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LONGITUDINAL ADAPTATIONS IN MUSCLE STRENGTH, FUNCTIONAL PERFORMANCE, GAIT BIOMECHANICS, AND PATIENT-REPORTED FUNCTION AFTER UNILATERAL TOTAL KNEE ARTHROPLASTY

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LONGITUDINAL ADAPTATIONS IN MUSCLE STRENGTH, FUNCTIONAL PERFORMANCE, GAIT BIOMECHANICS, AND PATIENT-REPORTED FUNCTION AFTER UNILATERAL TOTAL KNEE ARTHROPLASTY

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in Rehabilitation Sciences
in the College of Health Sciences
at the University of Kentucky

By

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Lexington, Kentucky

2017

ABSTRACT

LONGITUDINAL ADAPTATIONS IN MUSCLE STRENGTH, FUNCTIONAL PERFORMANCE, GAIT BIOMECHANICS, AND PATIENT-REPORTED FUNCTION AFTER UNILATERAL TOTAL KNEE ARTHROPLASTY

Objective: The aims of this research were to identify gaps in the literature related to impairments after total knee arthroplasty (TKA) (Aim 1) and define recovery between 3 and 6 months after TKA across four domains: 1) hip and knee muscle performance, 2) functional performance, 3) patient-reported function, and 4) biomechanics of walking and stair descent (Aim 2). Additionally, this project sought to explore the relationships between each domain (Aim 3) and establish predictive models to allow clinicians to use clinical measures to predict future gait biomechanics in patients after TKA (Aim 4). Ultimately, the results of this research would quantify post-rehabilitative recovery after TKA and identify potential targets for objective criteria needed for discharge from outpatient rehabilitation.

Participants: Thirty-nine individuals completed the study protocol, 21 in the TKA group (7 male, 14 female, height: 1.68 ± 0.08 m, mass: 90.95 ± 21.04 kg, BMI: 32.27 ± 7.4 kg/m^2, Age: 60.6 ± 8.1 years) and 18 matched control subjects (7 male, 11 female, height: 1.69 ± 0.10 m, mass: 83.69 ± 20.2 kg, BMI: 29.2 ± 5.5 kg/m^2, Age: 61.2 ± 8.8 years).

Methods: For Aim 1, a systematic review of the literature related to the four previously stated domains was conducted. In Aims 2-4, a longitudinal design with 3 and 6 months post-surgery assessment time points was used for the TKA group. At both assessment time points, participants underwent maximal voluntary isometric strength testing of bilateral hip abduction, hip external rotation, and knee extension to determine peak strength and rate of torque development (RTD). Participants also performed the five-time sit-to-stand test (FTSTS) and underwent three-dimensional motion analysis while walking at a self-selected speed and during a stair descent task. Patient-reported function was measured using the Knee Injury & Osteoarthritis Outcome Score (KOOS). The control subjects completed the same testing procedures at a single time point.

Main Outcome Measures: Outcomes were assessed across four domains. The first domain included peak isometric muscle strength and RTD of hip abduction, hip external rotation, and knee extension. The second and third domains represented functional performance as assessed by the FTSTS and patient-reported function as measured by the KOOS, respectively. The final domain included hip and knee joint kinematics and kinetics during walking and stair descent as measured using three-dimensional motion analysis and inverse dynamics.

Statistical Analysis: Aim 1: no formal statistics were utilized in the systematic review. Aim 2 utilized paired sample t-tests for between-limb (operative vs non-operative) and within-limb (3 months vs 6 months post-surgery) comparisons across all four domains. Additionally, independent two-sample t-tests were used to compare the operative and non-operative limbs of the TKA group to the matched control group. In Aim 3, Pearson product-moment correlations were performed to assess the relationships between muscle performance, FTSTS performance, and KOOS scores in the TKA group at 1) 3 months post-surgery, 2) 6 months post-surgery, and 3) between the improvements in these outcomes from 3 to 6 months post-surgery. Lastly, Aim 4 utilized Pearson product-moment correlations and stepwise multiple linear regressions to develop a predictive model using clinical measures assessed at 3 months post-operatively to predict knee flexion excursion during walking at 6 months post-surgery.

Results: Aim 1: Improvements in KOOS scores, deficits in peak quadriceps strength, and altered knee joint biomechanics during walking are present during the first 6 months following TKA. Limited evidence exists regarding hip muscle strength deficits, FTSTS performance, and stair descent biomechanics after TKA. Aim 2: Quadriceps and hip external rotation peak strength and RTD, FTSTS performance, gait and stair descent biomechanics, and KOOS scores all demonstrated significant, but modest, improvement between 3 and 6 months post-surgery. However, persistent deficits in quadriceps and hip external rotation peak strength and RTD, FTSTS, movement biomechanics, and KOOS scores compared to control subjects indicate incomplete recovery after TKA both immediately after rehabilitation and following the early post-rehabilitative period. Aim 3: Peak hip muscle strength and FTSTS performance are significantly correlated with KOOS Pain, activities of daily living, and Sport subscales at 3 months post-surgery. Fewer relationships were observed at 6 months post-surgery and between improvements from 3 to 6 months. Aim 4: Quadriceps RTD, hip external rotation RTD, and FTSTS performance were predictive of knee flexion excursion during walking, with quadriceps RTD the strongest of the three predictors. Faster quadriceps RTD, slower hip external rotation RTD, and faster FTSTS performance are predicted to lead to greater knee flexion excursion.

Conclusions: Modest improvement in muscle strength and RTD, FTSTS performance, patient-reported function, and biomechanics occur during the post-rehabilitative period after TKA, but all domains remain impaired compared to matched control subjects. Furthermore, muscle strength and RTD and FTSTS performance contribute to greater patient-perceived function and future knee flexion excursion during walking. In order to improve outcomes across domains after TKA, emphasizing improvement in muscle strength, RTD, and FTSTS ability during the first 3 months after surgery is critical as persistent deficits do not resolve by 6 months post-surgery. Lastly, maximizing quadriceps RTD by 3 months post-surgery is likely to lead to improved walking biomechanics at 6 months post-surgery.

Keywords: total knee arthroplasty, biomechanics, muscle strength, rate of torque development, gait

Paul W. Kline

April 12th, 2017

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April 12th, 2017

DEDICATION

First, I dedicate this dissertation to my parents, Tim and Cindy. Without your unconditional love and support I would never be the person I am today. You have always been there to celebrate my successes and to provide solace after my failures. For that, I am forever grateful. To Lauren, for helping me keep perspective and enjoy life's little moments. Finally, to the mentors throughout my life who always encouraged me to be "the man in the arena".

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LIST OF ABBREVIATIONS

% Stance: Percentage of Stance Phase

6MWT: Six-Minute Walk Test

A or ADL: Activities of Daily Living subscale

ABD: Abduction

Add: Adduction angle

Adj: Adjusted

BMI: Body Mass Index

BW: Percentage Bodyweight

CI: Confidence Interval

CR: Cruciate Retaining

ER: External Rotation

Ext: Extension angle

F: Female

Flex: Flexion angle

FTSTS: Five-time Sit-to-Stand

GRF: Ground Reaction Force

HEM: Hip Extensor Moment

HFLEXC: Hip Flexion Excursion

IC: Initial Contact

KEM: Knee Extensor Moment

KFLEXC: Knee Flexion Excursion

KOOS: Knee Injury and Osteoarthritis Outcome Score

M: Male

Mo: Month

NON: Non-operative limb

P/Pain: Pain subscale

PASE: Physical Activity Scale for the Elderly

PCL: Posterior Cruciate Ligament

Pre: Preoperatively

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-analysis

PRO: Patient-reported Outcome

PS: Posterior Stabilized

Q or QoL: Quality of Life subscale

Quad: Quadriceps

RTD: Rate of Torque Development

SCT: Stair Climbing Test

SD: Standard Deviation

Sp/R or Sport: Sport/Recreation subscale

Sy/Sym: Symptoms subscale

TKA: Total Knee Arthroplasty

TUG: Timed Up-And-Go Test

vGRF: Vertical Ground Reaction Force

VMO: Vastus Medialis Oblique

Chapter 1. Introduction & Specific Aims

1.1 Statement of the Problem

As the current gold-standard intervention for end-stage knee osteoarthritis, more than 600,000 persons undergo total knee arthroplasty (TKA) annually in the United States, with the frequency of this procedure expected to increase by 673% over the next decade to 3.48 million[1-3]. Despite most patients reporting significant pain reduction after surgery, 52% of patients who undergo TKA continue to report limited mobility after surgery and rehabilitation, which may predispose these individuals to future disability [4-7]. More importantly, the greatest difficulty is reported with tasks that are basic and essential to normal daily function, including ambulation and stair descent [6].

Current rehabilitation practices for patients after TKA emphasize recovery of knee joint range of motion, quadriceps muscle strength, and weaning from use of assistive devices during walking [8]. Patients are often discharged from physical therapy within 8-12 weeks after surgery when knee joint pain has improved, sufficient knee joint range of motion achieved, and the patient no longer requires an assistive device to ambulate [9]. Minimal quantitative assessment of gait or functional performance is currently utilized in discharge decision-making. Given the persistent asymmetrical movement patterns and mobility impairments reported by patients after TKA, assessing clinical tools for their potential use in informing clinicians of patient performance and movement biomechanics may improve the quality of care and outcomes for many after TKA. In order to do so, the current knowledge gaps require examination of factors that contribute to successful performance of gait and stair tasks after TKA and evaluation of recovery across multiple domains during the early post-rehabilitative period (>3 months post-surgery). Presently, recovery of quadriceps strength has been thoroughly studied, but other important domains including the recovery of hip muscle strength, functional performance, patient reported outcomes, and biomechanics of gait and stair descent during the first 6 months after TKA are less well-defined. Furthermore, the relationships between muscular and functional performance measures and gait and stair descent mechanics are unexplored. Given the long-term impairments noted after TKA, it is critical to longitudinally observe early post-rehabilitative recovery after TKA across multiple domains and identify key modifiable targets for intervention to improve movement biomechanics and patient outcomes from this procedure.

1.2 Justification of Research

Though the precise mechanism(s) of persistent asymmetries in gait patterns during level walking and stair descent are unknown, quadriceps strength is believed to be an important determinant for successful functional mobility after TKA [10-12]. Peak isometric quadriceps strength is associated with improvements in functional ability, gait mechanics, and patient satisfaction [11, 13, 14]. However, limitations in walking ability, gait mechanics, and poor patient-reported function are noted in patients with full recovery of quadriceps strength, indicating the likelihood of additional contributing factors [15, 16]. Early investigations of peak isometric hip muscle strength after TKA indicate that stronger patients have less difficulty with daily activities [17]. However, lack of biomechanical measures limits full understanding of the role hip muscle strength serves in restoring normal joint mechanics during dynamic activities. Furthermore, due to a lack of previous longitudinal studies of hip muscle strength after TKA, it is unclear if hip muscle strength is maintained, increased, or reduced during the post-rehabilitative period.

Thus, further study into the role of hip muscle performance after TKA is needed. Furthermore, while measurement of peak strength has proven valuable, it does not reflect how the lower extremity muscles function during critical times of dynamic functional activities which require rapid torque production. For this reason, rate of torque development (RTD) has been proposed as a novel method to assess the ability of muscles to generate torque rapidly [18, 19]. Additionally, functional performance measures, such as the Five-time Sit-to-Stand test, provide clinicians with rapid and reliable assessment of patient function [20]. To date, knowledge of performance impairments of this task following TKA are limited and the relationships between this clinically available performance test, patient-reported outcomes, and biomechanics of gait and stair descent are unknown.

This dissertation will define recovery between 3 and 6 months after TKA across four domains: 1) hip abductor, hip external rotator, and quadriceps muscle performance (peak strength and RTD), 2) functional performance as measured by the five-time sit-to-stand test, 3) the Knee Injury and Osteoarthritis Outcome (KOOS) patient-reported outcome questionnaire, and 4) biomechanics of walking and stair descent. Furthermore, this project will test the relationships between each of these four domains of recovery in order to explore potential interactions across domains of recovery and to identify possible targets for intervention during rehabilitation after TKA. Also, this project aims to use clinical measures assessed at 3 months after TKA to establish a predictive model of knee joint biomechanics during walking at 6 months after TKA. Ultimately, the purpose of this dissertation is to quantify early post-rehabilitative recovery after TKA and identify potential objective criteria for discharge from outpatient physical therapy after TKA that are likely to lead to improved gait mechanics and functional mobility after TKA.

1.3 Specific Aims

The Specific Aims of this dissertation research comprised the following:

AIM 1: To conduct a systematic review of the literature on recovery of muscle strength, five-time sit-to-stand performance, gait and stair biomechanics, and KOOS scores during the first 6 months after TKA.

Hypotheses: No specific hypothesis was needed due to the nature of a systematic review of the current literature. **Significance of Aim 1:** The results of this systematic review will provide a synthesis of expected recovery during the first 6 months after TKA compared to pre-operative function and control subjects across four domains including muscle strength, functional performance as measured by the five-time sit-to-stand test, gait and stair biomechanics, and KOOS score. This systematic review will also identify current gaps in the literature involving these four domains and the relationships between domains.

AIM 2: To quantify recovery in four domains: 1) hip abductor, hip external rotator, and quadriceps muscle performance, 2) Five-time sit-to-stand performance, 3) patient-reported outcome scores, and 4) gait and stair descent biomechanics between 3 and 6 months after TKA and compared to sex, age, and body mass index matched controls.

Hypothesis 2A: Significant improvements in all four domains would be observed in the TKA group at 6 months compared to 3 months after TKA. **Hypothesis 2B:** Significant impairments in all 4 domains would persist at 6 months after TKA compared to matched controls. **Hypothesis 2C:** Subjective patient-reported outcome measures will demonstrate greater relative improvement between 3 and 6 months after TKA compared to objective physical measures of muscle performance, five-time sit-to-stand, and gait and stair descent biomechanics. **Significance of Aim 2:** Gait mechanics and quadriceps strength impairments have been noted to improve longitudinally after TKA. Conflicting evidence exists regarding deficits compared to the contralateral quadriceps and that of a control group. Peak hip strength and RTD of either the hip or the quadriceps are minimally documented after TKA. Similarly, functional performance and stair descent biomechanical improvements have not been evaluated. The results of this aim will provide evidence of the degree of recovery across multiple domains during the post-rehabilitative period between 3 and 6 months post TKA, addressing gaps in the literature identified in Aim 1.

AIM 3: To evaluate the association between quadriceps and hip muscle performance, functional performance, and patient-reported outcomes scores at 3 months and 6 months after TKA and determine the association between the changes in the three measures from 3 to 6 months after TKA.

Hypothesis 3A: Muscle performance will be positively associated with functional performance and patient-reported outcomes at both 3 and 6 months after TKA and between the changes from 3 to 6 months. **Hypothesis 3B:** No significant relationships will be observed between functional performance and patient-reported outcomes at either 3 or 6 months after TKA or between the changes between time points. **Significance of Aim 3:** The results of Aim 3 will explore the relationships between three clinical domains assessed in Aim 2. These data will determine if the domains are assessing unique constructs related to recovery or if performance from one domain influences performance in another. From this aim, the utility of easily implemented clinical assessments (functional performance and patient-reported outcomes) in providing information related to outcomes with a higher equipment burden (muscle performance) will be assessed, potentially rapidly enhancing clinical decision-making.

AIM 4: To determine the utility of clinical assessments performed 3 months after TKA in predicting knee biomechanics during walking at 6 months after TKA.

Hypothesis 4: Measures of physical performance, but not patient-reported outcomes, will predict knee mechanics during walking in individuals after TKA. **Significance of Aim 4:** Although positive relationships between quadriceps strength and more symmetrical gait biomechanics are reported early after TKA, there are no predictive models for clinicians to determine future knee biomechanics using variables measured during rehabilitation. This data will provide clinicians and researchers with practical information to determine readiness for discharge based upon likelihood of achieving more normal knee motion patterns during walking, possibly improving long-term outcomes.

1.4 Organization of Dissertation

This dissertation is organized in a manner that the main findings (Chapters 3-6) detail the four distinct aims conducted over a period of 3 years (2014-2017) at the University of Kentucky. Each aim is written in manuscript format for publication in peer-reviewed journals.

The literature review (Chapter 2) provides the background and motivation for this dissertation. Chapter 3 features a systematic review of recovery after TKA during the first 6 months post-surgery with the purpose to define typical recovery across multiple domains and to identify knowledge gaps in the literature. Chapters 4-6 were part of a longitudinal study of recovery after unilateral TKA with assessments occurring at 3 months and 6 months post-surgery. Chapter 4 examined changes from 3 to 6 months in muscle performance, functional performance (i.e. five-time sit-to-stand), gait and stair descent biomechanics, and patient-reported outcomes (i.e. KOOS scores) and to compare these changes to the performance of a sex, age, and body mass index-matched control group. To do so, two assessment points were required for the TKA group (3 and 6 months post-surgery) and a single assessment time for control participants. Subjects performed identical tasks at each visit. Chapter 5 explored the relationships between the three clinically assessable domains described in Chapter 4. To examine these relationships, correlations were utilized to identify any significant relationships between the domains at 3 months, 6 months, and the change in performance between each time point. Chapter 6 utilized muscle performance, functional performance, and patient-reported outcome scores assessed at 3 months after surgery to predict knee flexion motion during gait at 6 months after surgery. Lastly, Chapter 7 highlights the outcomes of Chapters 4-6, discusses the limitations of the findings and outlines future directions for additional study related to these projects.

Chapter 2: Literature Review

The purpose of this review is to detail the prevalence of TKA, implant types and surgical approaches, typical post-operative rehabilitation, and outline consequences of TKA on muscle strength and performance, functional performance, gait and stair descent biomechanics, and patient-reported outcomes.

2.1 Prevalence of Total Knee Arthroplasty

As the incidence of osteoarthritis continues to rise, 25% of the adult population in the United States are projected to be diagnosed with knee osteoarthritis in the next 10 years [21]. TKA is the current gold-standard intervention for end-stage knee osteoarthritis [3]. Reflecting the rise in osteoarthritis incidence, in 2010 it was reported that over 600,000 TKA's were performed annually and this number is projected to increase by 673% to reach 3.5 million per year in the United States by 2030[2]. Furthermore, the typical candidate for TKA is now younger than previous candidates as noted in the substantial increase in patients under 60 years old undergoing TKA[22]. In combination, these trends suggest a dramatic rise in the prevalence of TKA with costs related to the procedure expected to approach $67 billion by the year 2030 [2, 23].

2.2 Types of Implant Design

When undergoing TKA, orthopedic surgeons have a range of decisions to make regarding prosthetic designs. These include deciding between fixed or mobile bearing designs, posterior stabilized or cruciate retaining designs, and whether or not to resurface the patella. Fixed vs mobile bearing designs refer to the polyethylene spacer used between the femoral and tibial components of a TKA. In fixed bearing designs, the spacer is secured to the tibial component. In contrast, in mobile bearing, also referred to as rotating platform, the spacer is free to rotate on the tibial component. The rotation allowed by the mobile bearing design more closely replicates the transverse plane motion of a normal knee and may reduce stress and wear on the femoral component, extending the life of the implant. Despite this theoretical construct, long term studies show similar survivorship of mobile and fixed bearing knees [24]. Additionally, gait mechanics and quadriceps strength outcomes are similar in both types of designs [25-27]. Furthermore, compared to fixed bearing designs, mobile bearing designs rely on surrounding ligaments and soft tissue to stabilize the knee joint. For this reason, and due to the potential restoration of more normal transverse plane knee motion, mobile bearing designs are more frequently recommended for younger and more active patients [28].

Another category of implant design involves how the posterior cruciate ligament (PCL) is treated during surgery. If the PCL is in good condition at the time of surgery, the surgeon may elect to keep the PCL intact. In this instance, a cruciate retaining (CR) knee would be utilized. If the PCL is removed, a posterior stabilizing implant is used to account for the lack of stabilization once provided by the PCL. Some of the proposed benefits of the posterior stabilized knee are more reliable restoration of knee motion, improved range of motion after surgery, and possible reductions in polyethylene wear. Advantages of the CR knee are less bone removal during the procedure and reduce potential for complications from using a polyethylene post. Long-term outcomes suggest muscle strength, gait mechanics, and implant wear are similar with each design [29-31].

Initially, TKA did not include resurfacing of the patella. However, high rates of patellofemoral joint pain and symptoms after TKA. In response these findings, surgeons began resurfacing the patella with favorable results of reduced complications, improved quadriceps strength, more pain relief, and reduced need for revision surgery due to ongoing symptoms [32]. However, considerable debate in the orthopedic surgery community continues regarding the decision on whether or not to resurface the patella. Reasons cited for not resurfacing the patella often include the presence of normal cartilage, younger patients, thin patella size, and surgeon preference [33].

With the improvements made in implant design in recent decades, orthopedic surgeons now have many options to consider in deciding the optimal implant for each patient. Although the long-term outcomes appear similar in all designs, implant type and design should be documented in studies assessing outcomes after TKA.

2.3 Types of Surgical Approaches in Total Knee Arthroplasty

In addition the various implant designs, surgeons also must decide the type of approach to use when making the surgical incision to access the knee joint during TKA. The two most common approaches (midline and medial parapatellar) are standard cutaneous incisions[34]. More recent approaches have been developed to minimize the invasiveness of the procedure by preserving the extensor mechanism of the knee and limit soft tissue damage peri-operatively and include the subvastus and midvastus approaches[34].

Beginning with the two most common approaches, the standard midline incision follows the midline of the knee beginning approximately 2 cm proximal to the superior aspect of the patella and end at the tibial tuberosity [35]. A modification of the standard midline incision, the medial parapatellar incision is curvilinear, with the convex side of the line facing medially. The incision begins and ends at the same locations as the midline incision [35].

The subvastus approach involves isolating the extensor mechanism and vastus medialis oblique (VMO), beginning the incision inferior to the VMO[36]. The incision then continues distally to the medial joint capsule and the extensor mechanism is laterally displaced. Research indicates that the subvastus approach allows similar joint exposure as the medial parapatellar approach but results in less blood loss, reduced prevalence of lateral release, less post-operative pain, and faster recovery of quadriceps strength[37, 38]. The midvastus approach offers similar protection of the extensor mechanism, with the majority of the VMO preserved[34]. Studies comparing the midvastus approach to the medial parapatellar approach report similar findings of reduced prevalence of lateral release and surgical blood loss[39]. However, no differences in quadriceps strength, knee joint range of motion, or proprioception were noted[39].

2.4 Post-operative Rehabilitation

Rehabilitation is commonly prescribed after TKA. While the duration of rehabilitation varies, recovery from TKA typically involves a 1 or 2 night inpatient stay before initiating outpatient physical therapy for the first 8-12 weeks after surgery[3, 40]. An average of 19 visits are utilized over that 8-12 week period with activities consisting of manual therapy to improve joint range of motion, patient education, functional training to wean patient from assistive devices, muscle strengthening exercises, and modalities for pain and swelling as needed[3, 8, 41]. Criteria for discharge from formal physical therapy typically included achievement of full knee extension and >120° of knee flexion range of motion, ability to ambulate without an assistive device, and minimal knee pain with daily activities [42]. The persistent impairment in functional recovery after TKA suggests the need for objective assessment of recovery to determine readiness for discharge.

2.5 Recovery of Muscle Strength & Muscle Performance

The quadriceps is the most studied muscle after TKA with multiple investigators reporting both isometric and isokinetic strength[43]. Quadriceps strength is most impaired during the first 2 months after surgery, with the strength deficits primarily driven by reduced neural activation[44]. Reduced strength is expected early after surgery due to the invasiveness of the procedure. However, one would expect strength to recover with increased time from surgery. Interestingly, quadriceps strength, both isometric and isokinetic, is impaired between 4-6 months after TKA compared to control subjects[45-48]. There is additional evidence demonstrating persistent weakness of the quadriceps compared to the non-operative limb during the first 6 months after surgery[12, 19, 46, 49-53]. Since post-operative rehabilitation typically concludes within the first 3 months after surgery, these results suggest that current rehabilitation practices do not adequately restore quadriceps function. Fewer studies have reported quadriceps strength 1-year or more after surgery, but the results of these studies show quadriceps weakness remains impaired. A recent meta-analysis concluded that persistent post-rehabilitative quadriceps weakness was evident at 4-6 months and as late as 1-3 years after surgery[43, 48, 54-60]. However, due to high heterogeneity in the results reported in each study, the quality of evidence was low.

Muscle strength of the hamstrings has also been evaluated after TKA. The results are mixed for isometric strength at 4-6 months and 1-3 years after TKA, with a recent meta-analysis finding no significant difference in isometric hamstring strength at either time point after TKA[43]. Fewer studies have investigated isokinetic hamstring strength with three studies reporting significant weakness in the TKA group 1-3 years post-surgery compared to controls[48, 59, 60]. Ultimately, a meta-analysis concluded that isokinetic hamstring strength was significantly weaker than controls between 1-3 years post-surgery, but not different 4-6 months post or >3 years post-operatively[43]. As with quadriceps strength, the quality of evidence was low for hamstring weakness after TKA.

Investigations of hip muscle strength after TKA are in their infancy. Prior studies have demonstrated hip muscle weakness in individuals with knee osteoarthritis[61]. It follows that without specific intervention hip weakness would persist following TKA. Surprisingly, no studies to date have evaluated hip muscle strength compared to control subjects. One study compared isometric hip abduction strength in the operative to the non-operative limb after TKA and found no significant difference [62]. However, improved strength in the hip abductors is associated with improved physical function justifying additional inquiry into possible muscular factors that may influence outcomes after TKA[17, 62]. One thing is clear, however, a thorough investigation of hip muscle strength after TKA is warranted to determine potential deficits both between-limbs and compared to a control group and to evaluate the influence of potential hip muscle weakness in outcomes after TKA.

Beyond peak muscle strength, early investigations into rapid torque production after TKA are of interest. Rate of torque development (RTD) measures how quickly an individual can generate torque in an isometric contraction. Since most daily functional activities such as walking, stair negotiation, and sit to stand occur relatively rapidly, adequate muscle torque must be generated during critical time periods for successful completion of the task. Since RTD measures the rate at which muscle torque is generated, it has potential to be a valuable measure of muscle performance and patient recovery after

TKA. Preliminary studies of quadriceps RTD in patients after TKA show that RTD is impaired pre-operatively through at least 6 months post-operatively and RTD significantly contributed to functional measures of recovery including walking and stair climbing [18]. A similar study also identified deficits in quadriceps RTD pre-operatively, 3 months, and 6 months post-operatively [19]. Additional investigations of quadriceps RTD are needed to fully capture recovery of quadriceps function and how deficits may interfere with functional tasks. Furthermore, measures of RTD in isometric hip muscle strength may also prove valuable as the role of the hip after TKA is further elucidated.

