014; Winter, 1980). The summation of the sagittal extensor moments of the lower limb, M_S, is considered a proxy measure of overall support to the body in stance (Winter, 1980). However, during the weight acceptance phase of decline walking, the large majority of the M_S is made up of the decelerative demands of the M_K (Hong et al., 2014; Komnik, Weiss, Fantini Pagani, & Potthast, 2015; Myles, Rowe, Walker, & Nutton, 2002). Proper knee extensor mechanics are critical for safe and effective use of the limb during this more physically demanding task.

Therefore, the purpose of this study was to test whether the level of knee extensor strength, lower limb extensor power, residual knee pain, and/or balance confidence explain the level of interlimb joint mechanical asymmetry during a high-demand, decline walking task at both 3 and 6 months following TKA. We hypothesized that each predictor variable would contribute to the variance explained by the interlimb asymmetry of the M_S and M_K at each time point.

5.3 Methods

5.3.1 Participants

A prospective cohort study (level of evidence, II) was conducted with 46 participants (24 men; mean ± SD age, 62.7 ± 7.8 years; BMI, 28.0 ± 4.8 kg/m^2) who underwent a primary unilateral TKA surgery between January 2015 and May 2016 (Table 5.1). Motion analysis and clinical measures were collected at both 3 (mean, 3.3 $\pm$ 0.2) and 6 (mean, 6.2 $\pm$ 0.3) months following surgery. All participants met the following inclusion criteria: between 45-75 years of age, BMI less than 40, UCLA activity scale of greater than 3, nonsurgical knee pain less than or equal to 4 out of 10 on a visual analog scale, no comorbidities that would have influenced the balance or walking ability, no current diagnosis or treatment for neurological conditions, no prior knee joint replacement procedure to either limb and no plans to undergo a TKA on the contralateral limb within 12 months after the initial procedure. All surgical procedures were performed by one of three orthopaedic surgeons and all participants were recruited from a single medical center (Salt Lake City, UT, USA). The study was approved by the University of Utah Institutional Review Board and all subjects consented to participation prior to enrollment.

5.3.2 Motion Analysis

Participants wore form-fitting shorts and shirts, and their own walking shoes. All participants were instrumented with 50 spherical retro-reflective markers (14 mm diameter) based on a modified Plug-In-Gait marker set (Vicon, Oxford Metrics Ltd., Oxford, UK). Markers were placed over the following landmarks: cervical spinous process, manubrium of the sternum, inferior body of the sternum, bilaterally on the anterior/posterior superior iliac spines, right spine of scapula, iliac crests, greater trochanters, acromions, medial and lateral epicondyles of the femurs, medial and lateral malleoli, 1st and 5th heads of the metatarsals, dorsum of the feet, and calcaneal tuberosities. One rigid cluster with 4 noncollinear markers were placed at the base of the lumbar spine and 2 nonrigid clusters with 4 noncollinear markers were placed at the lateral side of each thigh and shank. A stationary trial was first taken with each participant in a neutral standing position to align with the global laboratory coordinate system. Each subject's local joint coordinates were aligned to their standing position to control for inter-subject variation in anatomical alignment during the static trial.

Trajectory data were recorded using a 10-camera motion analysis system (Vicon, Oxford Metrics Ltd., London, UK) at a sampling rate of 200 Hz and analog data were collected on a duel-belt treadmill instrumented with two force platforms (Bertec Corp; Columbus, OH, USA) at a sampling rate of 1000 Hz. All participants were asked to walk on a 10° decline sloped treadmill position. A warm-up period, approximately 3-5 minutes, was provided to allow the participants to become comfortable walking on the instrumented treadmill. Once participants verbally confirmed they felt comfortable with the task, the participants were instructed to "walk as normally as possible as if walking downhill" at a constrained treadmill velocity of 0.8 m/s. Trials in which participants lost their balance, used their upper extremities for support on the surrounding bars, or stepped onto the adjacent force platform were excluded.