2.6 Five-time Sit-to-Stand

The five-time sit-to-stand test (FTSTS) is a commonly utilized, clinically-feasible functional test that is often used to document recovery after lower extremity surgery or injury. To complete the test, patients are asked to perform five consecutive sit-to-stands without using their hands or upper extremities for propulsion. The task is timed from the initiation of the first sit-to-stand through completion of the final sit after the fifth sit-to-stand. The minimal detectable change of the FTSTS is 2.5 seconds, meaning that a reduction in time to complete the test is considered beyond measurement error only if performance is reduced by greater than or equal to 2.5 seconds[63]. In patients after TKA, FTSTS performance worsens during the 1st post-operative month compared to pre-operative performance[49]. After this initial decline in performance, performance improves throughout the first year of recovery[49, 64, 65]. However, performance on the FTSTS in patients with TKA is noted to be worse than controls at all time points pre and post-operatively and improvements with additional time from surgery, on average, do not exceed the minimal detectable change. This suggests that recovery in functional performance, as measured by the FTSTS, is incomplete after TKA. Providing further evidence to this point, a recent study with pre-operative and 1-year post-operative assessments demonstrated that patients whose FTSTS performance improved by greater than 2.5 seconds were significantly more likely to demonstrate more normal and symmetrical gait patterns[66]. Findings such as those of this recent study highlight the potential for the FTSTS to be utilized as an objective assessment to determine readiness for discharge from rehabilitation after TKA. Future studies should include common clinical assessments, including the FTSTS, to document expected performance of patients after TKA at various time points. These data would also allow for more information to be derived from FTSTS performance and arm clinicians with better tools to evaluate recovery and readiness for discharge from rehabilitation after TKA.

2.7 Walking Biomechanics

Walking is a fundamental task for many activities of daily living. Prior to TKA, patients with knee osteoarthritis report difficulty walking to the point that their quality of life is reduced. Evaluation of walking after TKA provides essential information of the level of recovery achieved and is considered a measure of success for the surgery. For this literature review, ground reaction force, kinematic, and kinetic variables were included. Emphasis was placed on changes within the operative limb at different time points after surgery, comparison to pre-operative gait, comparison to the non-operative limb, and comparison to control subjects in order to fully evaluate the impact of TKA and recovery of gait after surgery and subsequent rehabilitation.

Ground Reaction Force

Ground reaction force (GRF) is recorded using force platforms and measures the force applied by a person when they are in contact with the ground. GRF is often used as a measure of external loading. Investigations into GRF variables after TKA have focused on vertical GRF, the highest magnitude GRF during most functional tasks. When comparing the TKA to the non-operative limb during self-selected walking, peak vertical GRF values were similar in a group of patients between 4-96 months post-surgery[67]. Also reported were loading rates, or the rate of increase in vertical GRF during early stance, with no significant differences identified[67]. A separate study compared the TKA and non-operative limbs at pre-surgery and 2 years post-surgery and found that peak vertical GRF was significantly greater in the non-operative limb at both time points [68]. Furthermore, peak vertical ground reaction force increased bilaterally 2 years post-surgery compared to pre-operative values, primarily due to increased walking speed at the 2-year time point. Although no differences in loading rates were observed between limbs at either time point, loading rates significantly increased 2 years post-TKA compared to pre-operatively, also due to faster walking speeds noted at 2 years post-surgery.

All of the previously discussed studies measured GRF variables at a self-selected walking speed. Given asymmetries in GRF variables pre-operatively, it is not surprising that individuals walk with a strategy to bear more load, and greater GRF, in the less affected limb after TKA. Study protocols evaluating only self-selected walking speed may mask deficits in loading as these patients may avoid walking at faster speeds in order to minimize dramatic increases in GRF in the non-operative limb. Thus, having TKA patients walk at a faster than normal pace may reveal asymmetries in GRF variables and better reflect recovery after surgery. Nonetheless, the finding of asymmetrical peak vertical GRF two years post-TKA suggests that patients continue to favor the non-operative limb and may explain the high likelihood of contralateral knee replacement in the decade following the initial TKA.

Sagittal Plane Joint Kinematics

Many studies have investigated sagittal plane kinematics of the knee after TKA. In this plane, commonly reported variables include knee flexion angle at initial ground contact, maximum knee flexion angle during both stance and swing, and knee flexion excursion, or the total knee flexion range of motion occurring during stance or swing.

Compared to control subjects, patients after TKA demonstrate similar knee flexion angle at initial contact with this finding replicated in multiple studies[69-71]. However, comparisons of maximum knee flexion angle during both stance and swing show significant reductions in knee flexion angle in TKA subjects[72-75]. The differences compared to controls in these studies ranged between 6-8° in peak knee flexion angle during stance phase. Similar findings were observed when comparing peak knee flexion during swing as between 8-10° less flexion was noted in the TKA limb than controls[69, 71, 75]. When combined, these findings suggest that patients after TKA have similar knee flexion angles at initial contact but undergo less knee flexion during stance and swing. As a result, knee flexion excursion is reduced in patients after TKA compared to controls with differences of 8° and 9° reported [69, 75]. The studies reporting findings contrary to those reported above either consisted of smaller sample sizes and thus were susceptible to Type II error or included TKA subjects and controls who walked at similar velocities[76]. It could be argued that these TKA subjects were more functionally capable as evidenced by their gait speed and thus had recovered to a level in which kinematic differences were not apparent. This finding strengthens the argument for use of gait mechanics as a valuable outcome measure after TKA. When compared to pre-operative values, reports of sagittal plane knee motion are varied. Studies of participants at 2 months and 6 months post-surgery reported reduced peak knee flexion angles post-operatively while the studies performed 1 year post-surgery report increased peak knee flexion[70, 72, 74, 77]. These findings indicate that pre-operative peak knee flexion values are likely achieved between 6-12 months after surgery. However, comparisons to pre-operative values should be interpreted with caution as using an arthritic knee set to undergo TKA as the standard for successful recovery may be unwise due to previously reported gait adaptations to knee osteoarthritis. For this reason, comparisons to well-matched control subjects may better establish potential impairments that remain during recovery from TKA.

Sagittal Plane Joint Kinetics

Kinetic analyses of gait often accompany kinematic variables as a means of determining joint moments to inform researchers and clinicians of the effects of GRF on lower extremity joints during gait. Moments can be reported as either internal or external, with one being equal in magnitude but opposite in direction than the other (i.e. external knee flexion moment = internal knee extensor moment). Peak internal knee extension moment is reduced in TKA subjects compared to controls in overall peak value, value at midstance, and at weight acceptance[69, 70, 74]. The magnitude of difference varied, ranging between a 20-50% deficit. Even in the studies with an average assessment date of

4 years post-surgery, reduced knee extensor moments were observed in patients with TKA compared to controls[75].

When comparing post-operative to pre-operative sagittal plane kinetics, the results vary depending on length of time since surgery. Studies featuring the earliest follow-up time (2 months) report reduced knee extensor moment post-operatively[74]. However, at 1 year follow-up, overall peak knee extensor moment was not significantly different than pre-operative measures despite post-operative peak moment at weight acceptance being significantly greater than pre-operative measures [70]. In addition to the methodological issues raised regarding the post-operative time points selected, the selection of appropriate control subjects is also a concern. None of the 8 studies utilizing a control group were matched to the TKA group for body mass or body mass index (BMI). This is problematic for two reasons: 1) obesity is a known risk factor for osteoarthritis so TKA subjects are often heavier than their corresponding control group, and 2) kinetic variables are commonly normalized to body mass. For these reasons, kinetic variables are potentially influenced by large differences in body mass between groups. A large mean body mass for the TKA group may artificially reduce the joint moments compared to a control with a lower body mass, potentially influencing the differences between groups noted above. For this reason, controls should be matched for body mass and/or BMI when possible.

Frontal Plane Joint Kinematics

One of the goals of TKA is to correct joint deformity and restore normal joint alignment. Deviations in the frontal plane with either knee varus or valgus deformity are common in knee osteoarthritis. Hence, measuring dynamic frontal plane knee motion is essential to a successful outcome after TKA.

Peak knee adduction angle during gait is a common measure reported in studies related to TKA. When compared to controls, peak knee adduction angle was similar after TKA with only a 0.2 degree difference on average[71, 78]. Similar knee adduction angles have been reported at various time points after TKA indicating that the procedure is successful in restoring a more neutral alignment[79-81]. As noted previously, sagittal plane mechanics appear to improve longitudinally after surgery. The fact that peak knee adduction angle is similar to control subjects early after surgery indicates that improvement in this variable are primarily due to surgery and not post-operative recovery.

In comparison to the non-operative limb, operative limb peak knee adduction values were reduced compared to the non-operative limb, further suggesting that the goal of more neutral frontal plane alignment is achieved[67, 82]. Reports of greater peak knee adduction angle in the non-operative limb are of interest given the likelihood of contralateral TKA within 10 years after the initial surgery[83].

Frontal Plane Joint Kinetics

Frontal plane kinetics are known to play a role in the progression of knee osteoarthritis as elevated frontal plane moments are thought to advance the severity of osteoarthritis, particularly in the medial compartment. Given that frontal plane kinematics and kinetics are linked, one would expect a reduction in frontal plane moments in conjunction with reduced peak knee adduction angles after TKA. Often utilized as a measure medial joint loading, external knee adduction (or internal knee abduction) moment are important to observe after TKA as a means of measuring the success of the procedure and to ensure excessive medial joint loading does not accelerate wear on the prosthesis.

External knee adduction moment of the TKA limb, when compared to control subjects, has been reported as either not significantly different or significantly reduced after TKA[67, 69, 76, 84]. A typical external knee adduction moment curve during gait exhibits a bimodal pattern, with most studies either reporting the peaks individually or reporting the highest of the two peaks. Regardless, TKA appears to successfully reduce external knee adduction moment to be equal to or less than controls. Compared to pre-operative values, peak external knee adduction moment is reduced at 6 months post-surgery and is similar to values observed in healthy controls [78, 81]. Interestingly, at 1 year post-surgery, one study reported an increase in peak external knee adduction moment to pre-operative levels[81]. The underlying mechanism behind the increase in frontal plane moment is unclear but may have been influenced by increased gait speed, decline of the contralateral limb requiring increased loading of the TKA limb, or increased loading through the operative limb as recovery continued between 6 months to 1 year post-surgery.

The identification of consistently reduced knee adduction moment after TKA is consistent with findings of reduced peak knee adduction angle. This is not surprising as greater knee adduction angles increase the distance of the moment arm of the vertical GRF vector from the knee joint, resulting in a subsequently greater external knee adduction moment. Taken together, TKA appears to successfully restore more neutral frontal plane knee alignment bringing both peak knee adduction angle and peak external knee adduction moments down to values observed in control subjects.

2.8 Stair Descent Biomechanics

Stair ascent and descent are more demanding tasks than level walking as evidenced by stair negotiation commonly listed as one of the most difficult activities for older adults, patients with knee osteoarthritis, and patients with TKA[85, 86]. This difficulty is reflected in stair negotiation being included in many subjective patient reported outcome questionnaires for patients with lower extremity impairments[87-89]. Specific to TKA, patients often report greater difficulty with stair descent than stair ascent[6]. Thus, an understanding of the effect of TKA on stair negotiation, in particular stair descent, is essential to determine the level of recovery in this demanding, but necessary, daily activity. Currently, very few studies have analyzed stair descent biomechanics after TKA.

Sagittal Plane Joint Kinematics

Initial studies of sagittal plane knee motion during stair descent after TKA have failed to reach consensus, with some reporting reduced knee flexion excursion after TKA and other reporting no significant differences compared to controls or the non-operative limb[75, 90-92]. These early studies raise several methodological concerns including use of a control group or comparisons to varying pre-operative or post-operative time points as well as controlling the manner in which the participants descended the stairs. Few studies have included a control group, pre-operative measures, or multiple post-operative time points, thus making an assessment of recovery in stair descent after TKA difficult.

Sagittal Plane Joint Kinetics

Again, few studies have thoroughly investigated stair descent after TKA. A single study reported reduced external knee flexion moment between a control limb and the TKA limb in patients 22-98 months post-surgery[75]. All other studies noted no differences between groups in external knee flexion moment between groups[90, 91, 93, 94].

Frontal Plane Joint Kinematics

To date, no studies have reported frontal plane knee angles during stair descent.

Frontal Plane Joint Kinetics

Similar to findings observed in previous studies of walking gait, no differences were observed between external knee adduction moments between patients after TKA and controls[91, 94, 95]. Although stair descent is more demanding than level walking, correction of the frontal plane static alignment of the knee joint during TKA appears to result normalize frontal plane knee moments to within normal values for healthy controls during dynamic activities.

In summary, it is clear that there is much to learn regarding stair descent after TKA. Future studies should evaluate not only the landing (or leading) limb during stair descent, but the stance limb (or trailing limb) as well. Since stair descent is a bipedal task, the strength and stability of the stance limb potentially influences the mechanics of the landing limb and should be considered in evaluating recovery after TKA.

2.9 Knee Injury & Osteoarthritis Outcome Score

Patient-reported outcome (PRO) measures have become nearly ubiquitous in all healthcare settings as a means of quickly tracking and evaluating outcomes. The Knee

Injury and Osteoarthritis Outcome Score (KOOS) is one of the most commonly used PRO measures for patients recovering from TKA and has been shown to be reliable and valid in this population[88]. The KOOS contains five subscales: 1) Pain, 2) Symptoms, 3) Activities of Daily Living, 4) Sport and Recreation function, and 5) knee-related Quality of Life. Each subscale is scored separately with scores ranging from zero (lowest functioning knee) to 100 (no knee problems/highest functioning knee)[96]. No distinct minimal important change (MIC) has been established that is specific to patients after TKA, but increases of 8-10 points on each subscale have been documented in other clinical populations[88]. Floor and ceiling effects have been documented in patients with TKA. A floor effect is most likely to occur pre-operatively, especially in the sports/recreation subscale, as 48% of patients scheduled for TKA have reported the worst possible score in this subscale[88]. Ceiling effects have been noted for the pain and sports/recreation subscale at 6 months post-TKA and in the pain and quality of life subscales at 1 year post-surgery[88].

Given the previously noted ceiling effects, documentation of changes in KOOS scores during recovery from TKA are of interest. After initial declines in KOOS score early after surgery, improvements in scores are noted to be time-dependent with scores across subscales improving with additional time from surgery[97-101]. Recent evidence has questioned the value of KOOS scores in long-term assessment of patient function after TKA. A strong correlation has been observed between KOOS Pain and KOOS ADL subscores, suggesting that as pain decreases patients perceive additional improvement in their ability to perform ADLs[100]. Other studies have demonstrated a lack of relationship between KOOS scores along with other PRO measures and patient's physical or functional performance[102, 103]. This evidence, combined with the potential for ceiling effects at 6 and 12 months post-operatively suggest that patients may perceive their recovery to be more complete than it actually has. Thus, the value of the KOOS may be especially important during the first 6 months of recovery prior to the onset of potential ceiling effects. Exploration of relationships between functional performance tests, biomechanics, and KOOS scores during the earlier phases of rehabilitation may provide clinicians with valuable information related to critical benchmarks for recovery after TKA and should be featured in future studies of patients after TKA.

2.10 Summary of Literature Review

Deficits in quadriceps strength and gait mechanics are common after TKA. Less evidence exists for hamstring strength, hip strength, RTD, and FTSTS performance deficits. Improvement in KOOS scores appear to be time-dependent for the first 6 months after surgery, after which the potential for ceiling effects increases. Minimal evidence exists regarding the biomechanics of stair descent, despite the fact that this task is commonly reported as one of the most difficult for patients after TKA. The findings of this review suggest that current rehabilitation practices to not restore full muscle strength or functional recovery in patients after TKA despite improvements in the patient-reported outcomes. Thus, additional studies investigating recovery during the first 6 months after TKA across multiple objective and patient-reported domains are needed to establish expected recovery and explore relationships between domains in order to better focus current rehabilitation decision-making and develop improved interventions.

Chapter 3: Early Alterations in Muscle Strength, Functional Performance, Gait and Stair Mechanics, and Patient Reported Outcomes after Total Knee Arthroplasty: A Systematic Review

3.1 ABSTRACT

Background: Total knee arthroplasty (TKA) is considered the gold-standard treatment for end-stage knee osteoarthritis and typically requires lengthy periods of rehabilitation to restore normal function. While TKA offers successful reduction in knee pain from osteoarthritis, persistent limitations in physical function indicate potentially incomplete recovery. Due to the expected surge in demand for TKA, a thorough understanding of recovery across multiple domains is critical. The aim of this systematic review was to determine changes in leg muscle strength, functional performance, gait and stair mechanics, as well as patient-reported outcome scores during the first 6 months after TKA to better understand the natural progression of pain, function, mobility, and independence.

Methods: A search of PubMed was conducted. To be included, studies had to be published since 1995, written in English, and include 2 of the following time points: preoperative, 3 months postoperative, 6 months postoperative.

Results: Forty-four studies met the inclusion criteria. Quadriceps strength is impaired during the first 3 months after TKA, with limited evidence that it normalizes after 6 months. Minimal evidence of strength impairments in other lower extremity muscles exists. KOOS scores improve with time after TKA. Few studies report longitudinal changes in functional performance and gait and stair mechanics during the first 6 months after TKA.

Conclusion: There is good evidence for improvement in KOOS scores after TKA, but limited evidence for improvement in leg muscle strength, functional performance, and gait and stair mechanics during the first 6 months after TKA. Physical performance measures demonstrate persistent deficits after TKA that may not be accurately measured by patient reported outcomes. Given limitations on access to rehabilitation after the first 6 months post-surgery, longitudinal assessments of physical performance measures after TKA are needed to identify potential impairments that could be addressed during early postoperative periods.

3.2 INTRODUCTION

Total knee arthroplasty (TKA) is considered the gold-standard treatment for end-stage knee osteoarthritis [3]. More than 600,000 TKAs are performed annually in the United States and the procedure is estimated to increase to 3.5 million by 2030 due to a growing older adult population and the high prevalence of obesity [1, 104]. While TKA is largely considered successful in reducing knee pain and the majority of patients are satisfied with the surgery, 34% of patients report not feeling normal after surgery and 52% report continued difficulty with functional tasks that are essential for normal daily function [5-7, 54, 105, 106]. Additionally, biomechanical asymmetries of gait are noted more than one year post surgery [107, 108]. These results suggest that restoration of physical function is incomplete and patient satisfaction may be an insensitive measure of functional recovery.

After TKA, patients often participate in post-operative physical therapy to restore muscle strength, knee range of motion, and functional mobility [3]. However, the duration, frequency, and intensity of therapy after TKA is variable and patients frequently demonstrate muscle strength, gait, and functional mobility deficits years after TKA [109]. Most commonly, patients receive supervised therapy for the first 8-12 weeks after surgery, with an average of 19 outpatient visits [3]. Although much attention has been given to long-term (≥1 year post) outcomes, there is little understanding of patient progress during the first 6 months after TKA when the effects of rehabilitation should be most apparent.

Post-acute care rehabilitation remains on the largest expenditures in patients undergoing TKA[110]. As the number of individuals requiring TKA increases, an understanding of recovery during the first 6 post-operative months is critical to improving outcomes from TKA. A variety of assessments have been established to quantify improvement after TKA including assessments of muscle strength, functional performance, gait and stair mechanics, and patient reported outcome (PRO) scores. A common test of functional performance includes the five-time sit-to-stand [49, 64-66] and one of the most common PRO measures is the Knee Injury and Osteoarthritis Outcome Score (KOOS) [43, 88, 108, 111, 112]. These assessments allow clinicians to assess patient progress throughout postoperative rehabilitation across multiple domains, but evidence of the typical progression during the first 6 months after TKA is not well established. In identifying early deficits in these domains, clinicians and researchers can work to develop more efficient and cost-effective intervention strategies to implement during the early months of rehabilitation to achieve better early outcomes and reduce the long-term deficits that have been previously reported after TKA [5, 6, 108, 113, 114].

The aim of this systematic review is to determine the expected muscle strength, functional performance, gait and stair mechanics, and KOOS scores in patients 3 months and 6 months post-TKA to better understand the natural progression of pain, function, mobility, and independence. In doing so, a profile of typical impairments will be established to guide rehabilitation professionals and clinical researchers in identifying modifiable factors to focus on during postoperative periods in which access to therapy is more common and accessible.

3.3 MATERIALS AND METHODS

Database and Searches

Studies were identified through a search of PubMed from 1995 to January 2015. The search was restricted to within the past 20 years due to changes in TKA implant design and surgical procedures that make older publications less representative of a current patient[115]. The search terms used to define the population are presented in Table 3.1A. Each outcome of interest was searched separately using the terms presented in Table 3.1(B-E).

After applying search limits (English, 20 years), the titles and abstracts were assessed according to predetermined inclusion and exclusion criteria. The full text articles were obtained for potentially eligible studies and in cases in which the information presented in the abstract was not sufficient to exclude an article. Studies that satisfied the inclusion and exclusion criteria were included in the final review. Lastly, the reference lists of all retrieved full text articles were reviewed for inclusion to supplement electronic searching.

Study Selection Criteria

In order to be included in the review, studies were required to investigate patients with a unilateral primary TKA for osteoarthritis, be published in English and within the past 20 years, and include two of the following three time points for the desired outcome measures: pre-surgery, 3 months post-TKA, and 6 months post-TKA. Additionally, motion analysis systems for data capture were required for all studies on gait and stair mechanics. Comparison to the non-operative limb or a control group was not required for inclusion, but these data have been included in the review when present. Revision TKAs were excluded due to the additional decline in outcomes and strength performance that are noted after this procedure [116, 117]. Lastly, gait and stair studies that included bilateral TKAs were excluded due to the potential influence of bilateral surgery on limb mechanics[118].

Data Extraction

Reporting for the current systematic review followed the Preferred Reporting Items for Systematic reviews and Meta-analysis (PRISMA) guidelines[119]. In cases in which the data were presented in graphical form, numerical values were estimated from the published graph(s) and figure(s) using NIH ImageJ software [18, 19, 46, 52, 99, 101, 120-124].

3.4 RESULTS

Selection of Studies

Forty-four studies were included in the review (17 for strength[12, 18, 19, 45, 46, 48-53, 122, 124-128], 3 for five-time sit-to-stand [49, 64, 65], 9 for walking gait[52, 72, 78-81, 103, 129, 130], 2 for stair navigation[72, 78], and 18 for KOOS scores[19, 97-101, 120, 121, 123, 129, 131-138]). Five studies were used for more than one outcome [19, 52, 72, 78, 129]. The most common reason for exclusion was lack of preoperative, 3 month, or 6 month post-TKA data. One gait study was excluded due to reporting coefficient of variance instead of discrete gait variables [139]. One KOOS study was excluded due to creating a hybrid measure from selected questions of the KOOS Activities of Daily Living (ADL) and Sports/Recreation subscales [140]. Figures 3.1A-D outline the flow of the selection process.

Study Characteristics

A summary of the included studies in each category is presented in Table 3.2. The number of subjects in each study ranged from 10 to 494 with 3,076 subjects overall (965 males, 2,012 females, 99 not stated). Ten studies included a control group and ranged from 10 to 30 subjects with 192 total subjects (57 males, 84 females, 51 not stated).

Outcome Measures

Muscle Strength

Quadriceps Strength

All but two studies reported strength deficits in the operative limb 3 months post-surgery compared to preoperative[50, 51]. In both instances, isokinetic knee extension was 5-7% improved in the operative knee 3 months after surgery. Of the included studies, quadriceps strength improved between 3 and 6 months for each study, but 4 out of 13 studies reported that the operative limb at 6 months remained weaker than preoperatively. Furthermore, compared to the nonoperative limb and a control group, the operative limb demonstrated reduced isokinetic and isometric strength preoperatively, 3 months, and 6 months post-TKA in 14 studies. Complete results are reported in Tables 3.3A and 3.3B.

Hamstring Strength

Six studies reported data for hamstring strength after TKA, with three of six reporting isokinetic strength data [48, 51, 128] and four of six reporting isometric [51, 53, 122, 125]. For isokinetic strength, the results are mixed. Lorentzen et al[51] reported increased isokinetic hamstring strength at 3 and 6 months compared to pre-operatively. However, at each time point the TKA limb was weaker than the nonoperative limb. Kim et al [48] reports a decrease at 3 months post-TKA compared to preoperative values, with values not significantly different at 6 months compared to preoperative. Rodgers et al[128] reported that the operative limb was weaker compared to the nonoperative prior to surgery, but strength values were equal 3 months post-surgery. Isometric hamstring strength results are also mixed. Calatayud et al. [125] and Lorentzen et al.[51] reported reductions postoperatively, while Judd et al.[122] found no difference preoperatively, 3 months post, or 6 months post. Another study found reductions in hamstring strength compared to a healthy group preoperatively and 6 months post-surgery, but no differences compared to the nonoperative limb at any time point [53].

Hip Abduction Strength

One study compared isometric hip abduction strength of the operative limb pre-operatively and 3 months postoperatively using a hand-held dynamometer [125]. Hip strength was reduced within the operative limb post-TKA, however, no comparisons to the nonoperative limb, a control group, or to 6 months post-surgery were made.

Five-time Sit-to-stand

Performance on the five-time sit-to-stand test was improved at both 3 months and 6 months post-operatively compared to pre-operative [49, 64, 65]. Further improvement was noted at 6 months compared to 3 months post-surgery [49]. However, due to the nature of these studies, statistical tests for significant differences between time points were not performed and none of the studies included comparison to a control group.

Gait Mechanics

Kinematics

There are no differences in sagittal plane knee motion during the first 3 months after TKA compared to preoperative motion [79, 103]. At 6 months post-TKA, two studies report that knee flexion motion is improved and is equal to the nonoperative limb [80, 130]. However, one of these studies along with one other demonstrated no change in peak knee flexion angle or knee flexion excursion during stance compared to preoperative values [80, 81].

Regarding frontal plane motion, no differences in peak knee adduction angle are noted compared to a control group but more frontal plane knee excursion is noted in the TKA group preoperatively and 3 months postoperatively compared to controls [78, 79]. After surgery, peak knee adduction angle is reduced 3 and 6 months postoperatively compared to preoperative values and a control group [78, 80, 81].

A single study reported hip kinematics and found that sagittal plane hip motion was reduced in the TKA group compared to controls[130]. Additionally, sagittal plane hip excursion reduced in the TKA limb 3 months after surgery compared with preoperatively[130].