5.3.3 Clinical Metrics

For the purposes of capturing a clinical snapshot of the overall outcome for this cohort of patients with TKA, we utilized the PROMIS CAT as a metric of patient-reported perception of physical function, pain interference, and mental health. The PF-CAT item bank v1.2 includes measures self-reported capability to perform various degree of physical activities. The PIF-CAT item bank v1.1 measures the extent to which pain hinders participants' engagement with social, cognitive, emotional, physical, and recreational activities. The DEP-CAT item bank v1.0 measures negative mood, views of self, and social cognition. These metrics have been used and validated for patient-reported outcomes in medical, surgical, and orthopedic specialties (Hart, Mioduski, & Stratford, 2005; Hung, Clegg, Greene, & Saltzman, 2011; McHorney, 2003; Wyrwich, Norquist, Lenderking, & Acaster, 2013). For clinical interpretation of the above PROMIS CAT measures, a standardized *T* score of 50 is defined as the average score for the U.S. general population with a standard deviation of 10 (Hung et al., 2011; Ware et al., 2003). These results are based on calibration testing performed on a large sample of the general population.

Isometric knee extensor strength was measured on a electromechanical dynamometer (Humac NORM, CSMi, Stoughton, MA, USA) as an indicator of quadriceps femoris strength (Snyder-Mackler, De Luca, Williams, Eastlack, & Bartolozzi, 1994). Prior to every testing session, the force plate was zeroed and load calibrated. Participants were harnessed into a seated position with the knee flexed to a 60° angle. A warm-up session of two submaximal (50% and 75%) and one maximal (100%) contraction was performed, prior to collecting three maximal isometric contractions with 1 minute of rest between trials. The three maximal trials were averaged for a single composite score of maximal torque output (Nm**)** for each limb. The nonsurgical limb was tested first, followed by the surgical limb. A quadriceps femoris index was computed by dividing the maximal torque output of the surgical knee by that of the nonsurgical knee. A percentage of complete symmetry (100%) was represented as the outcome, with values less than 100% indicating weakness of the surgical limb compared to the nonsurgical limb. This method of strength testing has shown good to excellent reliability (r = 0.81-0.98; de Carvalho Froufe Andrade, Caserotti, de Carvalho, de Azevedo Abade, & da Eira Sampaio, 2013; Snyder-Mackler et al., 1994).

Lower limb power testing of the limb extensors was performed using the Leg Extension Power Rig (Medical Engineering Unit, Nottingham, UK) as an indicator of gross concentric lower limb power output. Prior to every testing session, the unit was zeroed and load calibrated. Participants were placed into a seated position with the knee flexed to 90° in the starting position and 10° short of full knee extension in the finishing position. A warm-up session of two submaximal (50% and 75%) and one maximal (100%) trials were performed, prior to collection of five maximal effort trials with 1 minute of rest between trials. The nonsurgical limb was tested first, followed by the surgical limb. The top three scores were averaged for a single composite score of maximal power output (W) for each limb. A power index was computed by dividing the maximal power output of the surgical limb by that of the nonsurgical limb. The leg extension power rig has been demonstrated to be a valid, reliable, and feasible means of assessing lower limb power output (Bassey & Short, 1990; Pearson, Cobbold, & Harridge, 2004; Pearson, Cobbold, Orrell, & Harridge, 2006).

Residual knee pain was measured using the NPRS, which is frequently used as an 11-point pain intensity scale, where 0 = *no pain* and 10 = *worst possible pain imaginable* (Hawker, Mian, Kendzerska, & French, 2011). Immediately following the decline walking trials, participants were asked to rate the level of pain experienced in the surgical knee during the trials. The NPRS has shown high test-retest reliability with arthritis patients ($r = 0.96$; Hawker et al., 2011). Balance confidence was measured using the Activities-specific Balance Confidence (ABC) scale, which is a 16-item survey of balance confidence across a wide spectrum of low- and high-demanding functional tasks

(Powell & Myers, 1995). The ABC scale was shown to be the best instrument for measuring balance confidence in moderate to highly functioning older adults (Skipper & Ellis, 2013). It has also shown excellent validity and test-retest reliability in a variety of patient populations (Skipper & Ellis, 2013).

5.3.4 Data Processing

Marker trajectory and analog data were recorded and synchronized using Nexus 2.1.1 software (Vicon, Oxford Metrics Ltd., Oxford, UK). Post processing and extraction of joint mechanic variables were performed using Visual3D v6.00.27 (C-motion, Inc., Germantown, MD, USA). Marker trajectory and analog data were low-pass filtered at 6 Hz and 25 Hz, respectively, using a 4th-order Butterworth digital filter based on residual analysis and visual inspection (Winter, 2005). Three-dimensional angular kinematics were calculated using a Visual3D model with a Cardan sequence (x, y, z), which defined the orientation coordinate system of the distal segment with respect to the proximal segment. Joint kinetics were computed through standard inverse dynamic methods. All joint mechanic variables of interest were extracted in the sagittal-plane (x-axis) during peak knee flexion angle during the weight acceptance phase (heel strike to mid-stance) of the decline walking trials. Ten complete steps (heel strike to toe off) on both limbs were collected for analysis.