Kinetics

Three studies investigated frontal plane knee moments [78, 80, 81]. Compared to a control group, TKA patients demonstrate a greater knee adduction moment prior to surgery[78]. Six months after TKA, knee adduction moment is not significantly different than the control group[78]. A similar reduction in knee adduction moment is noted at both 3 and 6 months postoperatively compared to preoperative values [80, 81].

Knee extensor moment differences have also been reported within 6 months after TKA. At 6 months postoperatively, knee extensor moment is reduced in TKA patients compared to controls[72]. Conflicting results were reported comparing 6 months knee extensor moment to preoperative values. One study reported a significant increase in knee extensor moment after surgery[80], while another reported no difference 6 months postoperatively[72].

Stair Mechanics

Only two studies have evaluated stair mechanics and only stair ascent was reported [72, 78]. Patients 6 months after TKA ascend stairs more slowly, with reduced stride length, reduced knee flexion angle, and reduced total lower extremity moment than a control group[72]. Additionally, no differences in frontal plane knee angle during stair ascent were observed between limbs or compared to a control group 6 months after TKA[78]. However, frontal plane knee moment was reduced in the TKA group after surgery compared to the control group[78].

KOOS Scores

A total of 18 studies reported at least one subscale of the KOOS. Of those, 14 presented data comparing 3 month scores to preoperative scores [19, 97-101, 129, 132-138]. All but 2 studies demonstrated an improvement in all subscales with the exception being the ADL subscale[136], Quality of Life subscale[136], and Symptom subscale[19], as each declined in a single study (Table 3.4A). Comparing 6 month scores to preoperative scores, only a single study [19] reported a 0.5% decline in the Symptoms subscale. All other studies reported improvement ranging from 6.5%[120] to 62.3%[101] (Table 3.4B). Lastly, 7 studies compared 3 month to 6 month scores and all demonstrated an improvement in all subscales [19, 97-101, 132].

3.5 DISCUSSION

This systematic review sought to determine changes in lower extremity muscle strength, functional performance as measured by the five-time sit-to-stand test, gait and stair mechanics, as well as KOOS scores during the first 6 months after TKA. The findings of this systematic review are pertinent to clinical practice and research related to rehabilitation after TKA. Patients undergo TKA to reduce pain and improve function. As the review has demonstrated, there are improvements in the KOOS while muscle strength, functional performance, and quantitative gait mechanics continue to demonstrate persistent deficits following surgery. This highlights the importance of pre-operative counseling with the patient to set appropriate expectations following surgery [141]. Additionally, these results emphasize the necessity of utilizing objective performance measures to determine recovery after TKA. The goals of rehabilitation are often to improve muscle strength, restore normal gait, and return the patient to independent functional mobility. Post-acute care costs account for nearly 45% of the total costs associated with TKA, which highlights the need for novel interventions to maximize outcomes within the first 3 months after surgery[110]. The early months after TKA represent the sole opportunity for rehabilitation to improve function and maximize patient ability in current health care practice. Given that deficits in strength, functional performance, gait, stairs, and patient reported abilities remain impaired for years after TKA [5, 6, 108, 111], a more thorough understanding of the deficits that exist after TKA is needed to identify the key modifiable factors early in rehabilitation that lead to the best long-term outcomes. The current systematic review highlights longitudinal changes across multiple domains that occur during post-operative periods when patients most likely have access to skilled rehabilitation and identifies key gaps in the literature in which additional research is needed.

Quadriceps strength is impaired at 3 months compared to preoperatively. All studies reported improvement in quadriceps strength from 3 to 6 months, but the operative limb remained weaker than the non-operative limb and the control groups. Less evidence was noted for changes in hamstring strength, but the operative limb is weaker than the nonoperative preoperatively, at 3 months, and at 6 months postoperatively. Mixed results were found for differences in hamstring strength of the operative limb at different time intervals. Additionally, there is limited evidence for changes in hip muscle strength post-TKA. Consistent with the findings of this systematic review, other systematic reviews and observational studies at various postoperative time points have identified quadriceps strength impairments after TKA [43, 142]. Quadriceps strength has been related to improvement in functional mobility after TKA and improving strength of this muscle group is a key component of postoperative rehabilitation [10, 105, 143, 144]. The mechanism behind continued quadriceps weakness has yet to be identified and research seeking to identify novel therapies to overcome post- strength deficits in a post-TKA population is ongoing [145-147]. Furthermore, the contribution of other lower extremity muscle groups to gait and functional ability after TKA have not been clearly established. Evidence is beginning to emerge linking hip abduction strength with improved mobility after TKA, but the time course of hip strength changes after TKA are not clearly established[17, 62]. Given the critical role of the hip muscles in providing stability during dynamic activities, additional research defining the contribution of hip muscle strength during the recovery of mobility during early postoperative periods after TKA is needed.

There is limited evidence for recovery of functional performance during the first 6 months after TKA as measured by the five-time sit-to-stand test. Three studies have reported improvement from pre-operative measures, but tests of statistical significance were not performed nor did the improvements exceed the minimal detectable change value of 2.5 seconds[63]. Tests of functional performance such as the five-time sit-to-stand are easily implemented in a clinical setting a represent an area of great potential for assessing recovery post TKA. One recent study noted that patients after TKA who exceeded the minimal detectable change in five-time sit-to-stand performance at 1 year post surgery compared to their pre-operative performance also demonstrated significant improvement in gait patterns [66]. These findings suggest that the five-time sit-to-stand test may serve as a valuable clinical measure of recovery after TKA. Additional studies are needed to determine the relationship of five-time sit-to-stand performance to specific gait parameters and the predictive properties of the test would improve the clinical utility of this functional performance measure.

Although impairments in sagittal and frontal plane knee mechanics of the operative knee have been reported across varying time points, there have been few studies reporting the longitudinal kinematic changes that occur during the first 6 months after TKA. Knee adduction moment is increased preoperatively compared to control groups, but the differences minimize 6 months after surgery. Knee extensor moment has been shown to be reduced preoperatively and possibly at 6 months after TKA. Reduced knee flexion angle and knee flexion excursion has been found after TKA, but the time course of gait kinematic and kinetic changes is not clear[108]. In bipedal tasks such as gait, the motion of one limb inherently influences the other and asymmetries in gait have been found to lead to further degeneration in the nonoperative limb[83]. A previous systematic review noted reduced knee flexion angle and knee flexion excursion in patients between 6 and 58 months post-TKA[108]. Asymmetrical gait patterns may lead to altered loading in the contralateral limb or in other joints of the operative limb. Changes in loading may have significant consequences as previous research demonstrated non-random evolution of degenerative joint osteoarthritis and subsequent joint replacement following unilateral joint replacement, with the contralateral joint most commonly requiring replacement [83]. Based on the current systematic review, sagittal plane kinematic asymmetries exist early is rehabilitation as well. One possible explanation for this gait pattern is the adoption of a "quadriceps avoidance" gait prior to TKA due to knee pain or postoperatively due to quadriceps weakness. The findings of consistent deficits both early after TKA and years later highlight the need for intervention to improve gait symmetry either before or after TKA as normal gait does not appear to be restored with time alone. The development of treatment strategies to restore knee flexion excursion and knee extensor moment either prior to TKA or during postoperative rehabilitation require additional understanding of the factors contributing to reduced sagittal plane knee motion.

With only two studies reporting stair ascent mechanics during the first 6 months post TKA, limited evidence exists for differences between-limbs or compared to a control group. Due to limited evidence, no sound conclusion can be made for longitudinal recovery of stair mechanics after TKA. Furthermore, data on stair descent was not reported in either study. Stair ascent and descent are tasks that patients after TKA report having the most difficulty performing [6]. Given the high proportion of dissatisfaction in their ability to perform this task, the limited number of studies investigating this task highlights a critical knowledge gap. In a systematic review of stair ascent, Standifird et al.[111] reports that one major limitation of the review stems from the inclusion of participants with varying post-surgical time points into the same study groups. This limitation creates difficulty in making accurate longitudinal comparisons or observations of recovery with increased time from surgery. The authors further report that caution should be used in assessing stair ability at very early time points in surgery[111]. However, identifying major kinetic and kinematic differences at an earlier time point (i.e. 3 months) would provide rehabilitation professionals with information regarding movement impairments that could be addressed prior to discharge from care. Furthermore, identifying early factors that most contribute to improved stair mechanics at later time points demands improved knowledge of motion at earlier postsurgical time points. Despite many patients specifically report stair negotiation as their most difficult task, impairments in this task are not given proportionate attention from the research community.

Data from the KOOS subscales demonstrates time-dependent improvement after TKA. Nearly all studies report improvement 3 months after TKA and additional subsequent improvement 6 months post-surgery. The subscale with the lowest relative score is most commonly the Sports/Recreation subscale. Given that this subscale reflects performance in higher level tasks, this finding is expected for this stage of recovery. Based on the findings of this systematic review, KOOS scores appear to improve independent of quadriceps strength, gait, and stair mechanics. Nearly all the articles reviewed report significant improvement with increased time after surgery. This would suggest that, for the first 6 months after TKA, time since surgery is influential in improving KOOS score. Differences of >10 points are considered clinically meaningful for the KOOS[88], and most of the studies in this review demonstrate meaningful improvement by 3 months post-TKA in the Pain, Symptoms, ADL, and Qualify of Life subscales. Improved KOOS scores, combined with other findings of this review, demonstrate that the patients' perception of function exceeds their actual physical function. The apparent disconnect between improvements in KOOS scores and improvements in physical measures warrants additional study. Previous work has demonstrated a strong correlation between KOOS Pain and ADL subscores, suggesting that as pain decreases the patients perceive their ability to perform ADLs is improved [100]. This suggests that reductions in pain are likely driving improvements in KOOS scores but do not influence physical performance. Given the long-term deficits noted in strength, gait, and stair navigation ability compared to relatively rapid improvement in KOOS scores, physical performance measures appear to be a better long-term outcome measure of a successful TKA than KOOS scores.

There are limitations to this review. A variety of implant types were compared and differences in location of the surgical incision may have affected the outcomes of specific studies. The limited number of studies that met the inclusion criteria for the outcomes of this review did not warrant additional study based on implant type or location of incision. Some longitudinal studies have noted that there is little difference in outcome with different implants or surgical approaches [148, 149]. However, it is possible that differences in femoral implant type, cruciate ligament management, soft tissue balancing techniques, articulation type (i.e. medial congruent), and location of incision may have a greater effect on strength and functional mobility during the first 6 months postoperatively which would warrant specific and separate analysis of these outcomes[48, 150, 151]. Furthermore, the lack of control participants and non-operative limb comparisons for some studies may underrepresent the level of impairment observed in patients after TKA. A recent study found that function of the non-operative limb was the best predictor of long-term outcomes in walking and stair climbing abilities following TKA so without a reference to the non-operative limb or a control group, comparisons of strength and functional mobility may be less sensitive[54]. Lastly, comparisons between sexes were not performed in any of the studies reported in this review despite females accounting for at least 62 percent of total subject pool. Future studies on sex differences are warranted as unique anatomical and physiological sex-specific processes may influence the outcomes utilized in this review [152].

The results of this systematic review highlight the need for longitudinal studies of strength and functional mobility preoperatively through the first 6 months postoperatively. This time period represents a potential period of rapid progress and is most likely the only period in which patients have access to skilled rehabilitation. A greater understanding of impairments in strength, gait, and stair mechanics early in post-operative care would be beneficial to both the clinical and research communities as clinicians would be able to determine if patients are making adequate progress throughout rehabilitation and effectively utilize shrinking post-operative resources. Researchers should continue to investigate novel interventions to address early impairments to improve long-term outcomes and identify primary early milestones that best predict a desirable postoperative outcome.

3.6 CONCLUSION

While patient-reported symptoms consistently improve during the early postoperative period, quadriceps weakness is present throughout the first 6 months after TKA. Furthermore, there is limited evidence on changes in leg muscle strength, functional performance, and gait and stair mechanics during the first 6 months after TKA. Physical performance measures demonstrate persistent deficits after TKA that may not be accurately measured by patient reported outcomes. Thus, physical performance tests should be used to assess longitudinal outcomes after TKA and relationships between these objective measures should be evaluated to improve clinical decision making during rehabilitation after TKA.

Table 3.1: Search terms utilized for A) Population, B) Muscle Strength, C) Five-time Sit-to-stand, D) Gait, E) Stairs, and F) KOOS.

A) Population

Search Number	Terminology
1	Arthroplasty
2	Replacement
3	Knee Prosthesis
4	Knee Replacement
5	Total Knee Replacement
6	Knee Arthroplast*
7	Total Knee Arthroplast*
8	Knee Prosthes*
9	TKR
10	TKA
11	Joint Replacement*
12	Arthroplast*
13	1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12

B) Leg Strength

Search Number	Terminology
14	Muscle*
15	Knee
16	Hip
17	Lower Extremity
18	Quadricep*
19	Hamstring*
20	Knee Extens*
21	Knee Flex*
22	Glute*
23	Hip Abduct*
24	Hip Adduct*
25	Hip Extens*
26	14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25
27	Muscle Strength
28	Torque
29	Muscle Weakness
30	Muscular Atrophy
31	Strength
32	Force
33	Isometric
34	Isokinetic
35	Dynamometer
36	Weak*
37	Atrophy
38	27 or 28 or 29 or 30 or 31 or 32 or 33 or 34 or 35 or 36 or 37
39	13 and 26 and 38

Table 3.1 (continued)

C) Five-time Sit-to-Stand

Search Number	Terminology
14	Sit to stand test
15	Five time sit-to-stand
16	1 or 2

D) Gait

Search Number	Terminology
14	Gait
15	Walk*
16	14 or 15
17	Motion
18	Kinematics
19	Kinetics
20	Biomechanics
21	Mechanics
22	17 or 18 or 19 or 20 or 21

E) Stairs

Search Number	Terminology
14	Gait
15	Walk*
16	Step*
17	Ascent
18	Descent
19	Stair*
20	Climbing
21	14 or 15 or 16 or 17 or 18 or 19 or 20
22	Motion
23	Kinematics
24	Kinetics
25	Biomechanics
26	Mechanics
27	22 or 23 or 24 or 25 or 26
28	13 and 21 and 27

F) KOOS

Search Number	Terminology
14	KOOS
15	Knee Injury and Osteoarthritis Outcome Score
16	14 or 15
17	13 and 16

Table 3.2: General Descriptions of Included Studies

Study	TKA Subjects Mean (SD)						Control Subjects Mean (SD)				Outcome
	Sample Size	Age (yrs)	Sex (M/F)	BMI (kg/m^2)	Time Points	Prosthesis Type/Surgical Approach	Sample Size	Age (yrs)	Sex (M/F)	BMI (kg/m^2)	
Abdel[129]	40	71	16/24	29.15	Pre,3	PS					Gait, KOOS
Alice[79]	90	68 (7.5)	36/54	30.7 (5.7)	Pre,3	PS	23	64.8 (8.3)	10/13	24.5 (3.4)	Gait
Arnold[80]	15	67.8 (10.4)		31.8 (5.5)	Pre,6						Gait
Bade[45]	24	65 (9.4)	12/12	30.7 (4.1)	Pre,3,6		17	66.8 (6.5)	9/8	27.2 (3.5)	Strength
Bejek[130]	45	68.3	22/23		Pre,3,6		21	76	9/12		Gait
Calatayud[125]	44	66.8	7/37	31.5	Pre,3	CR					Strength
Christiansen[49]	36	63.4 (7.7)	13/23		Pre,3,6						Strength, STS
Christiansen[64]	26	67.4 (8.4)	13/13		Pre,6						STS
Davis[131]	44	64.2 (11.5)	11/33		Pre,6						KOOS
Davis[132]	494	65 (10)	173/321		Pre,3,6						KOOS
Dere[133]	78	66.5 (5.8)	0/78		Pre,3						KOOS
Ejaz[120]	64	68 (8)	35/29		Pre,6						KOOS
Gapeyeva[46]	10	64	0/10	30	Pre,6	CR & PS/Medial parapatellar	10	64	0/10	27	Strength
Gothesen[134]	189	68	72/117		Pre,3						KOOS

Table 3.2 (continued)

Study	TKA Subjects Mean (SD)						Control Subjects Mean (SD)				Outcome
	Sample Size	Age (yrs)	Sex (M/F)	BMI (kg/m^2)	Time Points	Prosthesis Type/Surgical Approach	Sample Size	Age (yrs)	Sex (M/F)	BMI (kg/m^2)	
Huang[121]	43	70.5 (7.6)	0/43	28.5 (3.2)	Pre,6						KOOS
Huber[136]	45	70.4	24/21	30.3	Pre,3	CR/Medial parapatellar					KOOS
Huber[135]	44	70.61 (8.1)	24/20	30.3 (5.2)	Pre,3						KOOS
Judd[122]	20	65.1 (7.8)	7/13	29.7 (4.3)	Pre,3,6	Medial parapatellar					Strength
Kim[38]	22	68	0/22	28.4	Pre,3,6	Medial parapatellar	30	66		27.3	Strength
Liebensteiner[103]	20	72			Pre,3	Medial parapatellar					Gait
Lorentzen[51]	30	74	5/25	30	Pre,3,6						Strength
Mandeville[72]	22	62.6	6/16	32.6 (1.08)	Pre,6	PS & CR	22	62.7	8/14	26.6 (0.73)	Stair, Gait
Mandeville[78]	21	62.8 (1.65)		32.9 (1.12)	Pre,6	PS	21	62.85 (0.9)		26.6 (0.73)	Stair, Gait
Mills[97]	272		84/188	30.3 (6.4)	Pre,3,6						KOOS
Minns Lowe[98]	107	69.23	45/62	30.34	Pre,3,6						KOOS
Mizner[12]	40	64 (9)	22/18	31.4 (3.7)	Pre,3,6						Strength
Molt[137]	60	67.5	21/39	28.8	Pre,3						KOOS
Nerhus[99]	50	70	17/33		Pre,3,6						KOOS
Nilsdotter[123]	102	76	39/63		Pre,6						KOOS
Orishimo[81]	15	65	7/8		Pre,6	PS					Gait

Table 3.2 (continued)

Study	TKA Subjects Mean (SD)						Control Subjects Mean (SD)				Outcome
	Sample Size	Age (yrs)	Sex (M/F)	BMI (kg/m^2)	Time Points	Prosthesis Type/Surgical Approach	Sample Size	Age (yrs)	Sex (M/F)	BMI (kg/m^2)	
Petterson[124]	61		27/34		Pre,3						Strength
Pua[127]	441	67.9 (7.8)	83/358	27.9 (4.8)	Pre,6						Strength
Pua[126]	85	67 (8)	24/61	26 (4.8)	Pre,3						Strength
Rodgers[128]	20	67.5	9/11		Pre,3	PS					Strength
Schroer[50]	50	68 (8)	15/35	33.2 (6)	Pre,3,6	PS/Mini subvastus					Strength
Shin[65]	87	71.6 (6.5)	9/78	25.5 (3.4)	Pre,3						STS
Stevens-Lapsley[147]	30	64.3 (9.2)	17/13	29.8 (4.3)	Pre,3,6	CR/Medial Parapatellar	15	66.5 (6.5)	9/6	27.1 (3.5)	Strength
Stevens-Lapsley[100]	39	64 (8.2)	17/22	29.1 (5.2)	Pre,3,6						KOOS
Thewlis[101]	10	64.7 (7.7)	5/5		Pre,3,6						KOOS
Vahtrik[19]	12	61	0/12	33	Pre,3,6						Strength, KOOS
Vahtrik[52]	13	60	0/13	33	Pre,3,6		10	47 - 70	0/10	27 - 38	Strength, Gait
Villadsen[138]	81	66.1	32/49	32.1	Pre,3						KOOS
Winters[18]	35	63.6 (7.9)	16/19		Pre,6		23	65.6 (0.9)	12/11		Strength

Table 3.3A: Absolute Quadriceps Strength

Study	Test Mode	Unit	Absolute Knee Extension Strength, mean (SD)						
			TKA operative			TKA nonoperative			Control
			Pre	3 Months	6 Months	Pre	3 Months	6 Months	
Bade[45]	Isometric 60°	Nm/kg	1.3 (0.5)	1.1 (0.5)	1.2 (0.5)				2.1 (0.5)
Lorentzen[51]	Isokinetic 30°/s	Nm	57	55	67	67	78	79	
	Isokinetic 120°/s	Nm	37	39	42	52	52	53	
	Isometric 75°	Nm	66	55	65	87	92	92	
Kim[48]	Isokinetic 60°/s	Nm	45.8	39.3	49.8				76.3
Vahtrik[19]	Isometric 90°/s	N	260	151	186	326	291	318	
Stevens-Lapsley[147]	Isometric 60°	Nm	121.7 (45.7)	100.4 (46.8)	113.3 (45.9)	154.2 (52.8)	146.8 (45.8)	145.9 (47.6)	165.3 (57.9)
Winters[18]	Isometric 60°	Nm	120		125				171
Pua[126]	Isometric 75°	Nm/kg	1.12 (.48)	1.03 (.09)					
Pua[127]	Isometric 30°	%BW	18	25.6					

Table 3.3A (continued)

Study	Test Mode	Unit	Absolute Knee Extension Strength, mean (SD)						
			TKA operative			TKA nonoperative			Control
			Pre	3 Months	6 Months	Pre	3 Months	6 Months	
Mizner[12]	Isometric 75°	N/BMI	18	15	18	23	23	23	
Schroer[50]	Isokinetic 60°/s	ft*lb	41.6	44.7	49.6	44.8	52.4	51.7	
Petterson[124]	Isometric 75°	N	576	509		730	708		
Gapeyeva[46]	Isometric 90°	N/kg	2.24		2.4	3.32		3.5	4.27
Judd[122]	Isometric 60°	Nm/kg	1.33	1.2	1.37				
Rodgers[128]	Isokinetic 60°/s	ft*lb	55	54.5		77	76		
	Isokinetic 180°/s	ft*lb	39.5	37.5		46	46		
Calatayud[125]	Isometric	kg	23.5	18.55					

TKA: Total Knee Arthroplasty Group, Nm: Newton*meters, N: Newtons, Nm/kg: Newton*meters per kilogram body weight, %BW: percentage of total body weight, N/BMI: Newtons per Body Mass Index, ft*lb: foot-pound, kg: kilogram, /s: per second

Table 3.3B: Percent Difference in Quadriceps Strength

Study	Test Mode	Percent Differences Quadriceps Strength (%)								
		Operative time point comparisons			Operative vs Nonoperative			Operative vs Control		
		3 - Pre	6 - Pre	6 - 3	Pre	3 Months	6 Months	Pre	3 Months	6 Months
Bade[45]	Isometric 60°	-16.67	-8.0	16.67				-47.06	-62.5	-54.55
Lorentzen[51]	Isokinetic 30°/s	-3.57	16.13	19.67	-16.13	-34.59	-16.44			
	Isokinetic 120°/s	5.26	12.66	7.41	-33.71	-28.57	-23.16			
	Isometric 75°	-18.18	-1.53	16.67	-27.45	-50.34	-34.4			
Kim[48]	Isokinetic 60°/s	-15.28	8.37	23.57				-49.96	-64.01	-42.03
Vahtrik[19]	Isometric 90°/s	-53.04	-33.18	20.77	-22.53	-63.35	-52.38			
Vahtrik[52]	Isometric Leg Press	-17.92	2.25	20.14	-25.95	-45.68	-45.69	-57.32	-73.35	-55.25
Stevens-Lapsley[147]	Isometric 60°	-19.18	-7.15	12.07	-23.56	-37.54	-25.14	-30.38	-48.85	-37.33
Winters[18]	Isometric 60°		4.08					-35.05		-31.08
Pua[126]	Isometric 75°	-8.37								
Pua[127]	Isometric 30°	-34.86								

Table 3.3B (continued)

Study	Test Mode	Percent Differences Quadriceps Strength (%)								
		Operative time point comparisons			Operative vs Nonoperative			Operative vs Control		
		3 - Pre	6 - Pre	6 - 3	Pre	3 Months	6 Months	Pre	3 Months	6 Months
Mizner[12]	Isometric 75°	-18.18	0	18.18	-24.39	-42.11	-24.39			
Schroer[50]	Isokinetic 60°/s	7.18	17.54	10.39	-7.4	-15.86	-4.15			
Petterson[124]	Isometric 75°	-12.35			-23.58	-32.7				
Gapeyeva[46]	Isometric 90°		6.9		-38.85		-37.29	-62.37		-56.07
Judd[122]	Isometric 60°	-10.28	2.96	13.23						
Rodgers[128]	Isokinetic 60°/s	-0.91			-33.33	-32.95				
	Isokinetic 180°/s	-5.2			-15.2	-20.36				
Christiansen[49]	Isometric 60°				-24.72	-27.27	-16.22			
Calatayud[125]	Isometric	-23.54								

3/3 Months: 3 months postoperative, Pre: preoperatively, 6/6 months: 6 Months postoperative, operative: surgical limb, nonoperative: nonsurgical limb, /s: per second

Table 3.4A: KOOS Subscale Absolute Scores

Study	KOOS Subscale Scores														
	Preoperative					3 Months					6 Months				
	P	Sy	A	Sp/R	Q	P	Sy	A	Sp/R	Q	P	Sy	A	Sp/R	Q
Abdel[129]	22	22	34	18	21	35	37	49	26	28					
Davis[131]	44.7										63.1				
Davis[132]	48					76					79				
Dere[133]	26.78	36.44	24.78	2.88	7.41	93.62	94.76	93.59	20.68	80.04					
Ejaz[120]	39.5	59.9	59.9	15.8	24.84						89.1	89.75	86.6	22.3	81
Gothesen[134]	45.4	53.75	49.7	29.5	39.05	68.95	63.85	73.3	43.85	70.45					
Huang[121]	51.5	48.9	57.4	17.3	30.9						71	76.14	78.2	40.4	55.6
Huber[136]			53.61					77.15							
Huber[135]	48.1	47.4	51.7	18.3	26.4	44.8	52	46.8	19.3	20.5					
Mills[97]	47.56	47.31	49.37	27.9	29.95	53.61	52.69	56.25	29.65	37.86	57.01	53.98	58.75	31.4	47.32
Minns Lowe[98]	40	39.3	44.7	11.3	23.45	70.65	69.65	72.5	36.7	54.7	75	74.1	75.1	42.5	59.4
Molt[137]	42.5	51.5	48	8.5	25	70.5	67.5	73	23.5	54					
Nerhus[99]	43.3	46.4	49.1	11.4	25.7	74.5	53.9	80.3	13.5	53.6	80.6	66.7	83.6	31.9	64.8
Nilsdotter[123]	39.5	41.5	48.3	17.7	19.5						79.6	73.5	78.5	48.5	60.3
Stevens-Lapsley[100]	48.22	48.08	58.33	18.72	26.12	75.28	66.21	84.35	49.23	63.3	80.94	72.37	87.92	50.53	66.96
Thewlis[101]	37	41.1	42.2	7.6	10.4	65.4	62.2	69.5	28.6	54.7	85.4	76.3	85.4	46.4	72.7
Vahtrk[19]	56.1	59.3	63.3	19	28.5	68.3	47.5	75.6	29	38	78.3	58.8	84.6	46.2	62
Villadsen[138]	43.75	53.55	48.6	15.35	29	65.9	80.45	73.05	20.6	52.75					

3 Months: 3 months postoperatively, 6 months: 6 months postoperatively, P: Pain subscale, Sy: Symptom subscale, A: ADL subscale, Sp/R: Sports/Recreation subscale, Q: Quality of Life subscale. Scores range from 0 – 100 with 100 representing the no impairment.

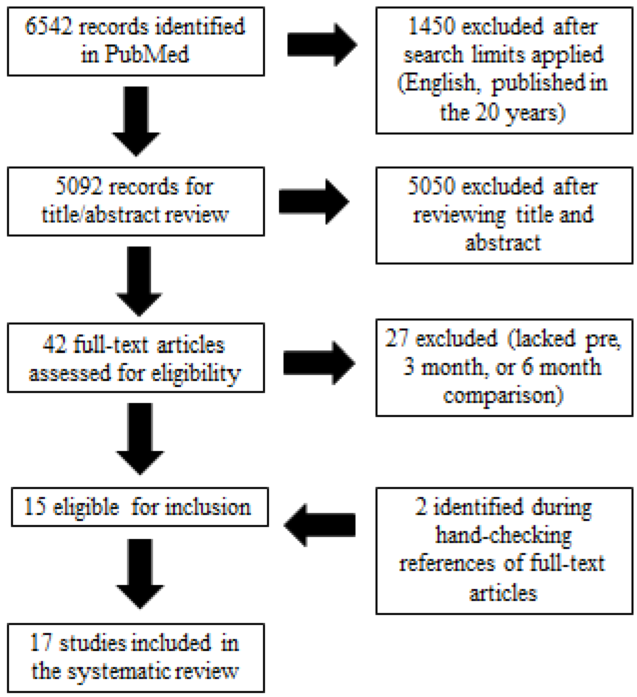
Table 3.4B: KOOS Subscale Percent Change

Study	Change in KOOS Subscale Scores (%)														
	3 Month compared to Preoperative					6 Month compared to Preoperative					6 Month compared to 3 month				
	P	Sy	A	Sp/R	Q	P	Sy	A	Sp/R	Q	P	Sy	A	Sp/R	Q
Abdel[129]	+13	+15	+15	+8	+7										
Davis[131]						+18.4									
Davis[132]	+28					+31					+3				
Dere[133]	+66.8	+58.3	+68.8	+17.8	+72.6										
Ejaz[120]						+49.6	+29.9	+26.7	+6.5	+56.2					
Gothesen[134]	+23.6	+10.1	+23.6	+14.4	+31.4										
Huang[121]						+19.5	+27.2	+20.8	+23.1	+24.7					
Huber[136]			23.54												
Huber[135]	-3.3	+4.6	-4.9	+1.0	-5.9										
Mills[97]	+6.05	+5.4	+6.9	+1.75	+7.9	+9.45	+6.7	+9.4	+3.5	+17.4	+3.4	+1.3	+2.5	+1.75	+9.5
Minns Lowe[98]	+30.7	+30.4	+27.8	+25.4	+31.3	+35	+34.8	+30.4	+31.2	+36	+4.3	+4.4	+2.6	+5.8	+4.7
Molt[137]	+28	+16	+25	+15	+29										
Nerhus[99]	+31.2	+7.5	+31.2	+2.1	+27.9	+37.3	+20.3	+34.5	+20.5	+39.1	+6.1	+12.8	+3.3	+18.4	+11.2
Nilsdotter[123]						+40.1	+32	+30.2	+30.8	+40.8					
Stevens-Lapsley[100]	+27.1	+18.1	+26	+30.5	+37.2	+32.7	+24.3	+29.6	+31.8	+40.8	+5.6	+6.2	+3.6	+1.3	+3.6
Thewlis[101]	+28.4	+21.1	+27.3	+21	+44.3	+48.4	+35.2	+43.2	+38.8	+62.3	+20	+14.1	+15.9	+17.8	+18
Vahtrk[19]	+12.2	-11.8	+12.3	+10	+9.5	+22.2	-0.5	+21.3	+27.2	+33.5	+10	+11.3	+9	+17.2	+24
Villadsen[138]	+22.2	+26.9	+24.5	+5.3	+23.8										

3 Month: 3 months postoperatively, 6 month: 6 months postoperatively, P: Pain subscale, Sy: Symptom subscale, A: ADL subscale, Sp/R: Sports/Recreation subscale, Q: Quality of Life subscale. Positive values represent an improvement in subscale score.

Figure 3.1: Flow Diagrams for literature search for A) Muscle Strength, B) Five-time Sit-to-Stand, C) Gait, D) Stairs, and E) KOOS.

A.



B.

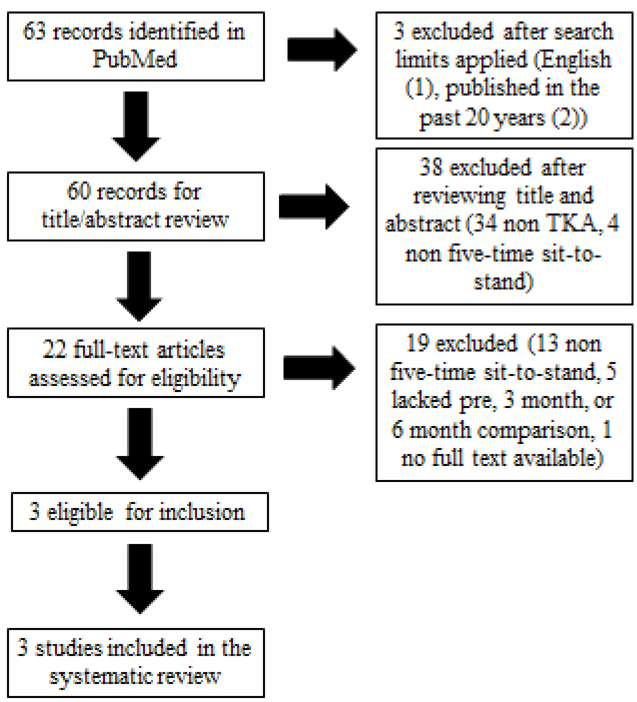
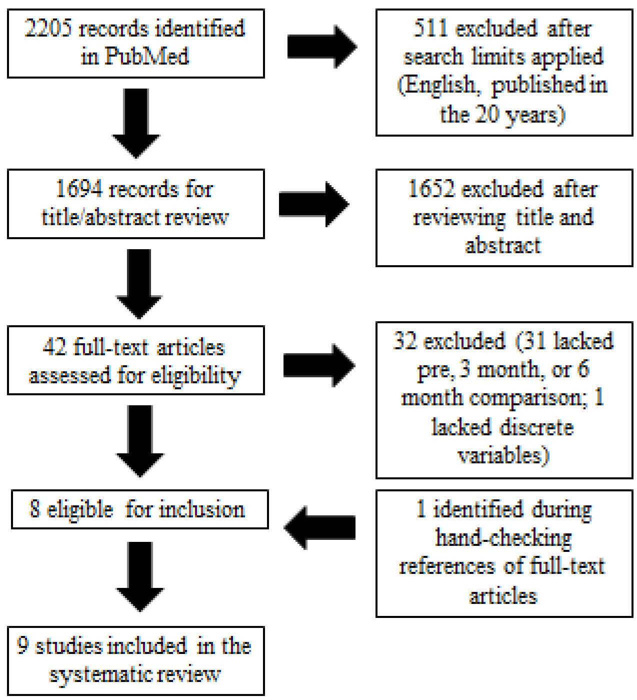


Figure 3.1 (continued)

C.



D.

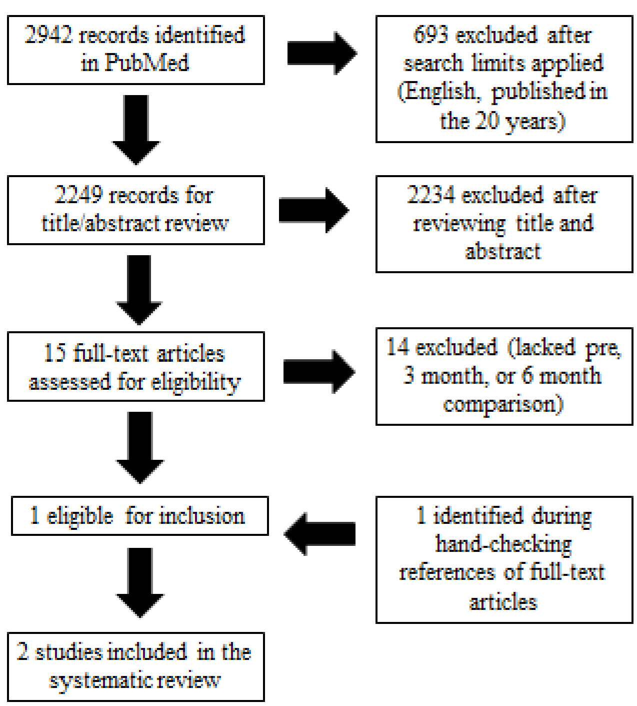
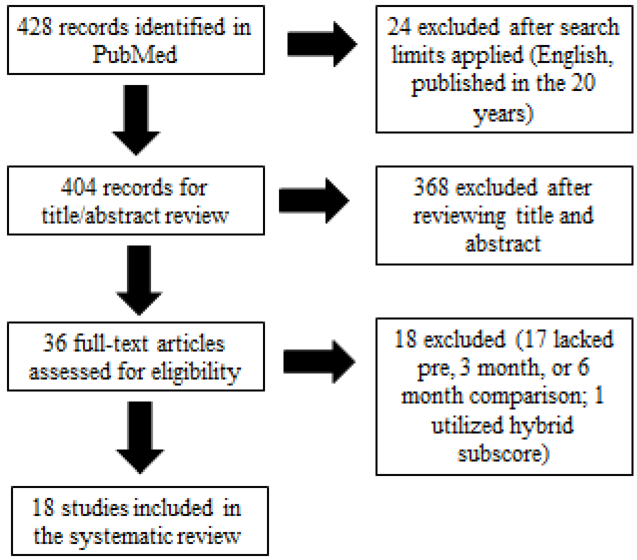


Figure 3.1 (continued)

E.



Chapter 4: Persistent Impairments in Muscle Strength, Functional Performance, Gait Mechanics, and Patient-Reported Outcomes after Total Knee Arthroplasty

4.1 ABSTRACT

Purpose and Hypothesis: Impairments in quadriceps strength and knee mechanics are observed after total knee arthroplasty (TKA). However, few studies have documented potential hip muscle weakness, hip mechanical deficits after TKA, or investigated recovery across multiple domains of physical function including both subjective and objective measures. It was hypothesized that 1) significant improvements would be observed in the TKA group at 6 months compared to 3 months in all domains, 2) significant impairments will persist at 6 months post-surgery compared to matched controls, and 3) subjective measures will demonstrate greater relative improvement compared to objective measures.

Methods: Patients after unilateral TKA were assessed at 3 and 6 months post-surgery and compared to matched controls. Assessments were performed in four domains: 1) hip and knee peak isometric strength and rate of torque development (RTD), 2) five-time sit-to-stand test (FTSTS), 3) motion analysis of walking and stair descent, and 4) the Knee Injury and Osteoarthritis Outcome questionnaire (KOOS). Between-limb and within-limb comparisons of the TKA group were made using two-tailed paired samples t-tests. To compare between-groups, independent two-sample t-tests were utilized. Effect sizes were calculated using Cohen's d to further compare changes in the TKA group between 3 and 6 months post-surgery.

Results: Thirty-nine subjects, 21 TKA (7 M, Age: 60.6 ± 8.1 years, BMI: 32.3 ± 7.4 kg/m^2) and 18 controls (7 M, Age: 61.2 ± 8.8 years, BMI: 29.2 ± 5.5 kg/m^2) were tested.

At both 3 and 6 months post-surgery, the TKA group demonstrated significantly less peak hip external rotation and quadriceps muscle strength and reduced RTD, lower KOOS scores, poorer FTSTS performance, and impaired gait mechanics of the hip and knee compared to control subjects. Significant improvements were observed in the TKA group between 3 and 6 months in all domains except gait mechanics as knee flexion excursion remained significantly reduced and hip abduction moments remained elevated. KOOS scores and FTSTS demonstrated the greatest improvement between 3 and 6 months.

Conclusion: Patients with unilateral TKA have persistent impairments compared to controls. The greatest improvements were observed in FTSTS and KOOS scores, indicating that muscle weakness and lower extremity mechanical impairments of the hip and knee may require more time or additional intervention for recovery. During walking, patients with TKA utilize greater hip moments for stability as a possible compensation for impaired quadriceps muscle strength or knee joint function. These findings suggest incomplete recovery and highlight a need for additional strategies to restore normal function after TKA.

4.2 INTRODUCTION

More than 600,000 total knee arthroplasties (TKA) are performed annually in the United States[1]. Due to the projected increase of older adults and high rates of obesity, the number of TKA's performed per year is expected to increase by 673% in the next 15 years[2]. Rehabilitation for TKA typically concludes within 2 to 3 months after surgery [3]. After this time, continued improvements are expected to occur with time. Given this expected increase in demand for TKA, a thorough understanding of outcomes during the early post-rehabilitative period following this procedure is critical.

Use of patient-reported outcome questionnaires and patient satisfaction scales are common after TKA, with the Knee Injury and Osteoarthritis Outcome Score (KOOS) one of the most frequently used [88, 112]. While patients report good overall satisfaction with their outcome and demonstrate increased KOOS scores after TKA, multiple studies have reported persistent physical impairments in muscle strength, functional performance, and gait mechanics indicating possible incomplete recovery from surgery [5-7, 105-107]. For this reason, there is a growing need to quantify recovery after TKA using a variety of physical measures in addition to subjective patient-reported measures. Previous studies have included objective measures of quadriceps muscle strength, functional performance, and three-dimensional motion analysis of gait and daily activities [12, 52, 153, 154].

Quadriceps muscle weakness after TKA may persist for years after surgery and has been associated with declined functional ability, asymmetrical gait mechanics, reduced patient satisfaction, and poor-patient reported outcomes [10, 43, 127, 142]. In addition to peak quadriceps strength, preliminary studies show quadriceps rate of torque development (RTD) may serve as a more sensitive indicator of recovery after TKA [18, 144]. Beyond the quadriceps, patients with greater peak isometric hip abduction strength demonstrate better functional performance in walking and stair climbing [17, 62]. Despite these early findings, few studies comparing quadriceps RTD and hip muscle strength (both peak and RTD) of the operative to the non-operative limb or to a control group exist. Unidentified deficits in quadriceps RTD and hip muscle strength and RTD may contribute to continued mobility deficits in patients after TKA, but these measures have yet to be explored.

As an alternative means of assessing muscle strength, the five-time sit-to-stand test (FTSTS) is an easily administered clinical test that measures functional performance and is strongly associated with leg strength [20, 155, 156]. Improvements in the FTSTS have been associated with more symmetrical gait mechanics after TKA, but the few studies that have longitudinally explored recovery of FTSTS performance after TKA have noted minimal improvement [49, 64-66].

Lastly, asymmetrical gait mechanics, especially knee kinematics and kinetics, have been documented as many as 3 years after TKA and are associated with decreased functional ability [15, 60]. To date, studies have focused on knee mechanics with minimal investigation into hip mechanics. As coupled joints, a thorough understanding of hip mechanical adaptations to TKA is needed in order to consider other possible etiologies of abnormal knee mechanics. Furthermore, although walking is an essential daily activity, patients after TKA often report the most difficulty with stair negotiation, specifically stair descent, a task that is more demanding than level walking [6, 85, 157]. Patients may be able to compensate for muscular impairments after TKA during walking and other lower demand tasks, but face difficulty when the demands of the task exceed their capacity for compensation. For these reasons, it is likely that the inclusion of hip mechanics in gait analyses and assessment of stair descent may provide an additional means of quantifying recovery after TKA.

The purpose of this study is to quantify post-rehabilitative recovery in four domains: 1) muscle strength of hip abduction, hip external rotation, and quadriceps muscle performance, 2) FTSTS performance, 3) gait and stair descent biomechanics, and 4) KOOS scores at 3 and 6 months post unilateral TKA and compared to sex-,age-, and body mass index-matched controls. Our hypotheses for three-fold: 1) significant improvements in all 4 domains would be observed in the TKA group at 6 months compared to 3 months, 2) significant impairments in all 4 domains would persist at 6 months post-surgery compared to matched controls, and 3) subjective patient-reported outcome measures will demonstrate greater relative improvement between 3 and 6 months post-surgery compared to objective physical measures of muscle strength, five-time sit-to-stand, and gait and stair descent biomechanics in the TKA group.

4.3 METHODS

<u>Study Design and Participants</u>

The study protocol was approved by the University Institutional Review Board. All participants read and signed an informed consent form prior to participation. Participants included in the TKA group were recruited from eligible patients at the University's orthopedic clinic and local outpatient physical therapy clinics. Inclusion criteria included: 1) between the ages of 40-90 years old, 2) undergone unilateral TKA within the past 3 months. Exclusion criteria included: 1) prior surgery to the contralateral knee, low back, or either hip, ankle, or foot, and 2) presence of neurological or balance disorder that requires use of an assistive device for mobility, and 3) inability to walk at least 10 minutes without an assistive device. Patients with contralateral knee osteoarthritis were not excluded from the study; however, if the contralateral knee was rated as more symptomatic than the TKA limb at 3 months post-surgery or the participant was scheduled for contralateral TKA within the next 3 months, the participant was excluded. All patients completed rehabilitation in community outpatient clinics as is the standard of care.

Participants included in the control group were taken from a sample of convenience from the community using flyers, digital displays, research participant registries, and word of mouth. To be included, all control subjects were required to be free of previous surgery and current injury in lower back and lower extremity joints, and match a TKA participant in sex, age, and body mass index.

Outcomes

Muscle Strength

All participants completed a series of isometric strength tests including: hip abduction, hip external rotation, and knee extension. All strength tests were performed using a Biodex System 4 (Biodex Systems, Shirley, NY). Hip abduction was assessed with the participant in sidelying, the hip neutrally positioned in the sagittal, frontal, and transverse plane. While in sideyling, with the superior limb as the test leg, the dynamometer arm was secured 5 cm proximal to the lateral tibiofemoral joint. Participants were instructed to raise their limb towards the ceiling. Hip external rotation was assessed in sitting, with the hip flexed to 85°, knee flexed to 90°, and hip in neutral rotation. The dynamometer arm was secured 5 cm proximal to the medial malleolus.

Participants were instructed to rotate their limb as if they were looking at the bottom of their shoe. For both hip abduction and hip external rotation, one practice trial and four experimental trials were performed for five seconds, with 30 seconds of rest between trials. For knee extension, participants were seated with the hips flexed to 85°, knees flexed to 90°, with the dynamometer secured 5 cm proximal to the medial malleolus. The participants were instructed to extend their knee as if to kick forward. One practice trial and three experimental trials were performed. Verbal encouragement was provided during all strength tests and patients were asked to give maximal effort with each experimental trial by performing the motion of interest with as much force and as quickly as possible.

Peak strength values and rate of torque development (RTD) were calculated for each experimental trial and an average calculated for each variable to be used in statistical analyses. To allow for comparison between groups, all experimental trials were normalized to body mass by dividing peak strength and RTD values by the subject's mass in kilograms. To calculate RTD, custom MATLAB code (MathWorks Inc, Natick, MA) was used to calculate the mean slope of the torque-time curve over the first 200 milliseconds of the linear portion between the onset of the trial and peak torque[158].

Five-time Sit- to-Stand

The five-time sit-to-stand (FTSTS) is a standardized clinical test used to quantify function in patients with a variety of orthopedic impairments. To complete the test, participants were asked to sit in an armless chair with a 42.0 cm seat height and complete five consecutive sit-to-stands as quickly as possible. Foot placement was not constrained and participants were not permitted to place their hands or other parts of their upper extremities on their lower limbs in order to prevent facilitation during either the rise or descent portions of the task. Time to complete the test was measured using a hand-held stopwatch. Time began upon initiation of the task from a seated position and stopped when the patient returned a sitting position after the 5th sit-to-stand. Two trials were allowed, with the fastest trial used for data analysis.

Gait Mechanics

All participants were outfitted with 32 anatomical and 24 tracking markers as previously noted in the literature[158]. Anatomical markers were placed on the following locations: sternal notch, spinous process of the 7th cervical vertebra, bilateral superior acromial processes, posterior 5th lumbar/1st sacral intervertebral joint, bilateral superior iliac crests, bilateral greater trochanters, bilateral posterior superior and anterior superior iliac spines, bilateral medial and lateral distal femurs, bilateral medial and lateral proximal tibias, bilateral medial and lateral malleoli, bilateral first and fifth metatarsal heads, and bilateral distal feet. Rigid plates with 4 tracking markers each were secured to bilateral thigh and shank segments. On each rearfoot, a single marker was placed on the proximal, distal, and lateral heel to track the foot segment. All participants wore neutral athletic shoes (New Balance 662, New Balance Athletic Shoe Inc., Boston, MA). Participants walked at a self-selected speed on an instrumented treadmill (Bertec, Columbus, OH) for approximately 5 minutes.

Stair Descent Mechanics

All participants also underwent motion analysis while descending a 20.3 cm step. Participants began on top of the step and were instructed to descend the step in a controlled manner and continue walking forward. Five complete trials were recorded with each limb as the landing limb during the step descent. In order for a trial to be considered complete, the participant was required to control the descent, land with the entire landing limb on the force plate, and continue walking forward at least 2 steps. For data analysis, the landing limb was defined as the limb advancing forward off the step to initially make contact with the force plate. The stance limb was defined as the limb remaining on the step during the lowering phase of the task.

Biomechanical Data Reduction

During both gait and stair descent tasks, marker trajectories were recorded using a 10-camera motion analysis system (Motion Analysis Corp, Santa Ana, CA) with sampling rate of 200 Hz. Force-plate data were simultaneously recorded at 1200 Hz from an instrumented Bertec treadmill (Bertec, Columbus, OH). Visual 3D software (C-Motion) was used to filter the data, calculate joint angles, and perform inverse dynamics to determine joint moments. Marker position and force data were filtered at 8 and 35 Hz, respectively, using a fourth-order, low-pass, zero-lag Butterworth filter. Angles and moments were calculated using Cardan XYZ angles referencing the distal segment to the proximal. Joint moments were normalized to body mass and height. Custom MATLAB code was used to extract ground reaction force data as well as sagittal and frontal plane kinetics and kinematics of the hip and knee.

KOOS and PASE

All participants completed the KOOS, which features five individual subscales: symptoms, pain, function in activities of daily living, function in sport and recreation, and knee-related quality of life. Each subscale is scored between 0 to 100 with 0 representing “worst” and 100 representing “best”. The KOOS is reliable in patients after TKA and has demonstrated adequate test-retest reliability [88, 112].

Participants also completed the Physical Activity Scale for the Elderly (PASE), a recall questionnaire that was specifically designed for individuals 65 years and older. It assesses frequency, duration, and intensity of activities performed during the previous week. The PASE has been shown to reliable in patients with knee osteoarthritis. Scores range from zero (least active) to 361 (most active)[159].

<u>Statistical Methods</u>

Between-limb (operative vs non-operative) and within-limb (3 month vs 6 month post-surgery) comparisons of the TKA group were made using two-tailed paired samples t-tests to compare muscle strength, FTSTS, gait speed, joint mechanics, KOOS scores. To compare the TKA group with the control group, independent two-sample t-tests were utilized. IBM SPSS Statistics version 22 (IBM, Armonk, NY) was utilized for all comparisons, with statistical significance defined as $p \leq 0.05$. Effect sizes were calculated using Cohen’s d to further compare changes in the TKA group between 3 and 6 months post-surgery.

4.4 RESULTS

<u>TKA and Control Participants</u>

A total of 39 participants (21 TKA, 18 controls) completed the study. No significant differences in mean age, height, weight, body mass index (BMI), or PASE physical activity level between the TKA and control groups were present at the time of testing (Table 4.1). Of the TKA group, 12 participants received a cruciate retaining prosthesis, 5 received posterior stabilized, 2 received bicruciate-stabilizing, and 2 were undocumented.

Muscle Strength

At 3 months post-TKA, muscle strength and RTD of the TKA limb is significantly reduced compared to the non-operative limb in all muscle groups tested, with the exception of hip abduction RTD. At 6 months post-surgery, the findings were similar with the TKA limb remaining significantly weaker than the non-operative limb except in hip abduction RTD. Despite persistent between-limb differences, muscle strength of the TKA limb significantly improved between 3 to 6 months post-surgery in all measures except hip abduction RTD and hip external rotation RTD. No significant changes were observed in peak strength or RTD of the non-operative limb between 3 and 6 months post-surgery. Compared to control subjects, peak strength and RTD were significantly weaker at 3 months post-surgery in all muscle groups. At 6 months post-surgery, no significant differences were observed in peak hip abduction strength and RTD compared to control subjects. However, the TKA limb in all other muscle groups remained significantly weaker at 6 months compared to control subjects. In the non-operative limb, peak isometric quadriceps strength and RTD were significantly weaker at both 3 and 6 months post-surgery compared to control subjects. Refer to Table 4.2, Figure 4.1, and Figure 4.2 for complete results. Effect sizes for changes in strength and RTD of the operative limb ranged from 0.23 to 0.35, indicating small to moderate improvement in peak muscle strength and RTD (Table 4.11).

FTSTS

Performance on the FTSTS significantly improved in the TKA group between 3 to 6 months post-surgery, demonstrating a large effect size of 0.64 (Table 4.11). At both time points, control subjects significantly outperformed the TKA group (Table 4.3; Figure 4.3).

Gait Mechanics

Ground Reaction Force & Gait Speed

No significant differences were observed in peak vertical ground reaction force between limbs in the TKA group at 3 months post-surgery. At 6 months post-surgery, peak vertical ground reaction force was significantly lower in the operative limb. However, no significant changes in peak vertical ground reaction force were observed between 3 and 6 months post-surgery in either the operative or non-operative limb in the TKA group. The effect size of changes in the TKA limb was 0.44, indicating a moderate to large effect despite no significant change (Table 4.12). Compared to control subjects, peak vertical ground reaction force was significantly greater in control subjects compared to both the operative and non-operative limbs of the TKA group at both time points. Vertical impact peak was significantly lower in the operative limb of the TKA group compared to control subjects at 3 months post-surgery, but this difference resolved at 6 months post-surgery. Refer to Table 4.4 and Figure 4.4 for complete results. Gait speed was not significantly different between groups. The TKA group walked at a mean velocity of 0.78 ± 0.2 m/s and 0.86 ± 0.2 m/s at 3 and 6 months post-surgery, respectively. The control group walked at 0.95 ± 0.2 m/s.