5.3.5 Data Analysis

Multivariable linear regression models were employed to investigate relationships between knee extensor strength, lower limb extensor power, residual knee pain, and balance confidence on peak joint mechanical interlimb asymmetry at both 3 and 6 months following TKA. To compare the effect of postoperative recovery on interlimb joint mechanic outcomes, we stratified for time by regressing the predictor variables onto the outcomes at both timepoints. Symmetry indexes were calculated for mean peak M_S of the limb, defined as the summation of the net joint (hip, knee, ankle) extensor moments, and M_K contribution of the body support during the weight acceptance phase of gait. Index scores were calculated as the value on the surgical limb divided by the scores on the nonsurgical limb. A score equal to 1 signified perfect symmetry, values greater than 1 signified greater scores on the surgical limb, and scores less than 1 signified lower scores on the surgical limb (Zeni, Abujaber, Flowers, Pozzi, & Snyder-Mackler, 2013). A 3-month assessment was identified as by 3 months as most patients have recovered from acute knee pain, restored peak knee range of motion, and been discharged from formal physical therapy. The 6-month assessment was identified as the physical performance recovery timepoint when functional improvements have peaked (Fortin et al., 2002; Mizner et al., 2011; Mizner, Petterson, & Snyder-Mackler, 2005). Effect sizes were calculated based on partial correlations (Cohen's f^2). Cohen's f^2 equal to or greater than 0.02 presents a small effect, equal to or greater than 0.15 presents a medium effect, and equal to or greater than 0.35 presents a strong effect (Cohen, 1988). An a priori power analysis was conducted based on previous work (Yoshida, Mizner, Ramsey, & Snyder-Mackler, 2008). A Pearson correlation of $r = 0.40$ indicated that 46 participants would be needed to detect significant differences, while providing 80% power with a two-sided alpha 0.05. This sample size estimate is in line with the recommended 10 events per predictor variable in a regression model to avoid statistical overfitting, which implies risk of unreliable correlations due to having too many predictor variables for the available sample size (Harrell, 2001; Harrell, Lee, & Mark, 1996). Data were analyzed using commercially available statistical software (Stata v14.1; Statacorp, LP, College Station, TX, USA).

5.4 Results

We screened a total of 85 patients for eligibility. Prior to surgery, 37 patients did not meet the eligibility criteria. Following surgery, two patients dropped out of the study, leaving 46 patients with TKA that completed all testing at each time-point (Table 5.1). The 3-month regression model on M_S asymmetry was significantly different from 0, F (4, 41) = 3.04, $p = 0.027$, with adjusted R^2 at 0.15, indicating that 15% of the variability in M_T asymmetry was explained by the predictors. Quadriceps femoris strength index showed a significant positive relationship on the M_S ($B = 0.006$; 95% CI = 0.003, 0.009; $p < 0.001$; Table 5.2; Figure 5.1). The 3-month regression model on M_K asymmetry was also significantly different from 0, F (4, 41) = 3.64, $p = 0.012$, with adjusted R^2 at 0.19, indicating that 19% of the variability in M_K asymmetry was explained by the predictors. Quadriceps femoris strength index showed a significant positive relationship on the M_K ($B = 0.011$; 95% CI = 0.008, 0.015; $p < 0.001$; Table 5.2; Figure 5.2). Quadriceps femoris strength index as an individual predictor had a medium to large effect of explaining interlimb M_S (Cohen's $f^2 = 0.23$) and M_K (Cohen's $f^2 = 0.32$) asymmetry above and beyond what the other predictors explained in the model.