Sagittal Plane Kinematics

At 3 months post-surgery, between-limb differences were observed in the TKA group in knee flexion excursion, knee flexion angle at initial contact, peak hip flexion angle, and peak hip extension angle. Knee flexion excursion was reduced in the operative limb compared to the non-operative limb, with the reduction primarily due to increased knee flexion angle at initial contact in the operative limb. The operative hip was also in greater flexion and reduced extension compared to the non-operative limb, but no significant difference was observed in hip flexion excursion. At 6 months post-surgery, reductions of knee flexion excursion persisted but no significant differences were observed in other sagittal plane kinematics. From 3 to 6 months post-surgery, the operative limb showed increased hip flexion excursion but no significant changes in any other variable. Interestingly, the non-operative knee was significantly more flexed at initial contact 6 months post-surgery compared to 3 months post. Further analysis of 3 to 6 month changes revealed an effect size of .22 for knee flexion excursion (Table 4.12). When compared to the control group, similar findings were observed with knee flexion excursion and peak knee flexion angle significantly reduced in the TKA limb at both 3 and 6 months post-surgery. The non-operative limb also showed reduced peak knee flexion angle compared to control subjects at both 3 and 6 months. Refer to Table 4.4, Figure 4.5, and Figure 4.6 for complete results.

Sagittal Plane Kinetics

No differences in knee extensor moment were found between limbs at 3 or 6 months post-surgery in the TKA group despite significant increases in knee extensor moment of the non-operative limb at 6 months post-TKA. Hip extensor moment was significantly reduced in the operative limb compared to the non-operative limb at the 3 month time point. Significant increases were observed in hip extensor moment of both limbs at 6 months with the operative limb increasing to near equal values of the non-operative limb. Hip extensor moment at 3 months post-surgery and knee extensor moments at both time points were significantly lower in the operative limb of the TKA group compared to control subjects. In the non-operative limb, knee extensor moment is greater in control subjects at 3 months post-surgery but no difference was observed at the 6 month time point. Refer to Table 4.4, Figure 4.7, and Figure 4.8 for complete results.

Frontal Plane Kinematics

In between-limb comparisons, reduced knee adduction angle was observed in the operative limb of the TKA group at 3 months, but no differences noted at 6 months post-surgery. No differences were observed in peak hip adduction angle between limbs at either 3 or 6 months post-surgery in the TKA group. From 3 to 6 months post-surgery, no changes were observed in the operative limb of the TKA group but the non-operative knee was less adducted at 6 months compared to 3 months post-surgery. Compared to control subjects, no differences were observed in frontal plane kinematics in either the knee or hip at 3 or 6 months post-surgery. Refer to Table 4.5, Figure 4.9, and Figure 4.10 for complete results.

Frontal Plane Kinetics

No differences in internal knee abduction moment were observed between limbs 3 months or 6 months post-surgery. A small, but significant, increase in knee abduction moment was found at 6 months post-surgery in the operative limb compared to 3 months post-surgery. No difference was noted for knee abduction moment of the operative limb vs control subjects at either 3 or 6 months post-surgery. In contrast, knee abduction moment was significantly greater in the non-operative limb at both time points compared to control subjects. Also noteworthy, hip abductor moment was greater bilaterally in the TKA group compared to control subjects at both time points. Refer to Table 4.5, Figure 4.11, and Figure 4.12 for complete results.

Step Descent Mechanics: Landing Leg

Ground Reaction Force

At 3 months post-surgery, peak vertical ground reaction force is increased in the non-operative limb compared to the operative limb but no between-limb differences were observed at 6 months post-surgery. Between 3 and 6 months, no significant change was observed in vertical ground reaction force in either limb of the TKA group. Compared to control subjects, no differences were apparent in peak vertical ground reaction force of the operative limb at either time point but the non-operative limb was significantly greater than control subjects at both 3 and 6 months post-surgery. Refer to Table 4.6 and Figure 4.13 for complete results.

Sagittal Plane Kinematics

Knee flexion excursion is reduced in the operative limb at both 3 and 6 months compared to the non-operative limb. This difference is primarily due to increased knee flexion at initial contact in the operative limb at 3 months, but reduced peak knee flexion at 6 months. No significant changes were observed between 3 and 6 months for either the operative or non-operative limbs. Compared to control subjects, knee flexion excursion is reduced in the operative limb at both time points but no significant differences in sagittal plane kinematics are noted in the non-operative limb. Refer to Table 4.6, Figure 4.14, and Figure 4.15 for complete results.

Sagittal Plane Kinetics

No significant differences were observed in knee extensor moment between limbs 3 months after surgery, but hip extensor moment was significantly reduced in the operative limb. At 6 months, reduced knee extensor moment was noted in the operative limb while no differences were noted in hip extensor moment. No differences were noted between 3 and 6 months post-surgery in either limb. No differences were noted in the non-operative compared to control subjects at either time point. However, hip extensor moment of the operative limb was significantly reduced at 3 months compared to control subjects while knee extensor moment was significantly reduced at 6 months. Refer to Table 4.6, Figure 4.16, and Figure 4.17 for complete results.

Frontal Plane Kinematics

No significant differences were noted in frontal plane knee kinematics between-limbs or between-groups at any time point. Increased hip adduction angle was noted in the operative limb compared to the non-operative at both 3 and 6 months, but no differences were observed in hip adduction angle of the operative limb compared to control subjects were noted. At 6 months, hip adduction angle was reduced in the non-operative limb compared to control subjects. Refer to Table 4.7, Figure 4.18, and Figure 4.19 for complete results.

Frontal Plane Kinetics

No significant differences were observed in frontal plane kinetics of either the hip or knee between-limbs or between-groups at either time point (Table 4.7, Figure 4.20, Figure 4.21).

Step Descent Mechanics: Stance Leg

Ground Reaction Force

No significant differences were found in peak vertical ground reaction force between-limbs or between-groups at any time point (Table 4.8, Figure 4.22).

Sagittal Plane Kinematics

At both 3 and 6 months, increased hip flexion angle is noted in the operative limb compared to the non-operative limb. No differences are noted between 3 and 6 months in either limb. When compared to control subjects, peak knee flexion angle is significantly reduced bilaterally in the TKA group. No differences were observed in peak hip flexion angle compared to control subjects in either limb of the TKA group. Refer to Table 4.8, Figure 4.23, and Figure 4.24 for complete results.

Sagittal Plane Kinetics

Knee extensor moment of the operative limb was significantly reduced compared to the non-operative at both 3 and 6 months post-surgery. No difference in between-limb hip flexor moment was observed at either time point. Knee extensor moment of the operative limb significantly improved between 3 and 6 months, but no significant change in hip flexor moment was observed. Lastly, reduced knee extensor and hip flexor moments were observed bilaterally in the TKA group compared to control subjects. Refer to Table 4.8, Figure 4.25, and Figure 4.26 for complete results.

Frontal Plane Kinematics

No significant differences were observed in frontal plane knee or hip kinematics between-limbs or between-groups at any time point. Refer to Table 4.9, Figure 4.27, and Figure 4.28 for complete results.

Frontal Plane Kinetics

No significant between-limb differences were observed in knee abduction or hip abduction moment at either time point. Furthermore, no significant changes were observed between 3 and 6 in either limb of the TKA group. However, knee abduction moment was significantly smaller bilaterally in the TKA group compared to control subjects. Refer to Table 4.9, Figure 4.29, and Figure 4.30 for complete results.

<u>KOOS</u>

Scores on all five KOOS subscales significantly improved from 3 to 6 months in the TKA group, with effect sized ranging between 0.28 for the Sports/Recreation subscale to 0.82 for the quality of life subscale (Table 4.11). Despite this improvement, control subjects scored still scored significantly higher in all subscales compared to the TKA group at both 3 and 6 months (Table 4.10, Figure 4.31).

4.5 DISCUSSION

Our initial hypothesis was partially supported as significant improvements in the TKA group were observed between 3 and 6 months in four of six muscle strength measures, FTSTS performance, and KOOS scores. Asymmetrical gait and stair descent mechanics persisted at 6 months, particularly in knee flexion excursion. Our second hypothesis was supported as the TKA group performed significantly worse in all 4 domains compared to control subjects. Our third hypothesis was also partially supported as TKA subjects showed the greatest improvement, as measured by effect size, in KOOS scores and FTSTS performance but less improvement in gait and stair descent mechanics (Tables 11, 12).

Quadriceps muscle weakness has been documented up to 3 years post TKA [43]. Our findings are consistent with previous reports which demonstrated deficits of 16 to 63% at 3 and 6 months post-surgery. Quadriceps RTD demonstrated greater percentage impairment than peak isometric strength compared to control subjects at 3 months (60 vs 56%) and 6 months post-surgery (51 vs 49%), suggesting that RTD may be a more sensitive measure of recovery than peak strength. This study is the first to compare RTD to age and BMI-matched control subjects and indicates dramatic impairments. Previous work has noted RTD to be more sensitive to recovery as larger deficits are observed both between limbs and, in this study, compared to control subjects [18, 144]. Given that walking, stair negotiation, and sit to stand require adequate force to be delivered within critical timing windows, RTD may better capture the quadriceps' ability to quickly deliver force for successful performance of the task. Furthermore, the contralateral quadriceps was significantly weaker than control subjects. Function of the contralateral limb is a strong predictor of post-operative performance [54, 160]. Based on the findings of this study, the onset of contralateral quadriceps weakness has occurred at least as early as the first 3 months after surgery. Given the high likelihood of patients undergoing contralateral TKA after initial unilateral TKA, patients may benefit from contralateral quadriceps strengthening during recovery from unilateral TKA[83].

To the author's knowledge, this is the first study to examine hip muscle strength between-limbs and compared to a control group after TKA. The results indicate that muscle strength is impaired proximally in hip external rotation strength as early as 3 months post-surgery and persists through 6 months post-surgery. Seated hip external rotation has been shown to primarily require the gluteus maximus and not the small external rotators[161]. Given the role of the hip musculature in more powerful tasks like sit-to-stand and stair negotiation, persistent difficulties with these tasks may be influenced by hip muscle weakness. Similarly to quadriceps RTD, hip external rotation RTD showed greater percentage impairment than peak hip external rotation strength and remained impaired at 6 months. Previously, hip abduction weakness has been observed in patients awaiting TKA and improved hip abduction strength post-operatively has been found to be associated with improved physical performance [17, 61, 62]. Interestingly, hip abduction strength was not significantly different between limbs or compared to control subjects. However, at 3 months, peak hip abduction strength was significantly weaker than control subjects, but no differences were observed at 6 months. A possible reason for lack of significant differences in peak hip abduction strength at 6 months may be due to strength gains from daily activity as individuals after TKA utilize greater hip strategy during ambulation.

This is the first study to statistically analyze FTSTS performance between 3 and 6 months post-surgery. Based on the FTSTS, participants with TKA demonstrated improved functional performance between 3 and 6 months post-surgery. While the improvement is statistically significant and demonstrated a large effect, the mean improvement did not exceed the minimal detectable change of 2.5 seconds suggesting that improvements were within measurement error for the TKA group[63]. Furthermore, the functional performance of the TKA group was significantly worse than control subjects at both time points. These results suggest that impairments in sit-to-stand ability persist at least 6 months after TKA. Evidence associating FTSTS performance with other measures of recovery after TKA is limited. A single study noted that a reduction in

FTSTS time of >2.5 seconds from pre-operative to 1 year post-operative resulted in more symmetrical walking gait [66]. A separate study found low to moderate correlations (-0.26 to -0.33) between FTSTS performance and weight bearing ratio between limbs during the FTSTS at 1, 3, and 6 months post-surgery [49]. These early findings indicate the FTSTS test may serve a useful clinical tool to longitudinally track progress after TKA, but additional study is warranted.

Gait asymmetries are known to persist after TKA and the results of this study provide further evidence that gait mechanics are not fully restored after TKA [107, 108, 162]. Although a greater number of asymmetries were observed at 3 months compared to 6 months, indicating that some asymmetries may resolve with time after TKA, those asymmetries that remain reveal unique adaptations to TKA that many contribute to prolonged impairment. When comparing between-limbs, knee flexion excursion of the operative limb was consistently reduced at both time points and demonstrated no significant improvement between 3 and 6 months. This finding is consistent with previous studies of reduced knee flexion motion during the stance phase of gait and has often been described as a "quadriceps avoidance" gait in which individuals limit greater knee flexion angles to avoid increasing the demand of the quadriceps to control the motion [69, 75, 108]. However, it is interesting to note that there were no significant changes in knee flexion excursion in the operative limb despite improvement in quadriceps strength and RTD. This would suggest that persistent deficits in knee flexion excursion may be a learned gait pattern that has not been resolved despite improved joint pain, range of motion, and quadriceps strength.

In order to further evaluate impairments in gait after TKA, comparisons to a control group are also useful. Similar to previous studies, peak vertical ground reaction force of the operative limb was reduced compared to control subjects at both time points. Furthermore, knee flexion excursion of the operative limb is reduced compared to control subjects at both time points. This is in agreement with previous studies as, compared to control subjects, both the operative and non-operative limbs demonstrated reduced peak knee flexion angles [71, 72, 74]. Additionally, knee extensor moment was significantly reduced bilaterally compared to control subjects. Given dramatic quadriceps muscle weakness, individuals may have adapted their gait patterns to reduce demand on the quadriceps bilaterally. It remains unclear if reduced knee extensor moment bilaterally results as a result of bilateral quadriceps weakness, or if the non-operative limb is adapting to become more symmetrical compared to the operative. Lastly, there were no significant differences in frontal plane knee kinetics or kinematics of the operative limb and control subjects, suggesting that TKA successfully corrects abnormal knee alignment and loading to within levels observed in control subjects.

This is one of few studies to examine hip joint mechanics after TKA. Hip kinematics did not differ between groups. Hip extensor moments were not significantly different than control subjects. However, hip abduction moment is significantly greater bilaterally in the TKA group at both time points. This finding, when considered in combination with reduced knee extensor moment bilaterally compared to control subjects, suggests that individuals after TKA adopt a hip strategy during ambulation to reduce loading through the knee joints. Despite no significant differences between-limb in hip abduction strength at 6 months post-surgery, reports of improved hip abductor strength being associated with improved physical function may be explained by individuals after TKA adopting a more hip-dominant strategy. As a result, those with stronger hip abductors or those who strengthen their hip abductors during rehabilitation may be more capable of successfully implementing greater hip strategy and perform functional tasks more easily.

As a more demanding task, one would expect to find greater impairments during stair descent than level walking. During landing, the non-operative limb experienced significantly greater peak vertical ground reaction force than the operative limb at both time points and compared to control subjects. Similar to walking, knee flexion excursion is reduced in the operative limb during landing compared to the non-operative limb at both time points and compared to control subjects. In the frontal plane, increased peak hip adduction angle in the operative limb was observed at both time points compared to the non-operative limb. These persistent differences identify unique landing strategies in each limb in individuals after TKA. Increased frontal plane motion at the hip may serve to absorb more load during landing due to reduced flexion excursion and limited load dissipation at the knee joint. However, during stair descent, the biomechanics of the landing limb are influenced by the ability of the stance limb to control the descent phase. For this reason, it is helpful to further explore potential deficits in both the landing and stance limbs together.

Given the significantly greater vertical ground reaction force during landing in the operative limb, the stance limb may be unable to control the demands of the stair descent. The most apparent differences in the stance limb involve knee extensor moment as the operative limb was significantly impaired compared to both the non-operative limb and control subject limb at both 3 and 6 months after surgery. Interestingly, in contrast to what was observed during level walking, the reduction in knee extensor moments was not accompanied with an increase in hip moments. Rather, hip flexion moments were decreased bilaterally compared to control subjects. This would suggest that while controlling descent, both the hip and knee of the operative limb are functioning near maximum capacity but the task demands are beyond what these muscles groups can achieve. Thus, use of a hip-dominant strategy may be an effective compensation during level walking, but this strategy does not seem to be present during stair descent. It could be, perhaps, that stair descent requires either a more quadriceps-dominant movement strategy or this task imposes demands in excess of the individual's capacity. It is also important to note that significant improvement in knee extensor moment was observed bilaterally between 3 and 6 months in the TKA group, despite not reaching the level of control subjects. This improvement could indicate adaptations in the motor strategy for stair descent. However, no kinematic changes were observed between time points suggesting that the overall movement pattern remained consistent. Alternatively, it may be that improvements in quadriceps function observed between 3 and 6 months post-surgery are manifested in higher knee extensor moments during stair descent. This would indicate that deficits in muscle strength and RTD may more greatly influence stair descent than movement strategy, but more work is needed to further explore this construct.

Scores in the KOOS subscales significantly improved between 3 and 6 months, but never reached the levels of control subjects. The knee-related quality of life subscale demonstrated the largest effect size of 0.82 and exceeded the clinically important change of 10 points[88]. The symptoms, pain, and activities of daily living subscales also demonstrated large effect sizes of 0.54, 0.71, and 0.68, respectively, but did not improve by >10 points (Table 4.11). As is typical in patients after TKA, the sports/recreation subscale was the lowest scoring and demonstrated a small effect size of 0.29[97, 98, 100]. Based on this data, the KOOS and FTSTS demonstrate more improvement between 3 and 6 months than measures of muscle strength and lower extremity biomechanics during walking and stair descent. Previous reports have noted that the KOOS may be insensitive to early recovery as patients often report significant improvement compared to pre-operative scores during the first month after surgery despite significant decline in physical measures of performance [100, 102, 153]. Thus, previous studies have concluded that patient reported outcomes measure different constructs of recovery than physical performance tests early after TKA. The findings of this study indicate that between 3 and 6 months post-surgery, large improvements in KOOS and FTSTS occur concurrently suggesting that physical performance and subjective patient-reported outcomes may measure similar constructs during this period. Early recovery in KOOS has been linked to reduction in arthritic pain as a result of the TKA and previous work attributes improvement in KOOS scores to reflect less pain with previously painful daily activities [153]. It may be that improvements in KOOS during later phases of recovery (3-6 months) are driven by improvements in physical function, but further inquiry is required.

The limitations of this study should be considered. Lack of pre-operative measures precludes assessment of improvements between pre-operative and post-operative measures. Use of a control group partially overcomes this limitation but this method establishes a higher standard for recovery after TKA as impairments in individuals awaiting TKA have been noted compared to control subjects [61, 163]. Additionally, use of a single stair descent task does not allow for a step-over-step pattern that is typical when descending a full flight of stairs. However, analyzing the mechanics of a single descent provides valuable information regarding the ability of both the landing and stance limbs to perform this more demanding activity and improves understanding of a single aspect of a larger task. Lastly, use of an instrumented treadmill for gait analysis may limit direct comparison of joint kinetic data collected during overground walking. Spatiotemporal and kinematic variables have been shown to be similar between conditions, but some differences have been noted in sagittal plane kinetics including reduced knee extensor moments[164]. Nonetheless, the treadmill was utilized for all participants, eliminating any influence of the treadmill in between-limb and between-group comparisons.

Future studies should investigate relationships between domains to further evaluate potential divergence or convergence in the constructs assessed in each domain. In particular, the relationships between easily implementable clinical tests (such as the FTSTS), patient-reported outcomes, and mechanics of walking and stair descent would provide clinicians with tools to determine the likelihood of restoring more symmetrical gait mechanics with additional time from surgery. Ultimately, exploration into predictors of optimal outcomes across domains after TKA is needed to guide clinical decision making during rehabilitation after TKA. Just as clinicians have benefited from return to sport criteria for patients after anterior cruciate ligament reconstruction, establishing criteria for discharge from rehabilitation for TKA based upon both subjective report and objective physical measures may improve long-term outcomes for a growing number of patients after TKA.

4.6 CONCLUSION

Despite improvements in muscle strength, FTSTS performance, gait mechanics, and KOOS scores between 3 and 6 months after surgery, patients with unilateral TKA have persistent impairments compared to matched controls at 6 months post-surgery. The greatest improvements were observed in FTSTS and KOOS scores, indicating that muscle weakness of hip external rotators and quadriceps and lower extremity mechanical impairments of the hip and knee may require more time or additional intervention for recovery. During walking and stair descent, patients after TKA utilize greater hip moments for stability as a possible compensation for impaired quadriceps muscle strength or knee joint function. These findings suggest that recovery from TKA is incomplete and additional strategies are needed to restore normal function during the first 6 months after surgery.

Table 4.1: Subject Demographics

	TKA	Control	p-value
Sex (M/F)	7/14	7/11	
Height (m)	1.68 ± 0.08	1.69 ± 0.10	.848
Mass (kg)	90.95 ± 21.04	83.69 ± 20.2	.281
BMI (kg/m^2)	32.27 ± 7.4	29.2 ± 5.5	.158
Age (years)	60.6 ± 8.1	61.2 ± 8.8	.811
PASE	184.9 ± 99.3	165.9 ± 81.8	.523

TKA: Subjects with total knee arthroplasty
M: Male
F: Female
BMI: Body Mass Index
PASE: Physical Activity Scale for the Elderly

Table 4.2: Summary of Muscle Strength Measures

	TKA 3 mo	NON 3 mo	TKA 6 mo	NON 6mo	Control
Hip Abd Peak	$0.58 \pm 0.3^{*\#\ddagger}$	0.66 ± 0.32	0.70 ± 0.35	0.72 ± 0.34	0.79 ± 0.18
Hip Abd RTD	$1.94 \pm 1.15^{\ddagger}$	2.15 ± 1.02	2.28 ± 1.29	2.58 ± 1.37	2.68 ± 0.79
Hip ER Peak	$0.29 \pm 0.11^{*\#\ddagger}$	$0.38 \pm 0.15^{\#}$	$0.34 \pm 0.14^{*\ddagger}$	0.43 ± 0.17	0.46 ± 0.12
Hip ER RTD	$0.72 \pm 0.41^{*\ddagger}$	1.15 ± 0.59	$0.81 \pm 0.46^{*\ddagger}$	1.17 ± 0.50	1.33 ± 0.51
Quad Peak	$0.86 \pm 0.34^{*\#\ddagger}$	$1.4 \pm 0.5^{\ddagger}$	$1.0 \pm 0.5^{*\ddagger}$	$1.41 \pm 0.59^{\ddagger}$	1.96 ± 0.64
Quad RTD	$2.43 \pm 1.28^{*\#\ddagger}$	$4.12 \pm 1.68^{\ddagger}$	$3.03 \pm 1.68^{*\ddagger}$	$4.08 \pm 1.98^{\ddagger}$	6.0 ± 2.0

*significant vs between limbs
$^{\#}$ significant 3 mo vs 6 mo
‡ significant vs Control

Abd: abduction
Peak: peak isometric strength (Nm/kg)
RTD: rate of torque development (Nm/kg*s)
ER: external rotation
TKA: operative limb
NON: non-operative limb
mo: month
Quad: quadriceps

Table 4.3: Summary of Five-time Sit-to-Stand Performance

	TKA 3 mo	TKA 6 mo	Control
FTSTS (s)	11.95 ± 3.08[#] [ǂ]	10.2 ± 2.83[ǂ]	8.18 ± 1.77

[#] significant 3 mo vs 6 mo
[ǂ] significant vs Control
FTSTS: Five-time Sit-to-Stand test
s: time in seconds

Table 4.4: Summary of Walking Gait Vertical Ground Reaction Force, Sagittal Plane Kinematics, and Kinetics

	TKA 3 mo	NON 3 mo	TKA 6 mo	NON 6 mo	Control
Peak vGRF	1.03 ± 0.05[ǂ]	1.03 ± 0.05[ǂ]	1.01 ± 0.04[*ǂ]	1.03 ± 0.04[ǂ]	1.09 ± 0.05
Peak Knee Flex	24.8 ± 7.9[ǂ]	23.0 ± 7.1[# ǂ]	23.8 ± 8.1[ǂ]	25.6 ± 5.4[ǂ]	31.4 ± 6.5
KFLEXC	9.1 ± 4.4[*ǂ]	12.5 ± 5.5	10.2 ± 3.8[*ǂ]	12.9 ± 5.0	15.6 ± 6.0
Knee Flex at IC	18.6 ± 6.5[*]	14.6 ± 6.7[# ǂ]	16.3 ± 6.5	16.7 ± 7.5	19.1 ± 5.5
Peak Hip Flex	34.6 ± 6.2[*]	32.0 ± 6.3[ǂ]	34.4 ± 7.1	33.7 ± 6.4	36.9 ± 6.5
Peak Hip Ext	4.3 ± 7.0[*]	1.8 ± 7.2	1.6 ± 9.4	1.1 ± 9.9	2.3 ± 8.1
HFLEXC	31.2 ± 6.3[#]	31.2 ± 6.7	33.3 ± 5.4	32.6 ± 5.8	34.6 ± 7.9
KEM	0.27 ± 0.14[ǂ]	0.26 ± 0.14[# ǂ]	0.29 ± 0.19[ǂ]	0.33 ± 0.20	0.45 ± 0.17
HEM	0.32 ± 0.11[*# ǂ]	0.38 ± 0.18	0.37± 0.08	0.39 ± 0.12	0.42 ± 0.13

[*]significant vs between limbs
[#] significant 3 mo vs 6 mo
[ǂ] significant vs Control

vGRF: vertical ground reaction force (measured in bodyweights (BW))
Flex: flexion angle
KFLEXC: knee flexion excursion
IC: initial contact
Ext: extension angle
HFLEXC: hip flexion excursion
KEM: knee extensor moment (Nm/kg)
HEM: hip extensor moment (Nm/kg)
TKA: operative limb
NON: non-operative limb
mo: month

Table 4.5: Summary of Walking Gait Frontal Plane Kinematics and Kinetics

	TKA 3 mo	NON 3 mo	TKA 6 mo	NON 6 mo	Control
Knee Add (°)	-1.9 ± 3.1[*]	1.4 ± 4.7	-1.8 ± 3.5	0.5 ± 4.5	0.5 ± 5.8
Hip Add (°)	6.3 ± 3.2	4.1 ± 4.6 [ǂ]	6.2 ± 3.0	5.07 ± 4.5	7.4 ± 4.4
Knee Abd Moment (Nm/kg)	0.15 ± 0.06[#]	0.2 ± 0.1[ǂ]	0.16 ± 0.06	0.21 ± 0.11[ǂ]	0.13 ± 0.6
Hip Abd Moment (Nm/kg)	0.41 ± 0.19[ǂ]	0.44 ± 0.22[ǂ]	0.38 ± 0.15[ǂ]	0.48 ± 0.22[ǂ]	0.29 ± 0.12