The 6-month regression model on M_S asymmetry was significantly different from 0, F (4, 41) = 3.15, $p = 0.037$, with adjusted R^2 at 0.16, indicating that 16% of the variability in M_S asymmetry was explained by the predictors. Quadriceps femoris strength index showed a significantly positive relationship on the M_S ($B = 0.008$; 95% CI = 0.003, 0.014; $p < 0.001$; Table 5.2; Figure 5.1). The 6-month regression model on M_K asymmetry was also significantly different from zero, F (4, 41) = 3.08, $p = 0.027$, with adjusted R^2 at 0.16, indicating that 16% of the variability in M_K asymmetry was explained by the predictors. Quadriceps femoris strength index showed a significant positive relationship on the M_K ($B = 0.018$; 95% CI = 0.005, 0.030, $p < 0.001$; Table 5.2; Figure 5.2). Quadriceps femoris strength index as an individual predictor had a medium to large effect of explaining interlimb M_S (Cohen's $f^2 = 0.16$) and M_K (Cohen's $f^2 = 0.27$) asymmetry above and beyond what the other predictors explained in the model.

5.5 Discussion

The purpose of this prospective study was to test whether the level of knee extensor strength, lower limb extensor power, residual knee pain, and/or balance confidence explained the level of interlimb joint mechanical asymmetry during a high-demand (decline walking) task at both 3 and 6 months following TKA. We hypothesized that each predictor variable would contribute to the variance explained by the interlimb asymmetry of the M_S and M_K at each time point.

Limited research has investigated the influence that risk factors, considered modifiable over time and reversible with rehabilitation, have on interlimb asymmetry during a mobility task that requires greater knee extensor demands, such as decline walking. These findings are clinically relevant as patients are eager to return to more physically demanding daily and recreational tasks following surgery. However, patients with TKA continue to display compensatory interlimb asymmetry deficits (McClelland et al., 2007; Milner, 2009). Compensatory strategies indicated by less knee flexion on the surgical knee and greater loading on the nonsurgical knee, may help explain limitations in returning to desired level of function and/or prevalence of subsequent knee and hip joint replacements observed after the primary TKA. Physical restoration to unimpaired ability after TKR is rare, with only 33% of patients reporting no functional limitations with their surgical knee (Wright et al., 2004). Approximately a fifth of TKR patients reported the surgery was not successful in allowing them to return to desired daily activities (Jones, Voaklander, Johnston, & Suarez-Almazor, 2000). Furthermore, studies have shown patients who undergo a primary unilateral TKA will also experience surgery of the contralateral knee joint as the most common second joint to undergo replacement (Shakoor, Block, Shott, & Case, 2002). Additionally, patients with end-stage arthritis for whom the second joint replacement was the hip, the contralateral side was more than twice as likely to undergo replacement as the ipsilateral side. Our findings suggest interlimb asymmetries observed during more physically demanding mobility could contribute to limited physical function and concerns of accelerated arthritic changes over time.

Restoration of lower limb strength, particularly the quadriceps femoris muscle, is an important determinant for functional performance. Marked weakness is often observed in the arthritic knee prior to surgery and as high as 60% residual weakness is seen within the first month of surgery compared to preoperative measures (Mizner, Petterson, Stevens, Vandenborne, & Snyder-Mackler, 2005). Although quadriceps femoris strength does improve postoperatively, deficits continue to be observed years after surgery and it is uncertain if restoration of the surgical limb strength ever reaches that of the contralateral limb or the strength of HMP (Noble et al., 2005). Quadriceps femoris weakness has significant functional consequences and is associated with decreased walking speed (Yoshida et al., 2008), chair rise (Mizner & Snyder-Mackler, 2005) and stair climbing (Valtonen et al., 2009) ability.

Asymmetry in quadriceps femoris strength has further shown to be correlated to interlimb asymmetry during both chair rising (Alnahdi, Zeni, & Snyder-Mackler, 2016; Mizner & Snyder-Mackler, 2005) and stair climbing (Gaffney et al., 2016) tasks. These findings are consistent with our results, providing further evidence that restoring quadriceps femoris strength is a critical component to proper joint mechanics during more physically demanding tasks. However, patients with TKA continue to display chronic compensatory movement patterns (McClelland et al., 2007; Vahtrik et al., 2014), despite improvements in quadriceps femoris strength over time (Yoshida et al., 2008). These deficits are commonly reported as a *quadriceps avoidance* strategy, characterized by reduced knee flexion during limb loading of gait, resulting in decreased contribution of the knee extensor musculature (Milner, 2009). This compensatory strategy is adopted prior to surgery, likely as a mechanism to avoid knee pain, and retained up to 18 months after surgery (Smith, Lloyd, & Wood, 2004).

Lower limb power was investigated as an alternative metric of leg extensor performance, effectively evaluating muscular function as a collective effort of the entire limb. Our findings did not find relationships between interlimb asymmetry and lower limb power discrepancies. This may be explained by the large degree of hip extensor muscle contribution required during power testing, while most joint kinetic demand during weight acceptance of decline walking was made up of predominantly knee and ankle extensor strategies (Hong et al., 2014). Additionally, the concentric muscle action of the extensors during power testing is contradictory to the eccentric muscle control required to perform the decline walking task. Further investigation evaluating eccentric muscle strength of the lower limb may likely be a more effective mode of identifying the influence specific muscles contribute to normalizing gait mechanics during high-demand mobility.

Residual knee pain and perceived confidence of the limb were originally hypothesized as modifiable factors that could explain some of the interlimb asymmetry during decline walking. Our findings did not coincide with this theory as the large majority of participants reported minimal knee pain and good confidence of the limb at each time point. Furthermore, patients' perception of physical function was nearly equivalent to the national average, signifying patients overall self-report of recovery was optimal, despite presenting with muscle strength and joint mechanic deficits. Self-reported outcomes provide valuable information related to patients' perception of functional ability and how particular factors influence activity limitations (Mizner et al., 2011). However, studies have shown self-reported outcomes do not identify the actual change in functional performance following surgery (Jacobs & Christensen, 2009; Ouellet & Moffet, 2002; Stratford, Kennedy, & Hanna, 2004). Outcomes on perceived function can be significantly influenced by patients' knee pain (Stratford & Kennedy, 2006; Stratford et al., 2004; Stratford, Kennedy, & Woodhouse, 2006) in addition to the degree of physical exertion required during a functional task (Stratford, Kennedy, Pagura, & Gollish, 2003; Stratford & Kennedy, 2006). Improvements in self-reported physical performance often are associated with pain reduction (Stratford & Kennedy, 2006; Stratford et al., 2006) and improved balance confidence (Webster et al., 2006). Our results provide evidence, however, that improved perception of knee pain and balance confidence are not effective markers that help explain interlimb asymmetry during a mobility task that requires larger knee extensor demands. Self-reported outcome measures may not be sensitive enough metrics to accurately determine compensatory strategies during gait in the TKA population. Future investigations should explore alternative metrics with larger sample sizes to determine potential inferences of explaining interlimb asymmetry.

Following TKA and postoperative rehabilitation, patients should be able to overcome muscle strength, knee pain and balance confidence deficits as well as improve interlimb asymmetry though this has not been fully realized in either low- or high-demand mobility tasks. It is important to understand how modifiable risk factors influence interlimb asymmetry as compensatory movement strategies have been shown to be surrogate measures of functional decline and increased arthritic changes in other joints (Mizner et al., 2011; Mizner & Snyder-Mackler, 2005; Shakoor et al., 2002; Shakoor et al., 2011). These movement compensations are likely related to a combination of poor muscle strength and a failure to integrate available muscle strength into functional movement, although the etiology of abnormal joint mechanics can be multifactorial in nature. Further research should consider integrating functional strength training during postoperative rehabilitation to improve daily and recreational activity performance. Although quadriceps femoris weakness showed medium to large effect sizes in explaining interlimb asymmetry, less than 20% of the variance was explained by these predictors. Thus, alternative factors need to be investigated to better explain why interlimb asymmetry continues to exist postoperatively. Determining how these factors influence interlimb asymmetry will provide the necessary framework to develop rehabilitation interventions that can be implemented into a longitudinal intervention trial. At this time, it seems clinically intuitive to continue to focus on knee extensor strength restoration and integrate this into functional movement retraining during formal rehabilitation.

This study has limitations that need to be considered when interpreting the data. First, data were acquired while participants walked on an instrumented treadmill, which may not be the same as an over-ground sloped environment. Second, concerns of nonrepresentative bias could be an issue as the cohort consisted of relatively healthy and active patients. Although this concern could compromise the external validity, it highlights that even ideal patients with TKA still present with compensatory strategies during a higher demanding mobility task. Third, our sample size was based on detecting medium to large effects, so a larger sample size with alternative clinical metrics is warranted to identify smaller effects, if they exist. Fourth, we did not track duration, type, or quality of physical therapy services provided, which could have been a significant confounder to these results. While this may have limited our internal validity, we felt our pragmatic study design allowed us to evaluate the average patients' functional recovery following surgery.