[*]significant vs between limbs
[#] significant 3 mo vs 6 mo
[ǂ] significant vs Control

Add: adduction
Abd: abduction
TKA: operative limb
NON: non-operative limb
mo: month

Table 4.6: Summary of Stair Descent Vertical Ground Reaction Force, Sagittal Plane Kinematics, and Kinetics of the Landing Limb

	TKA 3 mo	NON 3 mo	TKA 6 mo	NON 6mo	Control
Peak vGRF	1.38 ± 0.25*	1.61 ± 0.37^{ǂ}	1.37 ± 0.29	1.55 ± 0.30^{ǂ}	1.27 ± 0.23
Peak Knee Flex	29.6 ± 7.1	32.3 ± 7.9	28.6 ± 7.3	35.4 ± 6.1	35.3 ± 6.6
KFLEXC	11.2 ± 3.6^{*ǂ}	18.1 ± 7.0	12.1 ± 4.8^{*ǂ}	18.6 ± 5.8	17.6 ± 5.2
Knee Flex at IC	18.5 ± 6.1*	14.3 ± 4.4	16.5 ± 5.2	16.7 ± 4.1	17.7 ± 4.2
Peak Hip Flex	29.3 ± 7.5	29.3 ± 8.5	27.1 ± 8.6	29.8 ± 8.9	28.9 ± 6.4
KEM	0.55 ± 0.30	0.62 ± 0.33	0.52 ± 0.27^{*ǂ}	0.76 ± 0.33	0.76 ± 0.38
HEM	0.44 ± 0.23^{*ǂ}	0.62 ± 0.28	0.48± 0.28	0.60 ± 0.25	0.60 ± 0.18

*significant vs between limbs
$^{\#}$ significant 3 mo vs 6 mo
^{ǂ} significant vs Control

vGRF: vertical ground reaction force (measured in bodyweights (BW))
Flex: flexion angle
KFLEXC: knee flexion excursion
IC: initial contact
KEM: knee extensor moment (Nm/kg)
HEM: hip extensor moment (Nm/kg)
TKA: operative limb
NON: non-operative limb
mo: month

Table 4.7: Summary of Stair Descent Frontal Plane Kinematics and Kinetics of the Landing Limb

	TKA 3 mo	NON 3 mo	TKA 6 mo	NON 6mo	Control
Knee Add (°)	-1.6 ± 3.1	1.1 ± 6.3	-1.7 ± 3.5	1.2 ± 4.5	1.1 ± 5.9
Hip Add (°)	2.2 ± 4.7*	-1.1 ± 5.5	2.3 ± 5.8*	-1.3 ± 5.1ǂ	2.9 ± 4.2
Knee Abd Moment (Nm/kg)	0.37 ± 0.15	0.43 ± 0.21	0.42 ± 0.26	0.45 ± 0.24	0.47 ± 0.17
Hip Abd Moment (Nm/kg)	0.98 ± 0.25	0.95 ± 0.33	1.02 ± 0.33	0.88 ± 0.29	1.07 ± 0.28

*significant vs between limbs
significant 3 mo vs 6 mo
ǂ significant vs Control

Add: adduction
Abd: abduction
TKA: operative limb
NON: non-operative limb
mo: month

Table 4.8: Summary of Stair Descent Vertical Ground Reaction Force, Sagittal Plane Kinematics, and Kinetics of the Stance Limb

	TKA 3 mo	NON 3 mo	TKA 6 mo	NON 6mo	Control
Peak vGRF	1.00 ± 0.05	1.01 ± 0.06	1.01 ± 0.04	1.02 ± 0.04	1.02 ± 0.05
Peak Knee Flex	68.1 ± 8.2ǂ	67.2 ± 8.5ǂ	71.0 ± 6.5ǂ	69.5 ± 9.0ǂ	79.3 ± 8.3
Peak Hip Flex	24.3 ± 11.7*	20.2 ± 10.9	25.9 ± 11.4*	21.4 ± 11.5	23.6 ± 6.5
KEM	1.32 ± 0.34*#ǂ	1.56 ± 0.36#ǂ	1.43 ± 0.36*ǂ	1.66 ± 0.38ǂ	2.1 ± 0.18
HFM	0.90 ± 0.5ǂ	0.97 ± 0.59ǂ	0.85 ± 0.50ǂ	0.90 ± 0.52ǂ	1.26 ± 0.22

*significant vs between limbs
significant 3 mo vs 6 mo
ǂ significant vs Control

vGRF: vertical ground reaction force (measured in bodyweights (BW))
Flex: flexion angle
KEM: knee extensor moment (Nm/kg)
HFM: hip flexor moment (Nm/kg)
TKA: operative limb
NON: non-operative limb
mo: month

Table 4.9: Summary of Stair Descent Frontal Plane Kinematics and Kinetics of the Stance Limb

	TKA 3 mo	NON 3 mo	TKA 6 mo	NON 6mo	Control
Knee Add (°)	3.5 ± 4.9	4.5 ± 5.9	3.2 ± 5.3	4.5 ± 6.3	4.7 ± 6.4
Hip Add (°)	10.5 ± 4.9	8.5 ± 4.7	11.2 ± 5.5	8.6 ± 5.4	11.0 ± 3.6
Knee Abd Moment (Nm/kg)	0.52 ± 0.21‡	0.50 ± 0.26‡	0.52 ± 0.25‡	0.51 ± 0.33‡	0.86 ± 0.13
Hip Abd Moment (Nm/kg)	0.94 ± 0.2	0.91 ± 0.16	0.98 ± 0.27	0.88 ± 0.21	0.91 ± 0.01

*significant vs between limbs
significant 3 mo vs 6 mo
‡ significant vs Control

Add: adduction
Abd: abduction
TKA: operative limb
NON: non-operative limb
mo: month

Table 4.10: Summary of Knee Injury and Osteoarthritis Outcome Scores

	TKA 3 mo	TKA 6 mo	Control
KOOS_Sym	67.7 ± 9.5[# ǂ]	73.9 ± 12.5[ǂ]	95.2 ± 5.3
KOOS_Pain	77.9 ± 9.6[# ǂ]	84.3 ± 10.2[ǂ]	97.4 ± 4.5
KOOS_ADL	83.1 ± 8.9[# ǂ]	88.7 ± 8.7[ǂ]	97.9 ± 3.7
KOOS_Sport	49.3 ± 24.8[ǂ]	55.0 ± 25.0[ǂ]	93.1 ± 11.5
KOOS_QoL	53.3 ± 21.2[# ǂ]	68.5 ± 20.8[ǂ]	95.1 ± 6.6

[#] significant 3 mo vs 6 mo
[ǂ] significant vs Control

KOOS: Knee Injury and Osteoarthritis Outcome Score
Sym: Symptoms subscale
Pain: Pain subscale
ADL: Activities of Daily Living subscale
Sport: Sports/Recreation subscale
QoL: Knee-related Quality of Life subscale
TKA: Total Knee Arthroplasty Group
mo: month

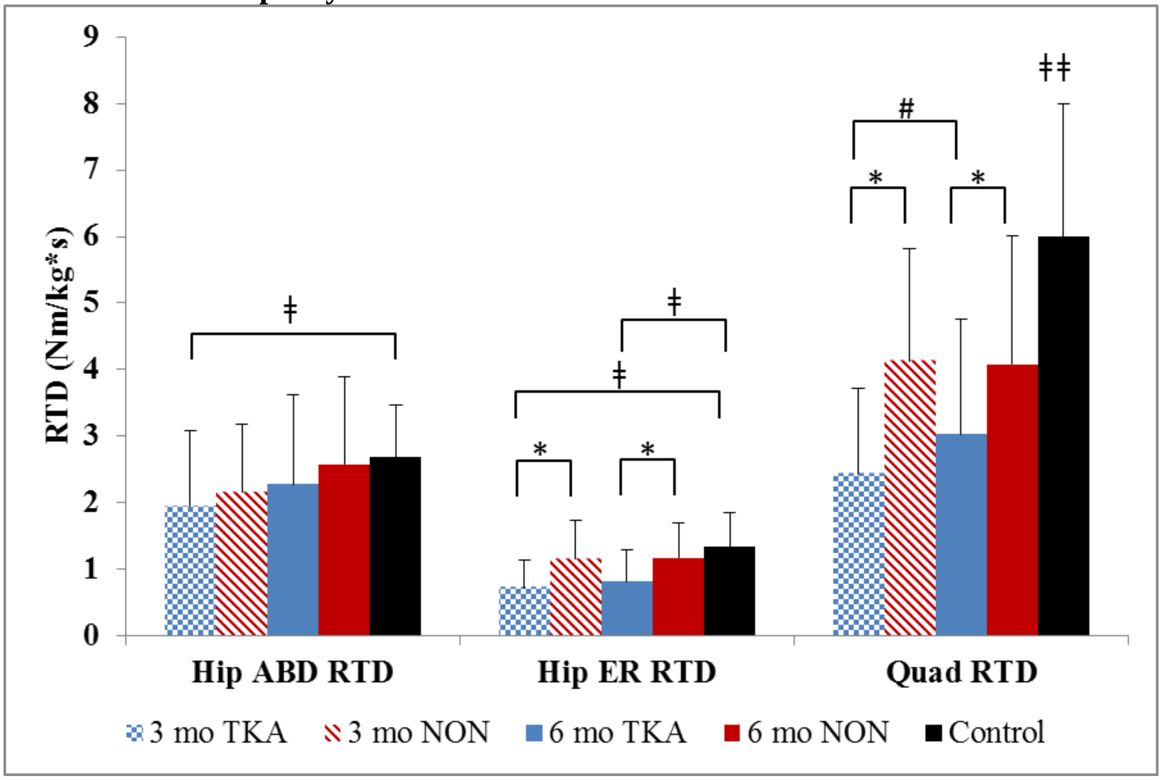
Table 4.11: Effect Sizes for Muscle Strength, FTSTS, and KOOS Scores Comparing the Operative Limb at 3 and 6 Months Post-surgery

Variable	Effect Size
Hip Abd Peak	0.31
Hip Abd RTD	0.30
Hip ER Peak	0.24
Hip ER RTD	0.23
Quad Peak	0.33
Quad RTD	0.35
FTSTS	0.64
KOOS_Sym	0.54
KOOS_Pain	0.71
KOOS_ADL	0.68
KOOS_Sport	0.29
KOOS_QOL	0.82

Table 4.12: Effect Sizes for Walking Gait, Stair Descent Landing Limb, and Stair Descent Stance Limb Comparing the Operative Limb at 3 and 6 months Post-surgery

Variable	Walking	Stair: Landing	Stair: Stance
Peak vGRF	0.44	0.037	0.22
Peak Knee Flex	0.28	0.14	0.4
KFLEXC	0.22	0.21	n/a
Knee Flex at IC	0.44	0.35	n/a
Peak Hip Flex	0.04	0.27	0.14
Peak Hip Ext	0.4	n/a	n/a
HFLEXC	0.36	n/a	n/a
KEM	0	0.1	0.31
HEM	0.53	0.16	n/a
Knee Add	0.03	0.03	0.06
Hip Add	0.03	0.02	0.14
Knee Abd Moment	0.17	0.24	0
Hip Abd Moment	0.24	0.14	0.17

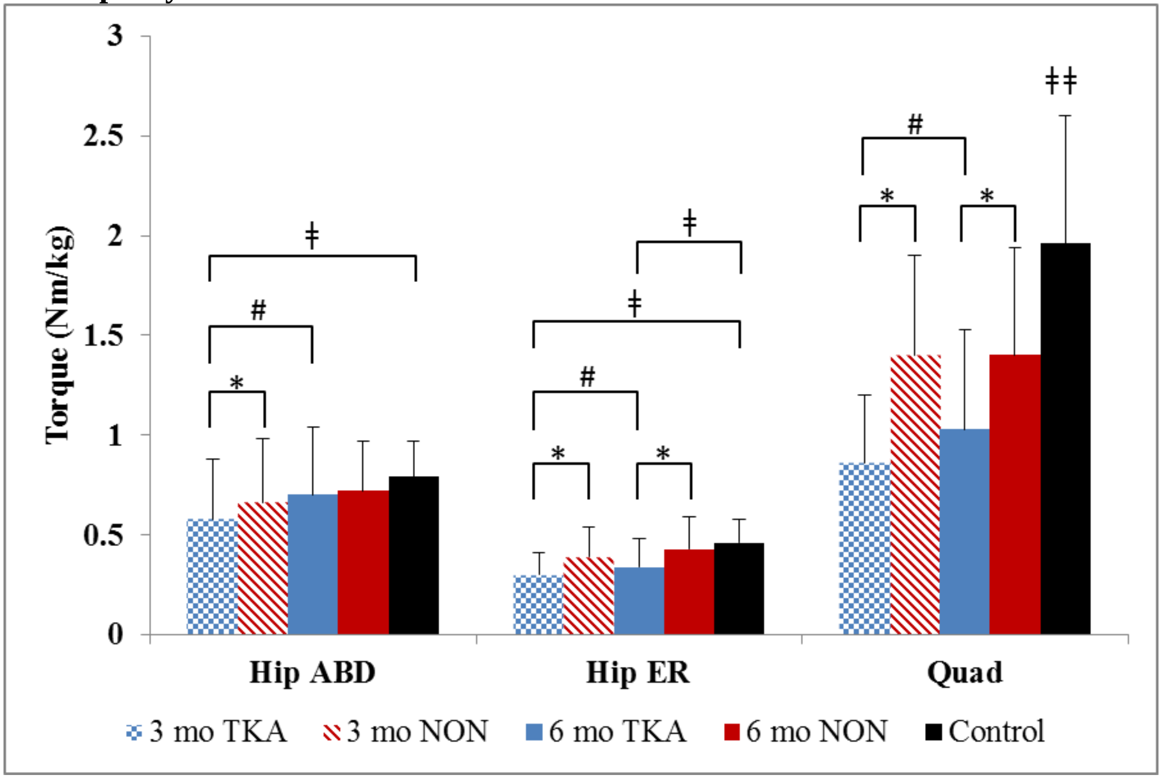
Figure 4.1: Bar Graphs Comparing Rate of Torque Development (RTD) of Hip Abductor, Hip External Rotator, and Quadriceps Muscle Groups in Patients after Total Knee Arthroplasty and Matched Controls



* significant vs NON
# significant 3 mo vs 6 mo
ǂ significant vs Control
ǂǂ both limbs and both time points significant vs Control

ABD: abduction
RTD: rate of torque development (N/kg*s)
ER: external rotation
TKA: operative limb
NON: non-operative limb
mo: month
Quad: quadriceps

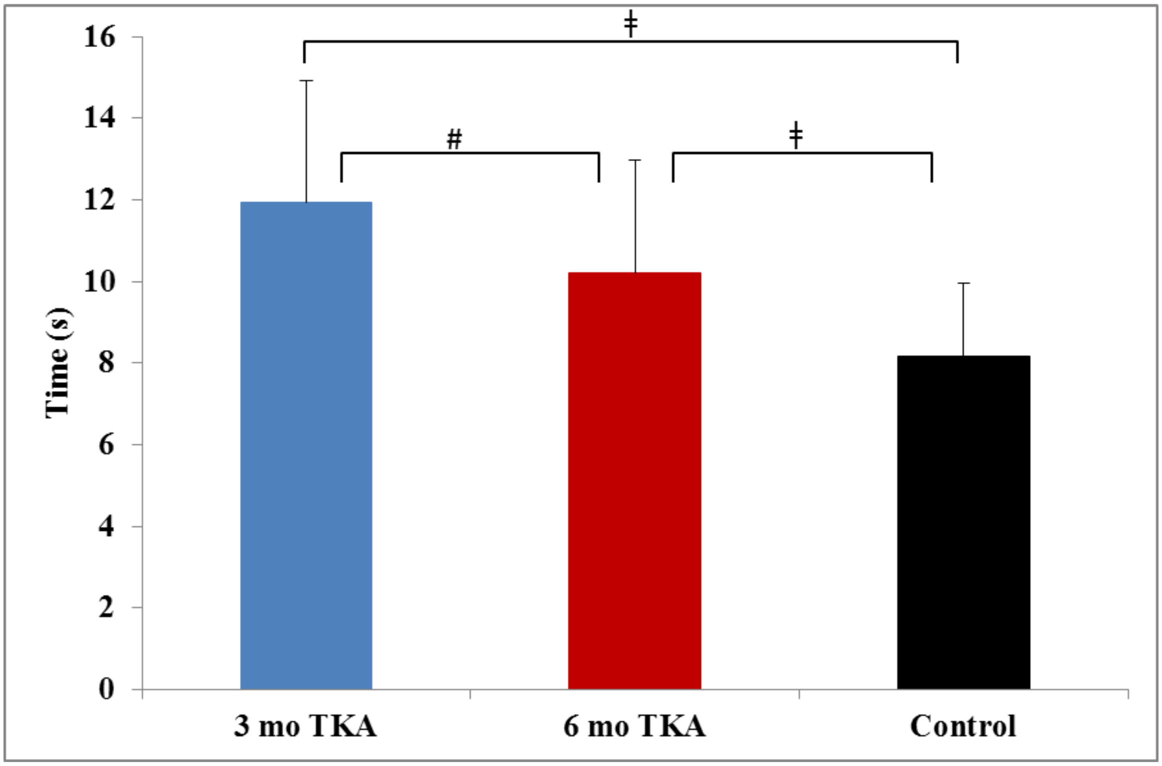
Figure 4.2: Bar Graphs Comparing Peak Isometric Strength of Hip Abductor, Hip External Rotator, and Quadriceps Muscle Groups in Patients after Total Knee Arthroplasty and Matched Controls



* significant vs NON
# significant 3 mo vs 6 mo
ǂ significant vs Control
ǂǂ both limbs and both time points significant vs Control

ABD: abduction
ER: external rotation
TKA: operative limb
NON: non-operative limb
mo: month
Quad: quadriceps

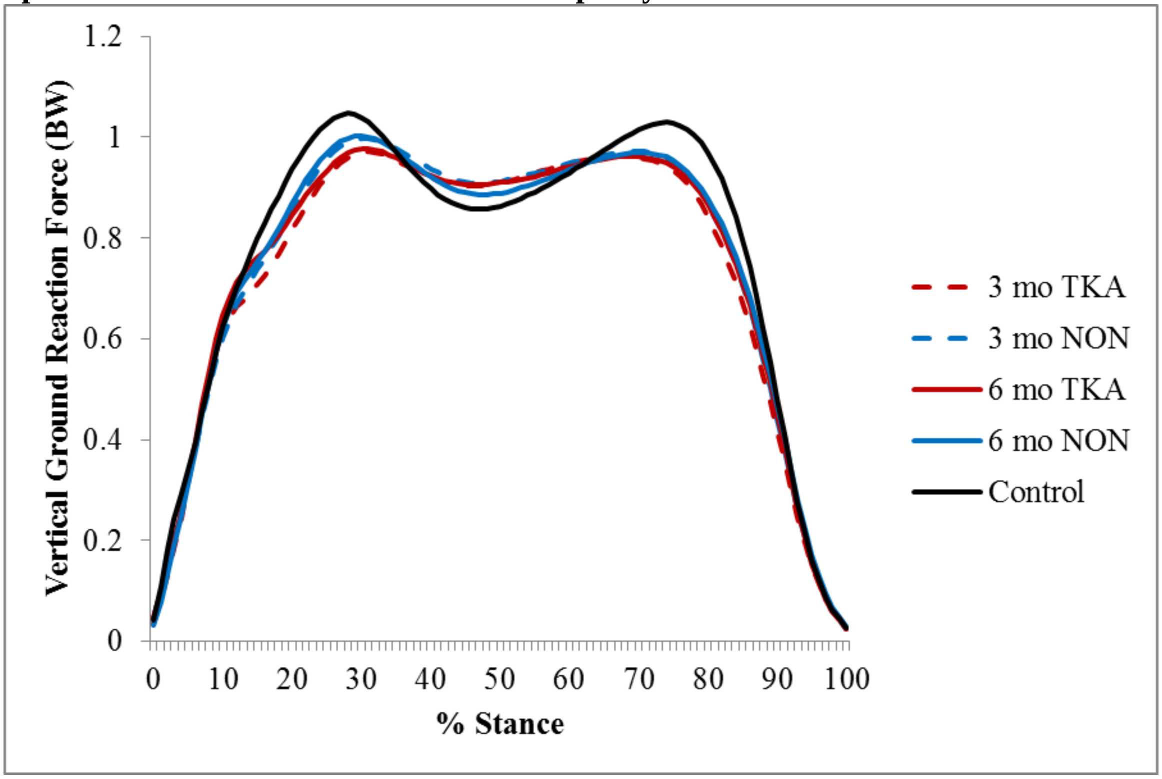
Figure 4.3: Bar Graph Comparing Five-Time Sit-to-Stand Performance in Patients after Total Knee Arthroplasty and Matched Controls



significant 3 mo vs 6 mo
ǂ significant vs Control

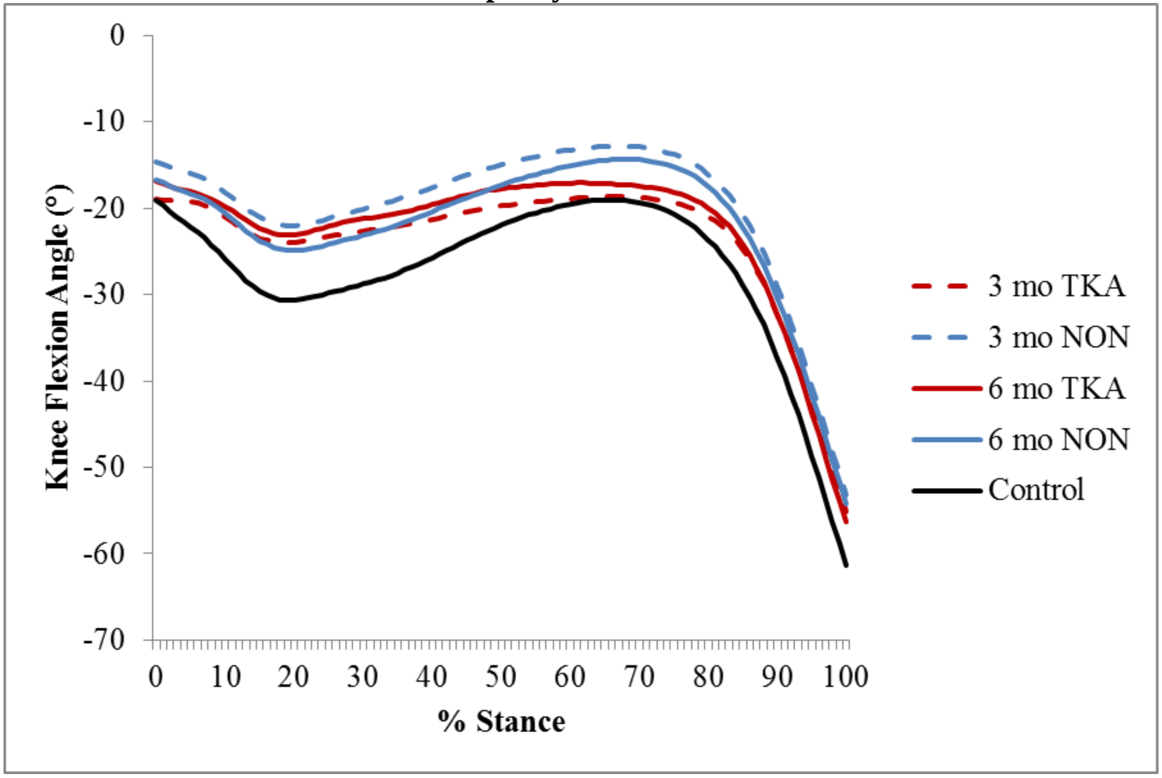
TKA: Total Knee Arthroplasty Group
mo: month

Figure 4.4: Vertical Ground Reaction Force during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



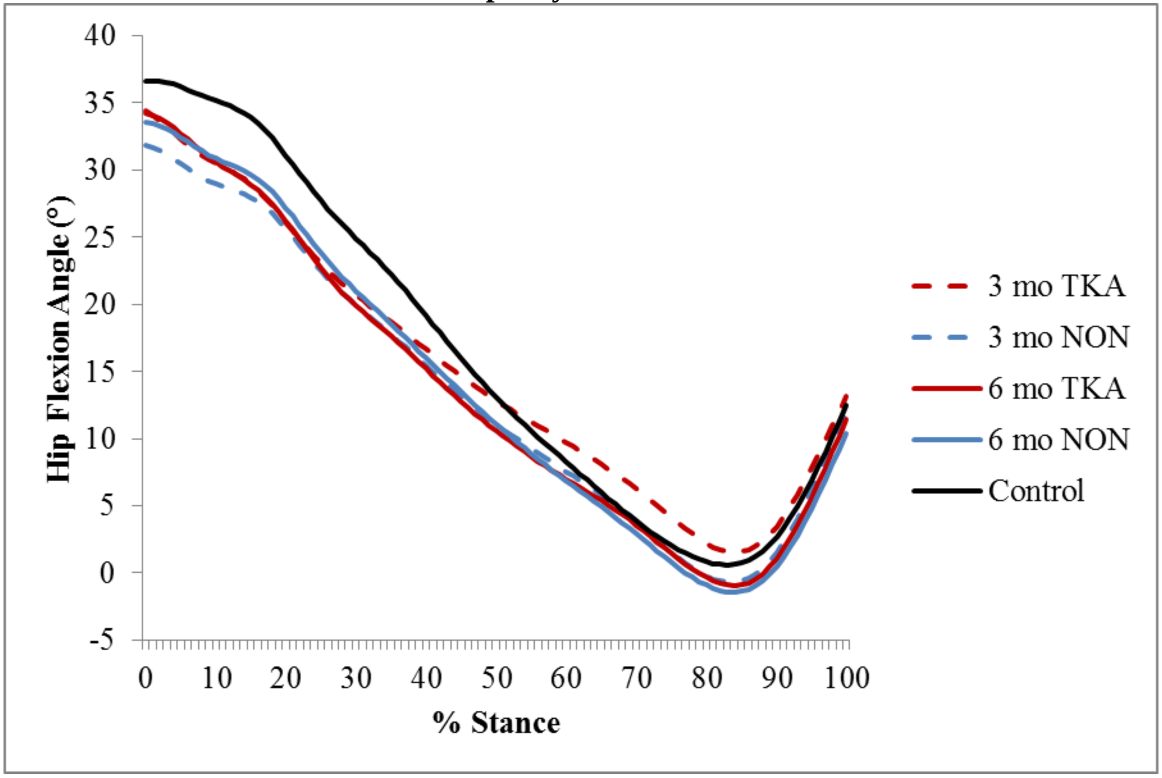
TKA: operative limb
NON: non-operative limb
mo: month
BW: percentage bodyweight (1.0 BW = 100% bodyweight)
% Stance: Percentage of Stance Phase