5.6 Conclusion

Asymmetry in knee extensor strength, indicated by quadriceps femoris weakness on the surgical knee, is linked to both interlimb total support moment and knee extensor moment asymmetry during the weight acceptance phase of decline walking at both 3 and 6 months following surgery. Lower limb extensor power, residual knee pain and balance confidence had no direct relationship to interlimb asymmetry measures at either timepoint.

5.7 Contributions

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Table 5.1 Descriptive characteristics

Variable	TKA Group (*n* = 46)
Age, y	62.7 (7.8)
Sex, % male	52
Weight, kg	83.2 (16.4)
Height, m	1.73 (0.1)
BMI (kg/m^2)	27.8 (4.2)
UCLA Activity Scale	5.9 (3-9)
PF-CAT T-Score	45.5 (4.6)
PI-CAT T-Score	52.9 (6.0)
DEP-CAT T-Score	47.6 (7.2)

Note: Values represented as mean (SD), unless otherwise stated. Values for UCLA activity scale represented as mean (range). TKA, total knee arthroplasty; BMI, body mass index; UCLA, University of California Los Angeles; PF-CAT, physical function computerized adaptive testing; PI-CAT, pain interference computerized adaptive testing; DEP-CAT, depression computerized adaptive testing.

Table 5.2 Multivariable regression models of clinical predictor variables on peak joint mechanical interlimb asymmetry at 3 and 6 months.

Variable/Time	Predictors	B[*]	SE	β[†]	Effect Size, Cohen f^2[§]	*P* Value
M_S, Nm/kg						
3 mo.	Quad Index	0.006	0.002	0.431	0.23	0.001
	Power Index	-0.00	0.003	-0.218	0.06	0.133
	NPRS	0.001	0.023	0.007	0.00	0.958
	ABC Score	-0.004	0.003	-0.190	0.04	0.187
6 mo.	Quad Index	0.008	0.003	0.432	0.16	0.005
	Power Index	-0.007	0.004	-0.258	0.06	0.119
	NPRS	0.000	0.022	0.001	0.00	0.993
	ABC Score	0.000	0.003	0.035	0.00	0.835
M_K, Nm/kg						
3 mo.	Quad Index	0.011	0.001	0.493	0.32	0.001
	Power Index	0.000	0.005	0.006	0.00	0.971
	NPRS	-0.012	0.033	-0.043	0.00	0.722
	ABC Score	-0.008	0.005	-0.205	0.05	0.099
6 mo.	Quad Index	0.018	0.007	0.534	0.27	0.007
	Power Index	-0.008	0.007	-0.171	0.03	0.351
	NPRS	-0.001	0.039	-0.005	0.00	0.972
	ABC Score	-0.000	0.004	-0.014	0.00	0.932

Abbreviations: M_S, total support moment; M_K, knee extensor moment; Quad, quadriceps femoris; NPRS, numeric pain rating scale for the knee; ABC, Activity Balance Confidence scale.