Figure 4.5: Sagittal Plane Knee Kinematics during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



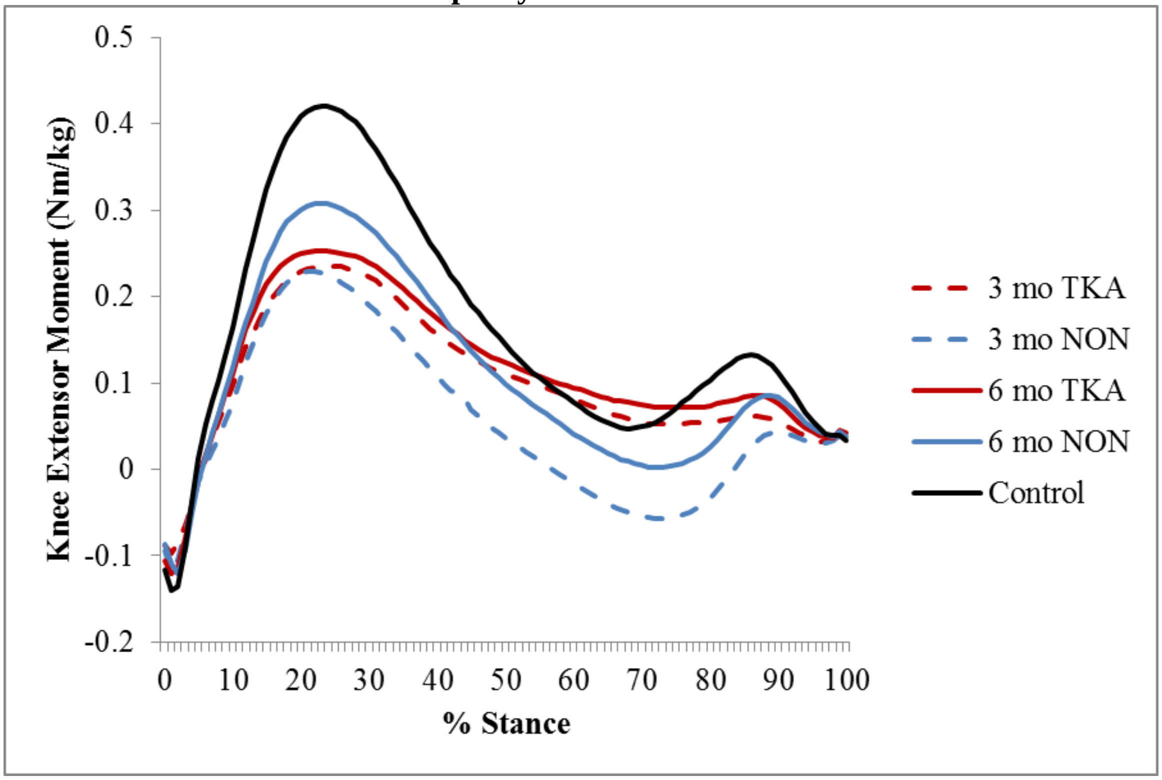
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.6: Sagittal Plane Hip Kinematics during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



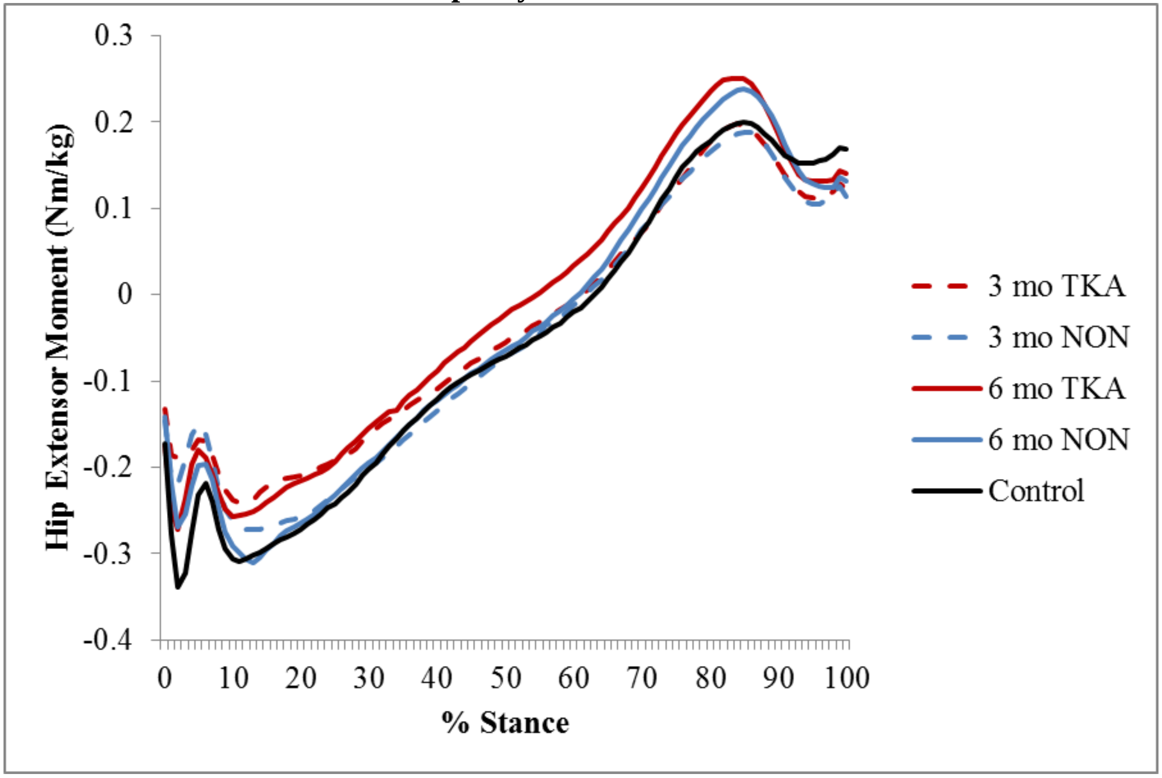
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.7: Knee Extensor Moment during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



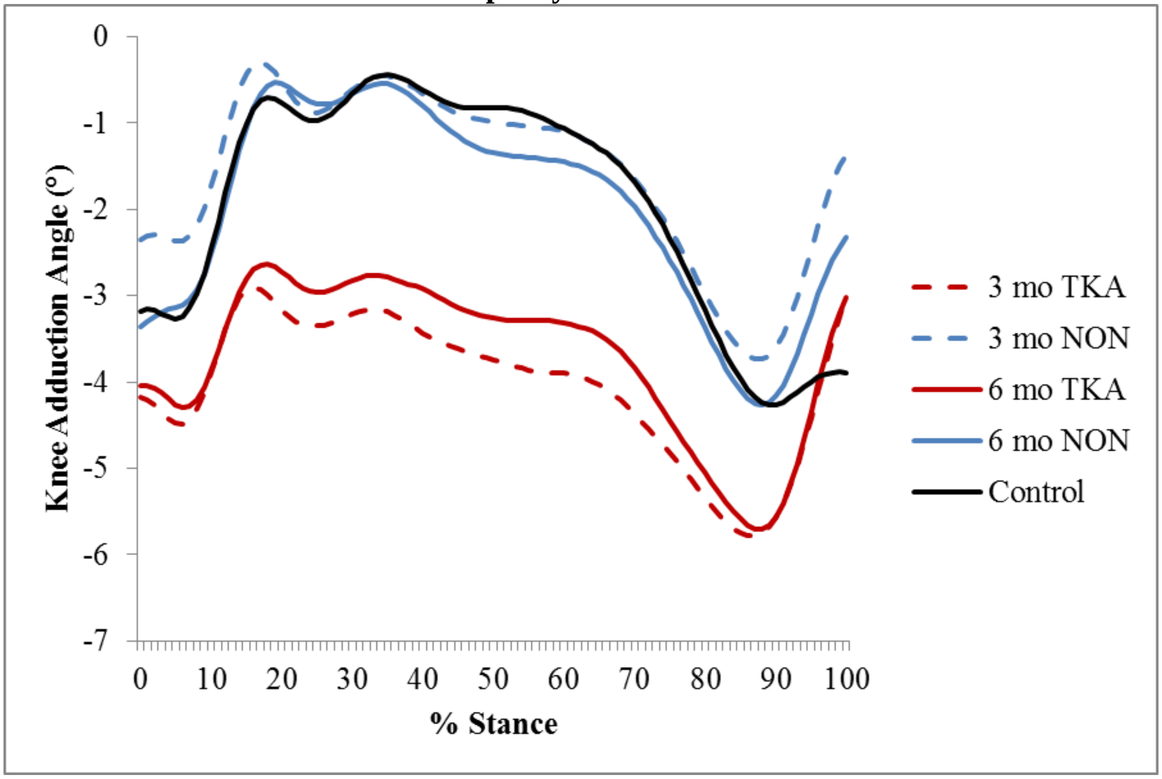
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.8: Hip Extensor Moment during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



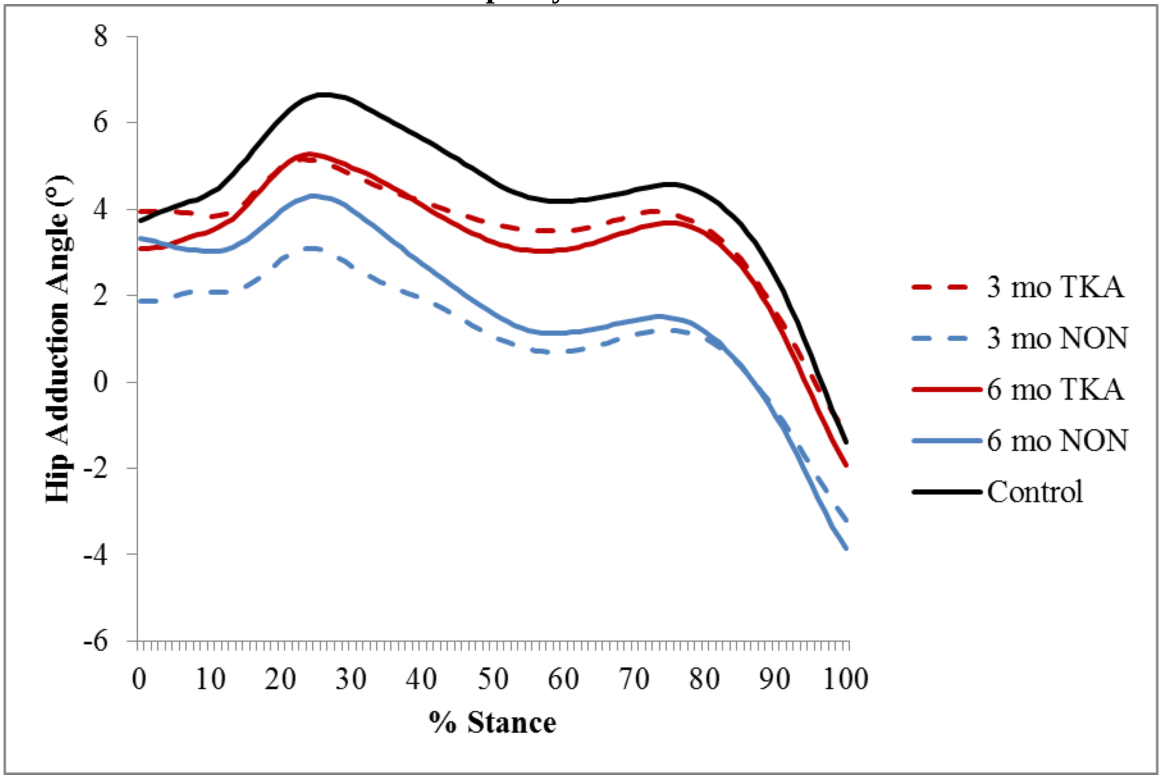
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.9: Frontal Plane Knee Kinematics during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



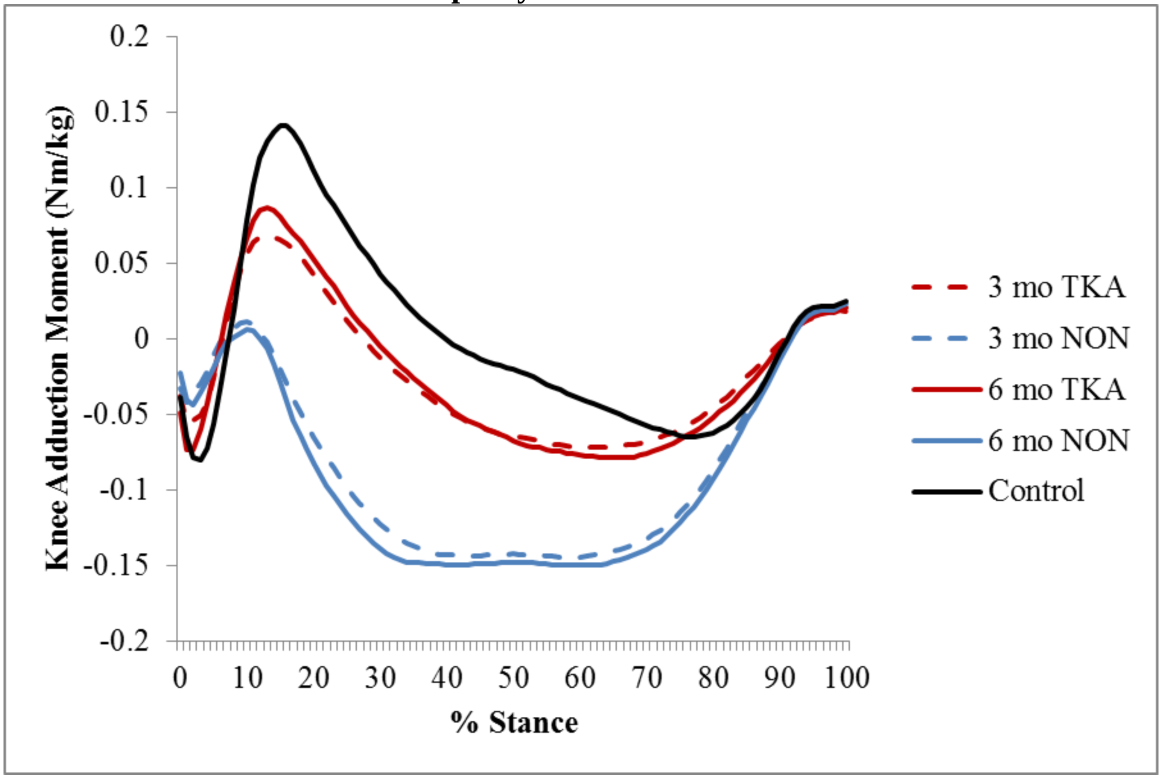
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.10: Frontal Plane Hip Kinematics during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



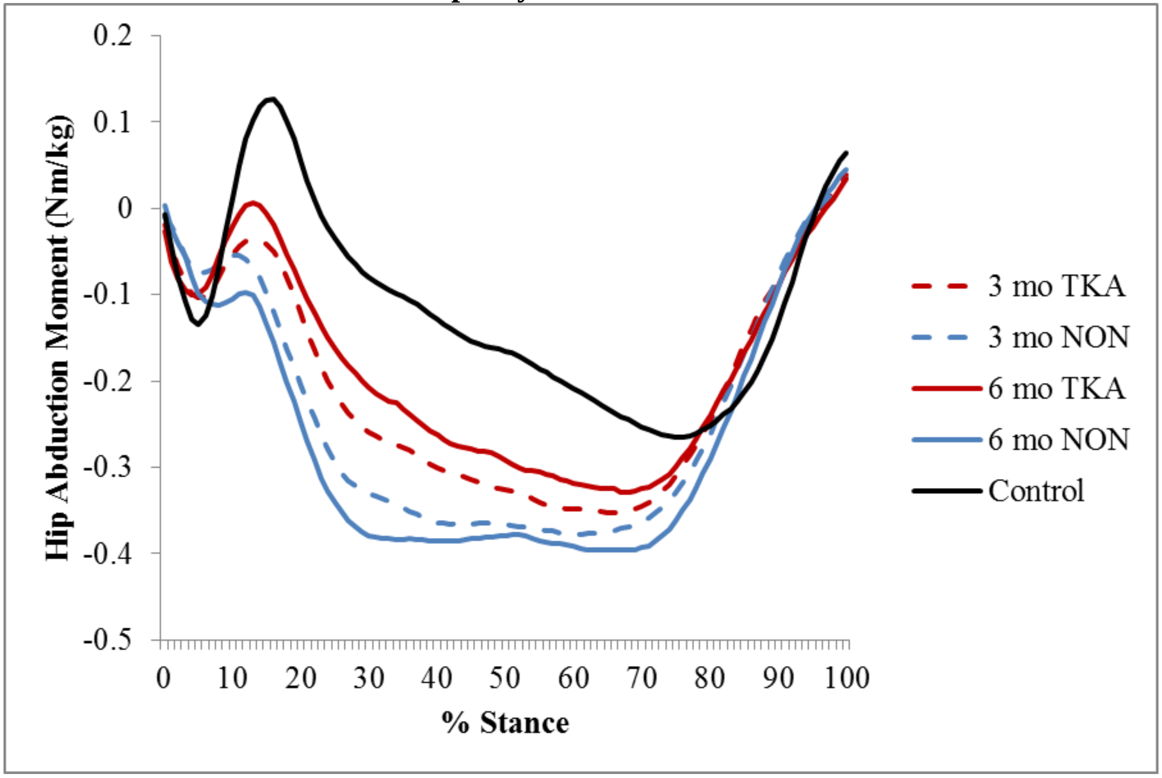
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.11: Knee Abduction Moment during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



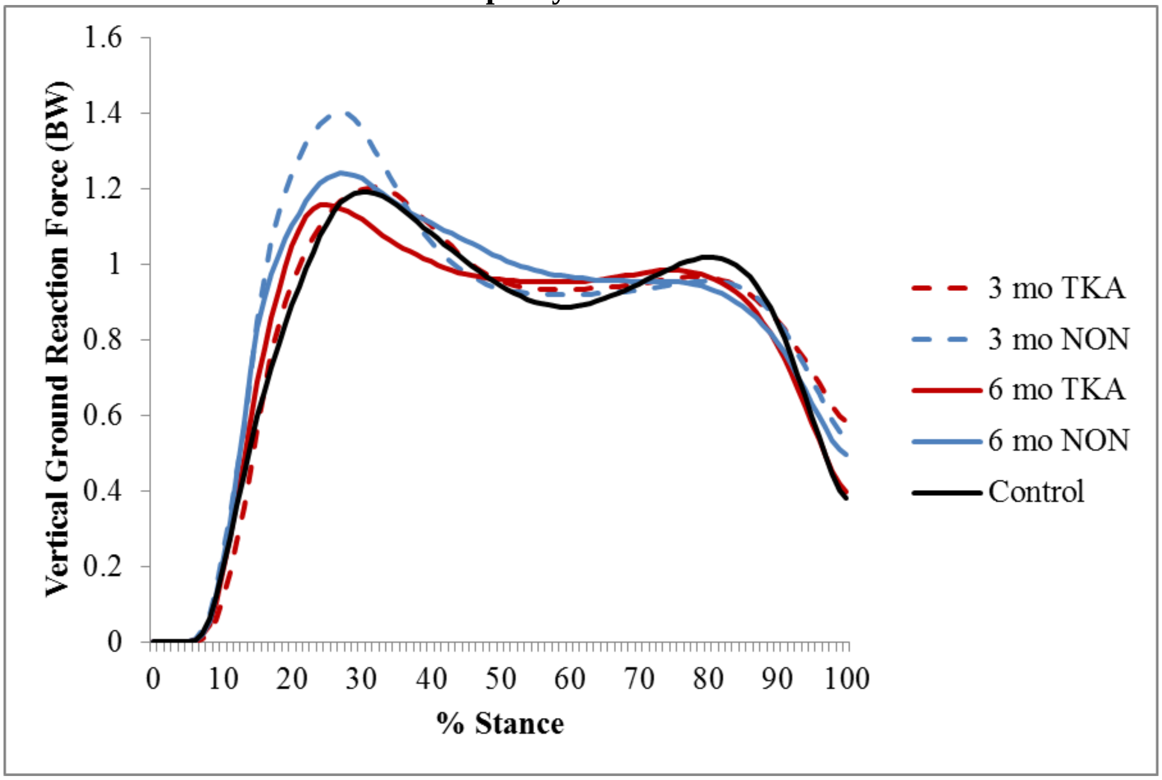
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.12: Hip Abduction Moment during Walking at a Self-Selected Speed in Patients after Total Knee Arthroplasty and Matched Controls



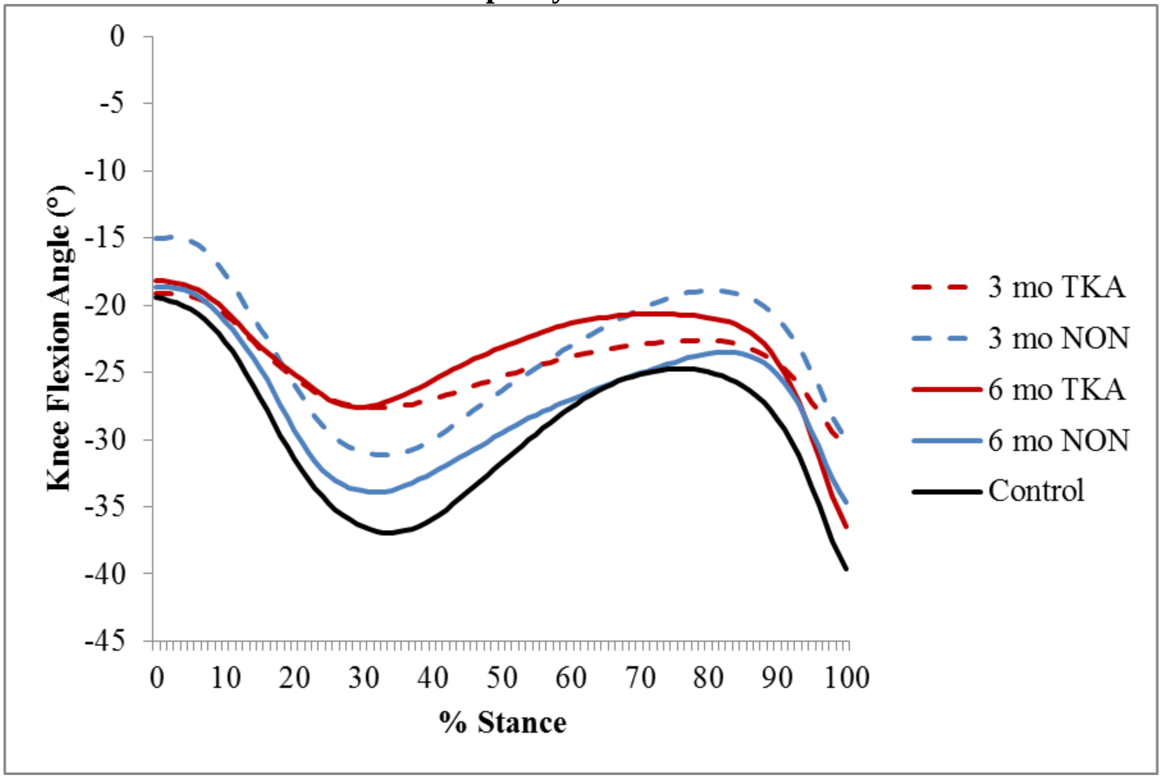
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.13: Vertical Ground Reaction Force during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



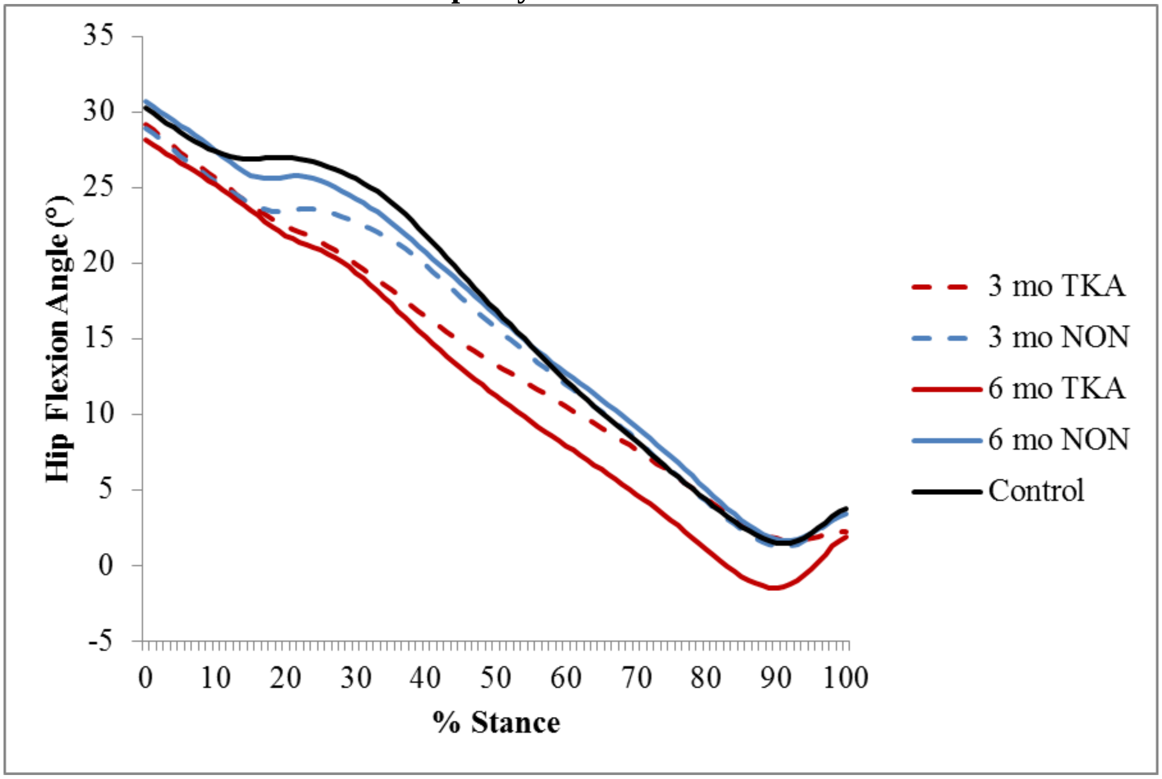
TKA: operative limb
NON: non-operative limb
mo: month
BW: percentage bodyweight (1.0 BW = 100% bodyweight)
% Stance: Percentage of Stance Phase