[*] *Unstandardized regression coefficient*

[†] *Standardized regression coefficient*

[§] *Effect size categories (0.02 = small, 0.15 = medium, 0.35 = large).*

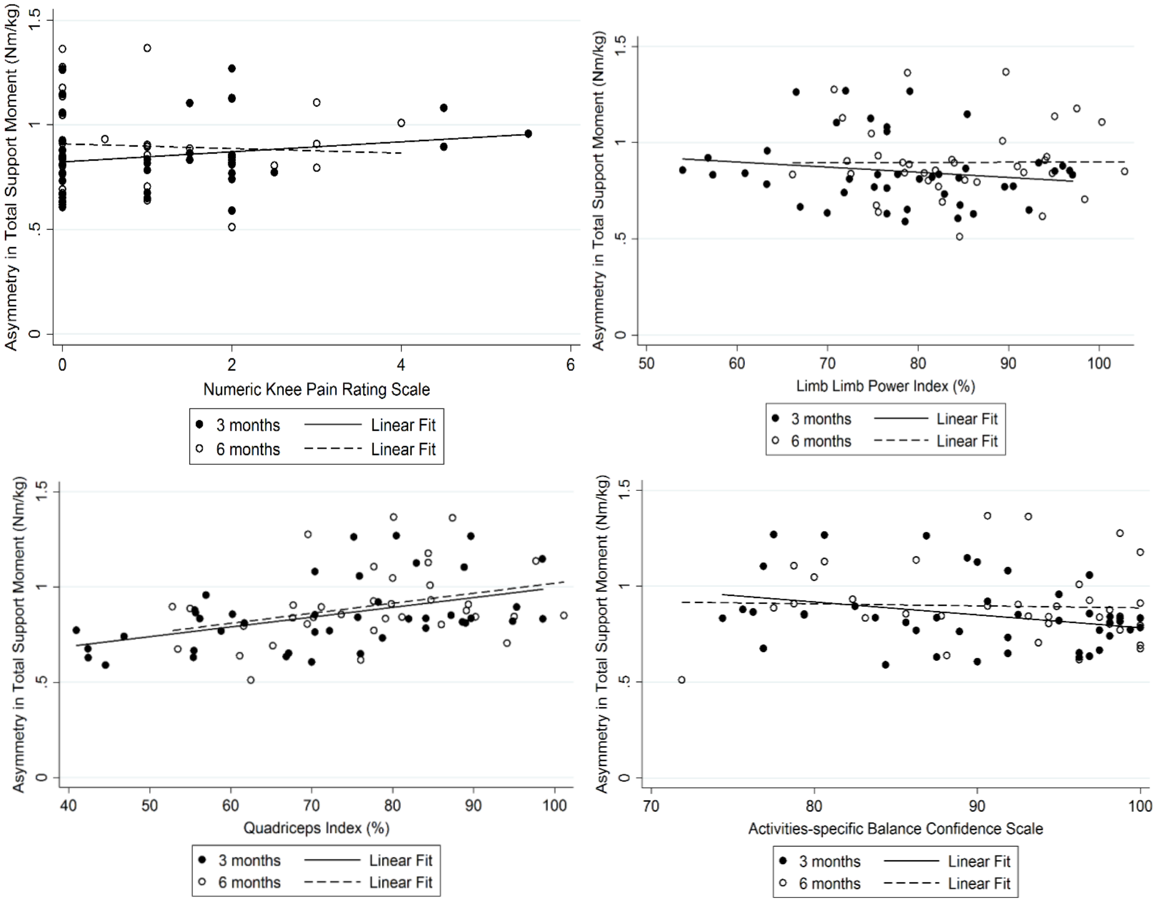

Figure 5.1 Relationship between predictors and total support moment asymmetry at weight acceptance at 3 and 6 months after total knee arthroplasty.

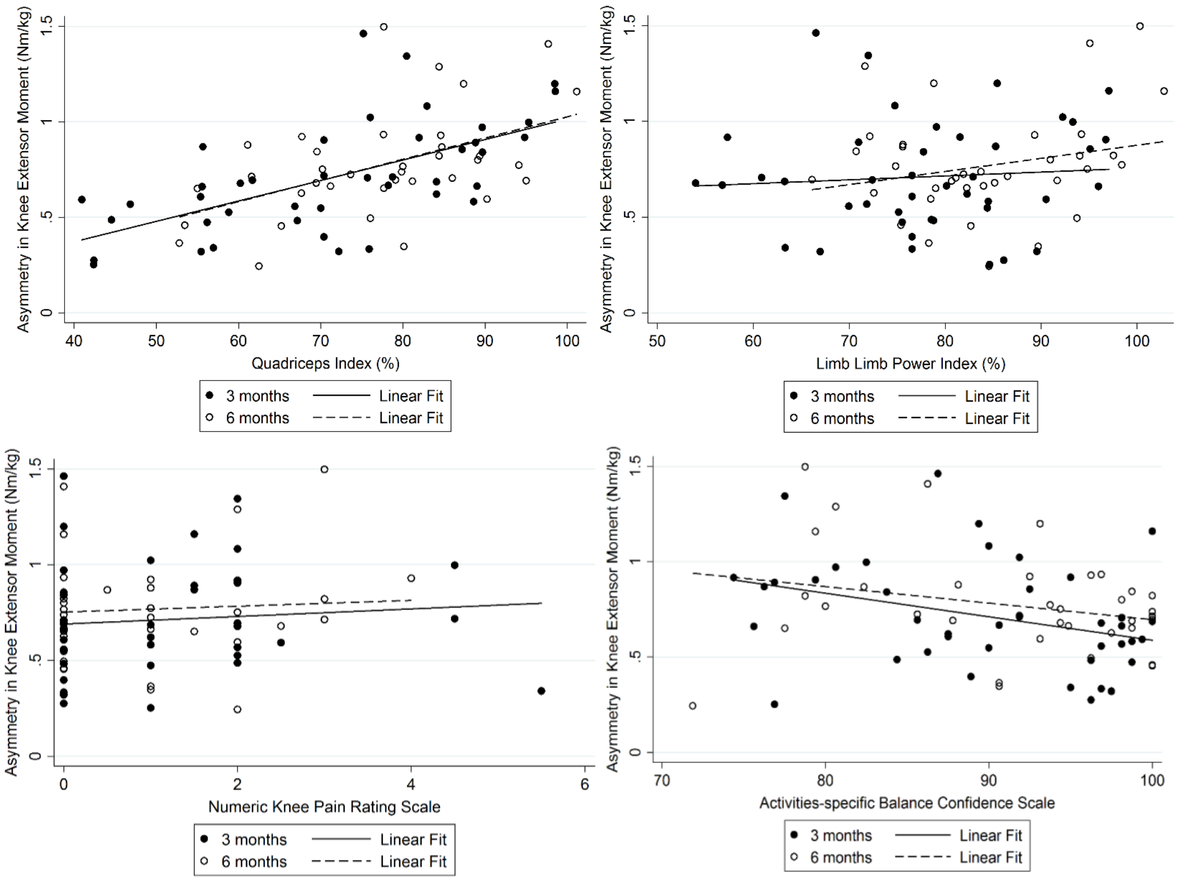

Figure 5.2 Relationship between predictors and knee extensor moment asymmetry at weight acceptance at 3 and 6 months after total knee arthroplasty.

CHAPTER 6

CONCLUSIONS

The results of this body of work reveal patients with TKA demonstrate larger interlimb asymmetry during a more physically demanding task such as decline walking compared a lower demanding task such as level walking. Patients with TKA also showed different joint mechanic strategies relative to HMP during both mobility tasks. Findings further revealed patients with TKA display compensatory strategies that persist over the first 6 months following surgery, despite improved perceived physical function and knee pain.

This work also highlighted how vGRF biofeedback was not as effective at correcting interlimb asymmetry in comparison to IKEM biofeedback. Patients with TKA could normalize their joint mechanics to similar levels to HMP with use of IKEM biofeedback, suggesting effective means of compensatory correction training can occur earlier in the recovery process. Patients did not have to wait for more recovery to occur at 6 months to attempt a prolonged training intervention as the patients had adequate physical resources to correct the aberrant mobility patterns with IKEM biofeedback as early as 3 months following surgery.

The research presented also concluded asymmetry in knee extensor strength, indicated by quadriceps weakness in the surgical knee, showed a strong relationship to both interlimb M_S and M_K asymmetry during the weight acceptance phase of decline walking following surgery. Lower limb extensor power, residual knee pain, and balance confidence had no direct relationship to interlimb asymmetry measures. These results provide evidence that improved perception of knee pain and balance confidence are not effective markers in explaining interlimb asymmetry during a mobility task that requires larger knee extensor demands. Further, self-reported outcome measures may not be sensitive enough metrics to accurately determine compensatory strategies during gait in the TKA population.

These findings are clinically relevant as the number of TKA procedures is rapidly increasing annually, with a wide range of people undergoing surgery, from medically compromised individuals to younger, more active, individuals that will be confronted with higher demand functional challenges following surgery. The evidence from this work suggests interlimb asymmetries are amplified as the task demands increase; that is, decline walking induces compensatory strategies of the surgical limb and overutilization of the nonsurgical limb. Unrealized recovery of the surgical limb means potentially reduced longevity of independent community mobility or limited recreational opportunities in younger patients.

In summary, it is evident that the patient population undergoing TKA is diverse ranging from relatively sedentary to recreationally active adults. Following TKA, patients tend to have reduced quadriceps strength and suboptimal functional abilities, particularly during more physically demanding activities. These discrepancies were apparent in the present body of work, and while there were significant postoperative improvements in self-reported outcome measures, continual interlimb compensatory strategies were present and abnormal joint mechanics were observed relative to HMP with healthy knees. These findings suggest that persistent interlimb compensatory strategies during higher demand mobility is a result of maladaptive motor learning and muscle weakness. Thus, future research needs to explore how pragmatic modes of knee kinetic biofeedback and functional movement retraining can be integrated into formal rehabilitation to correct compensatory strategies that can translate to long-term functional improvement.