Figure 4.14: Sagittal Plane Knee Kinematics during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



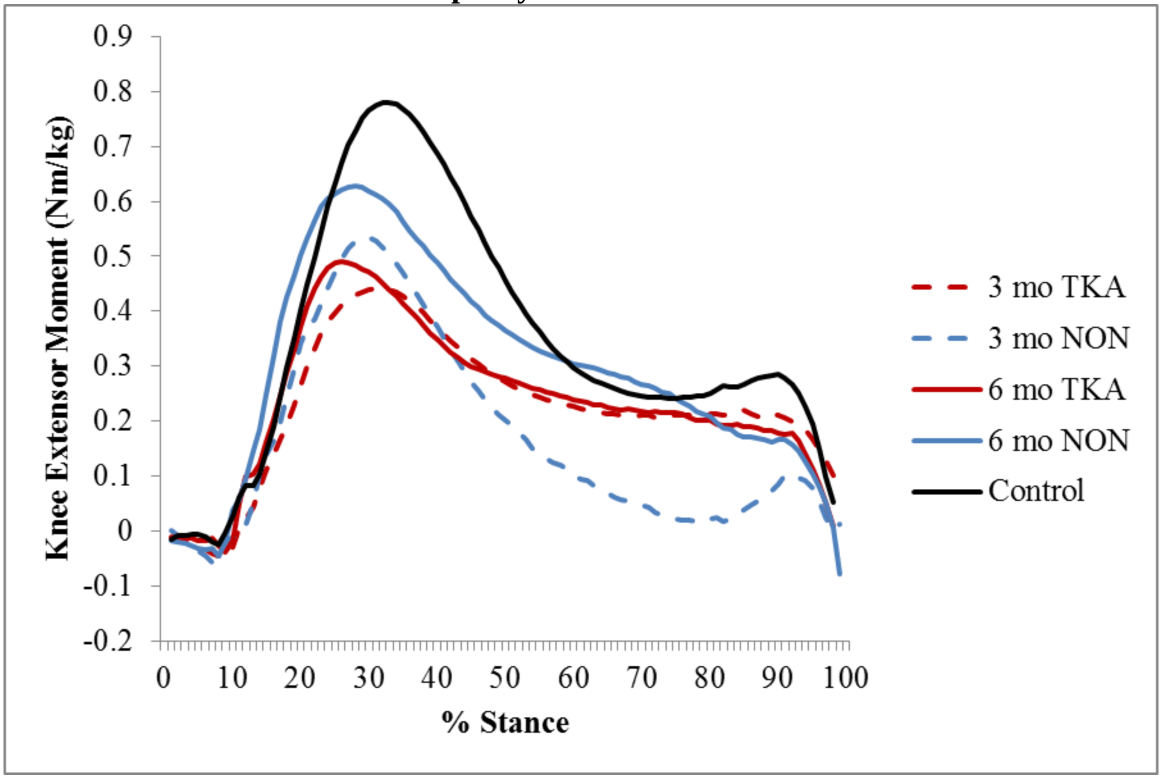
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.15: Sagittal Plane Hip Kinematics during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



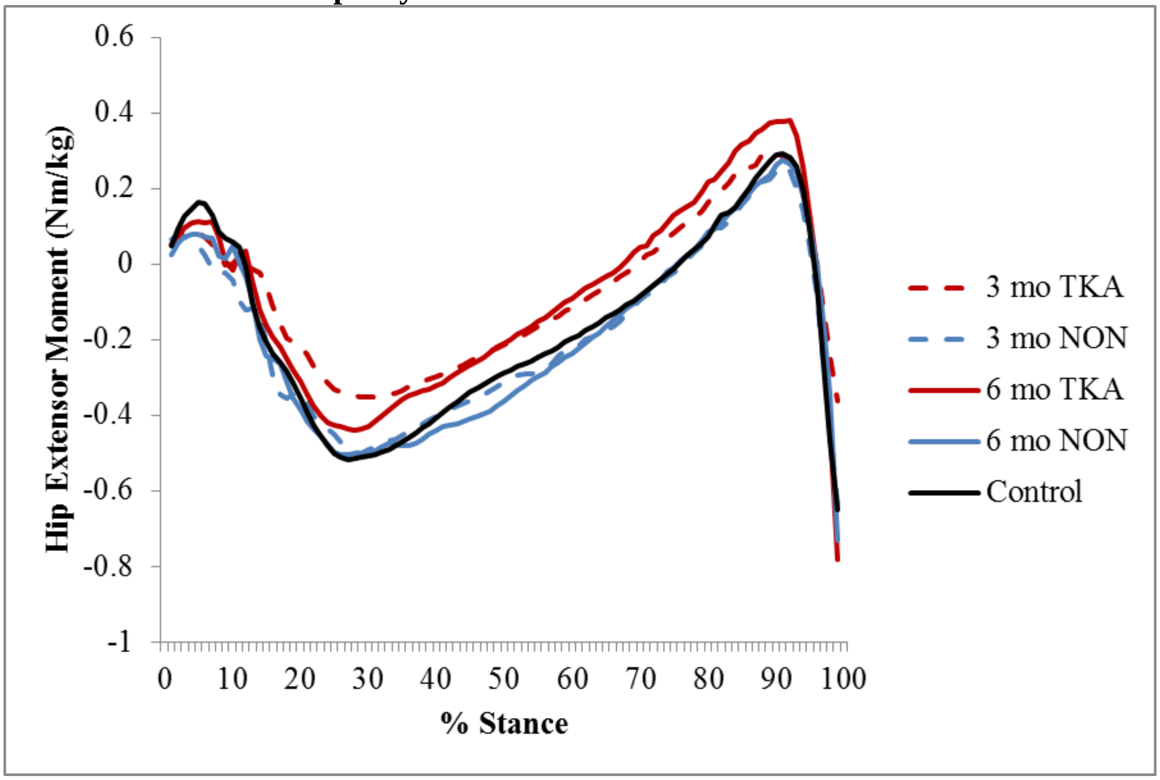
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.16: Knee Extensor Moment during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



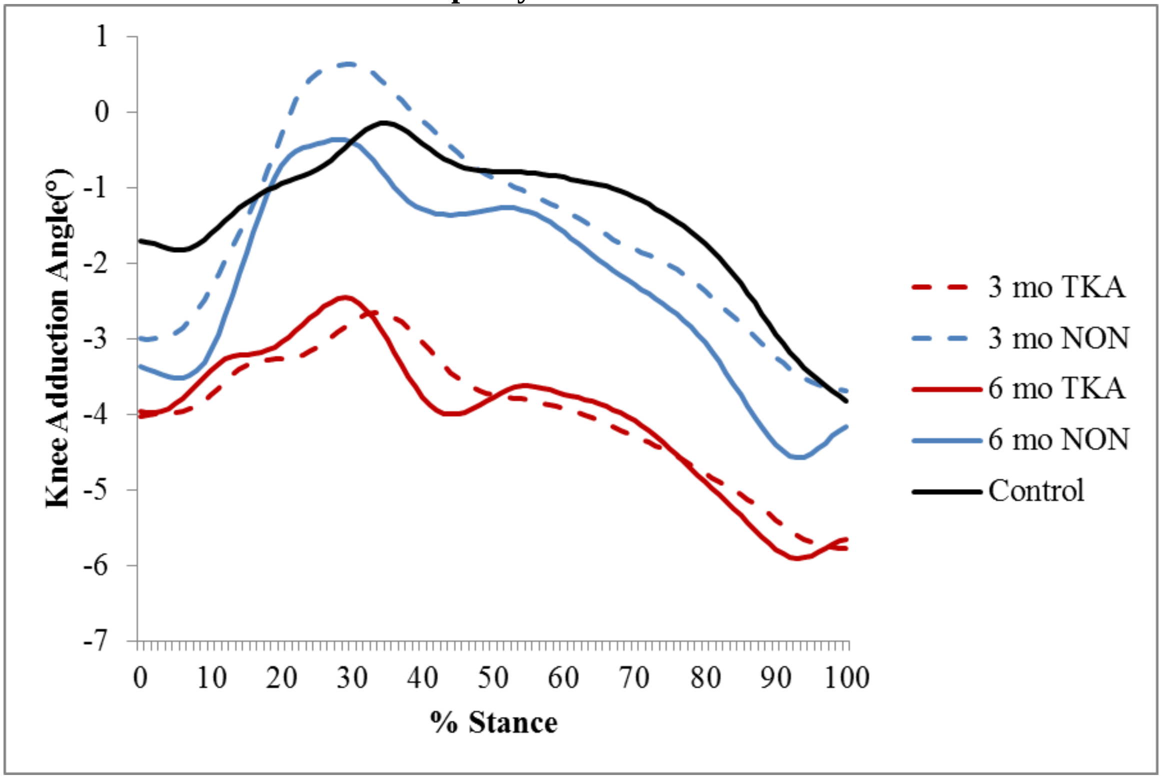
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.17: Hip Extensor Moment during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



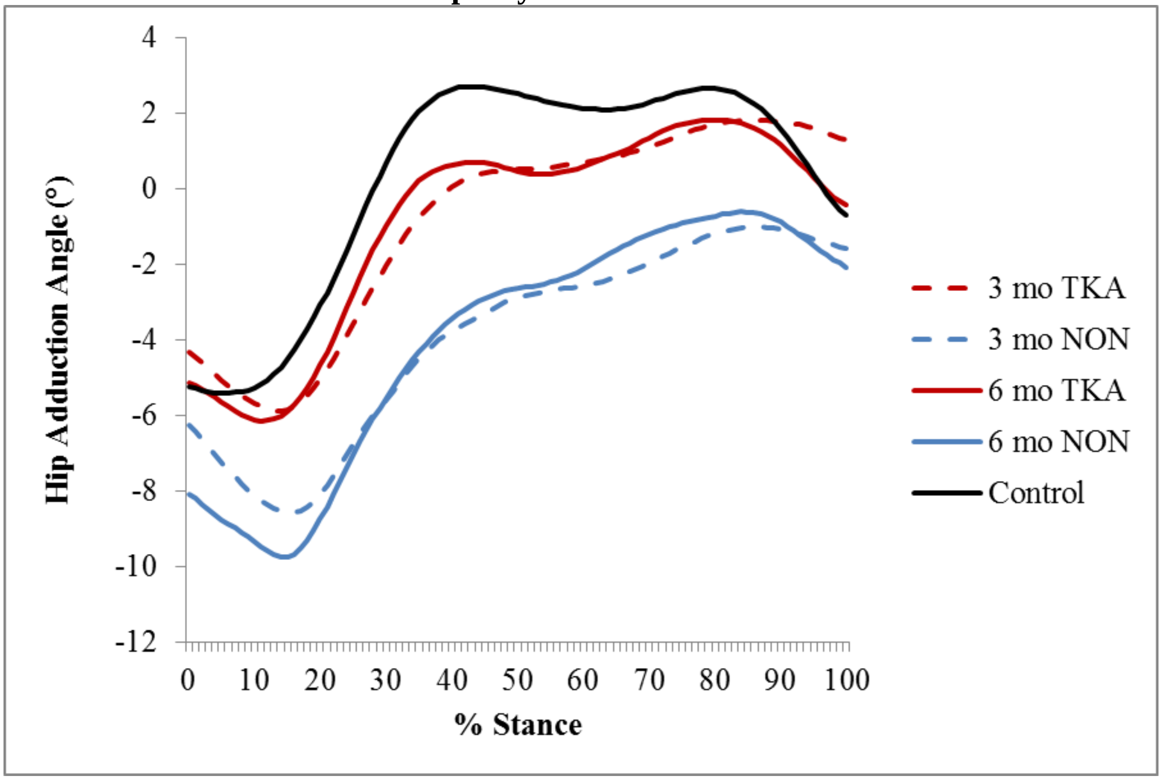
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.18: Frontal Plane Knee Kinematics during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



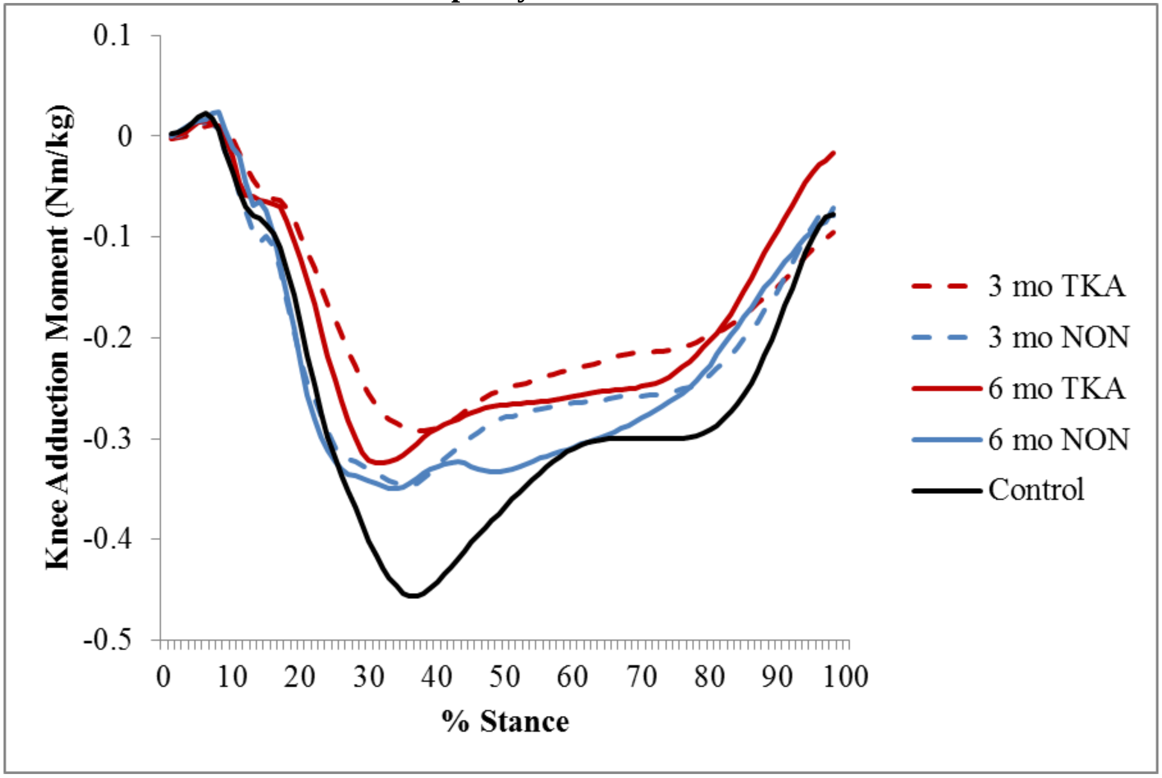
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.19: Frontal Plane Hip Kinematics during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



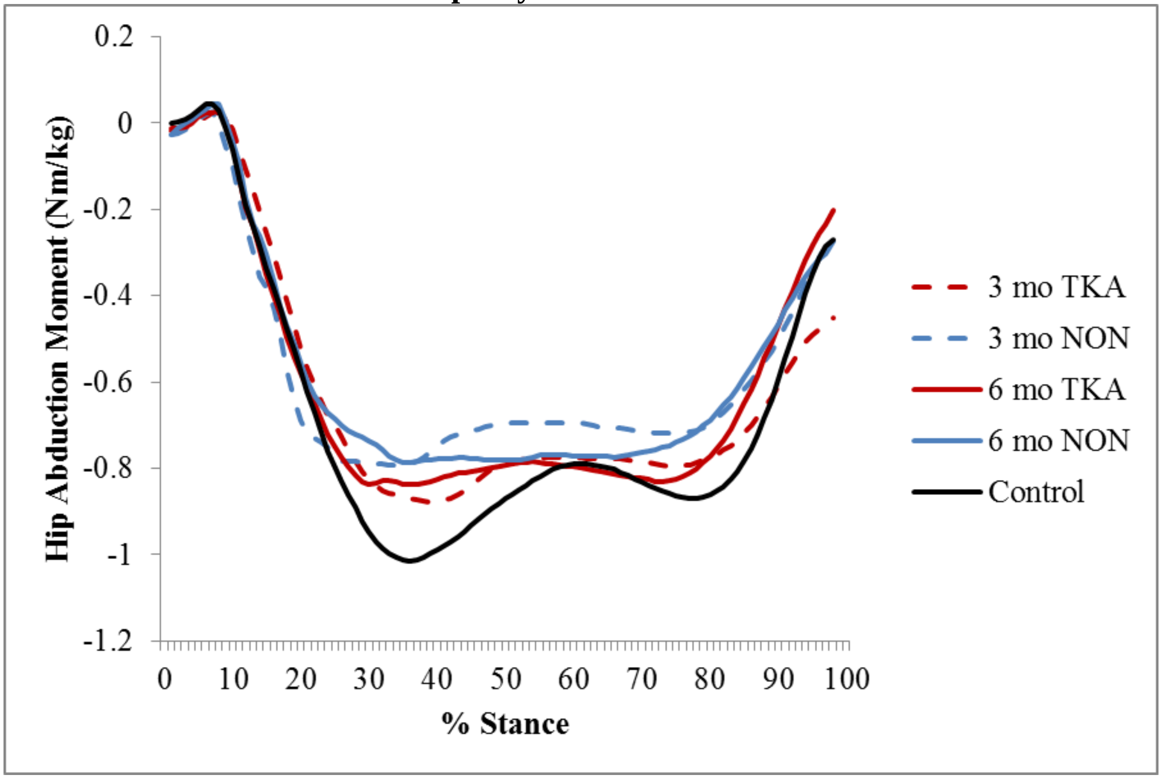
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.20: Knee Abduction Moment during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



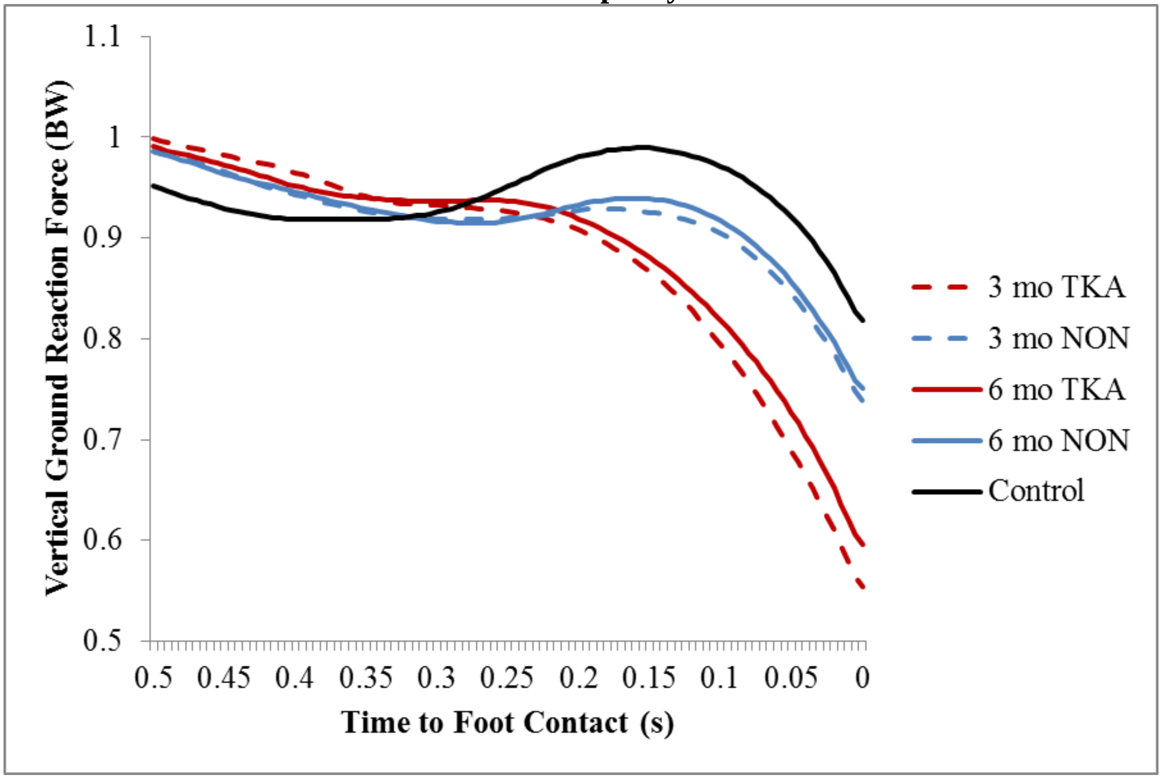
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.21: Hip Abduction Moment during Landing from a Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



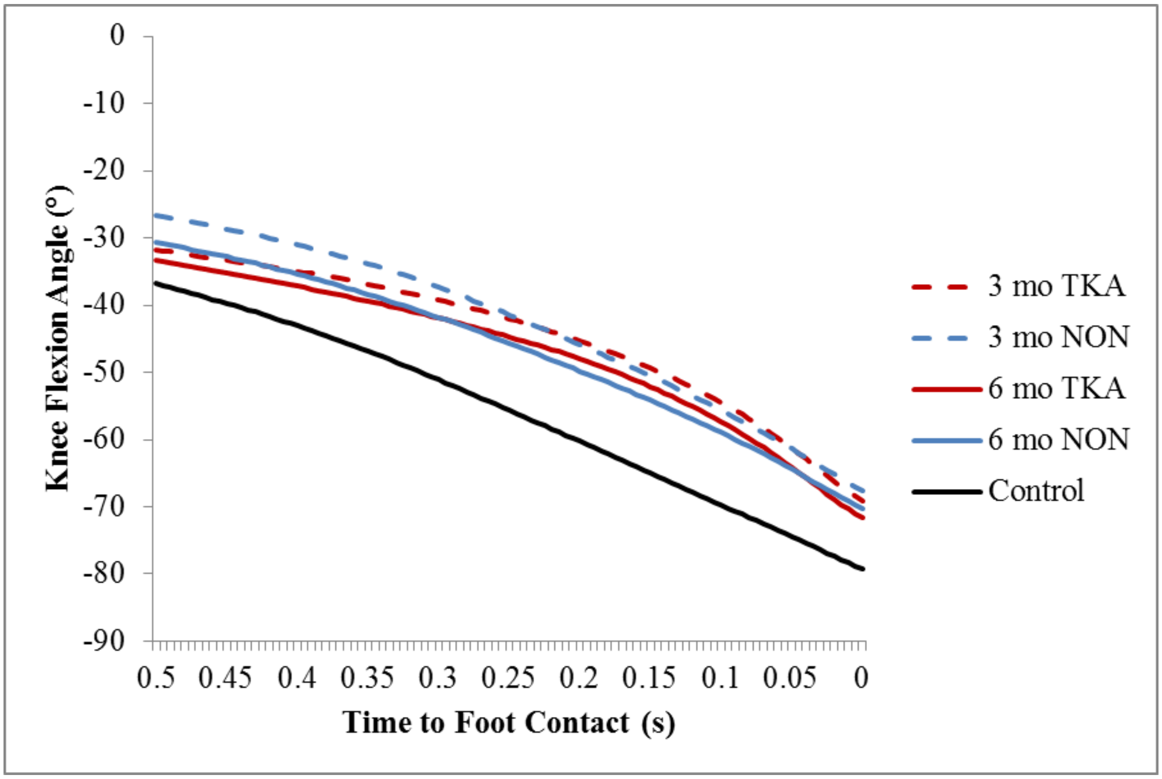
TKA: operative limb
NON: non-operative limb
mo: month
% Stance: Percentage of Stance Phase

Figure 4.22: Vertical Ground Reaction Force of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



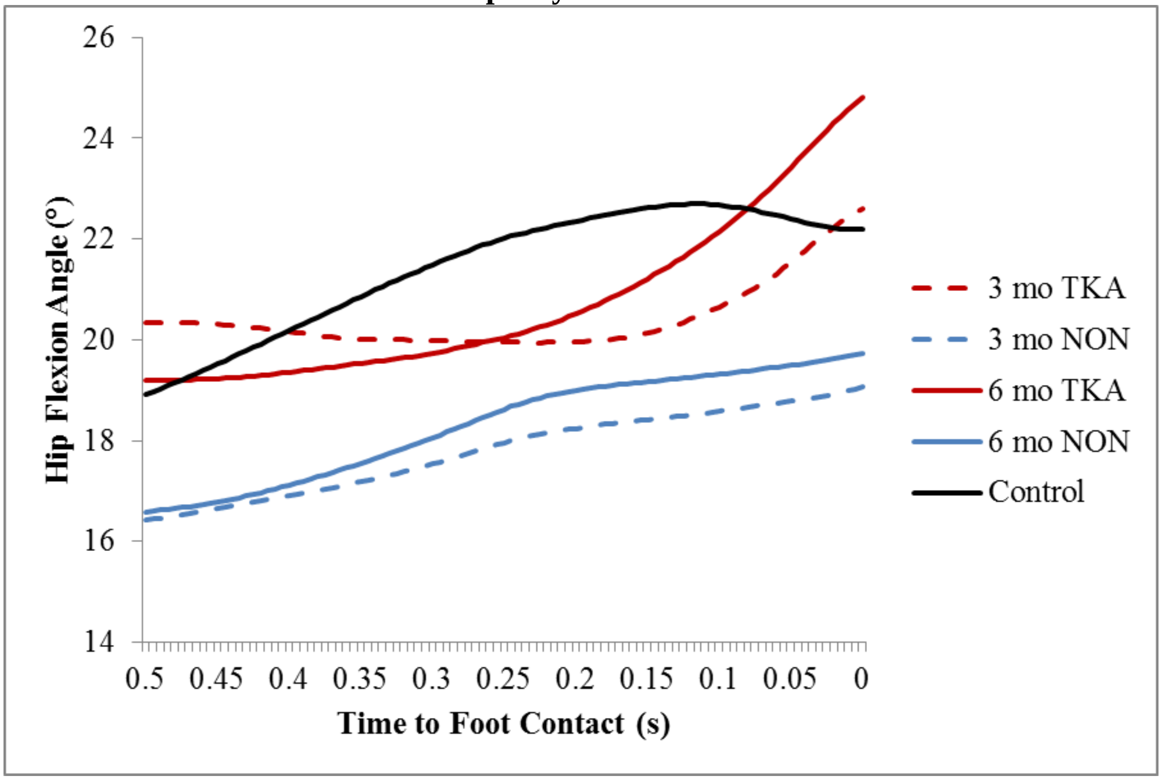
TKA: operative limb
NON: non-operative limb
mo: month
BW: percentage bodyweight (1.0 BW = 100% bodyweight)
% Stance: Percentage of Stance Phase

Figure 4.23: Sagittal Plane Knee Kinematics of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



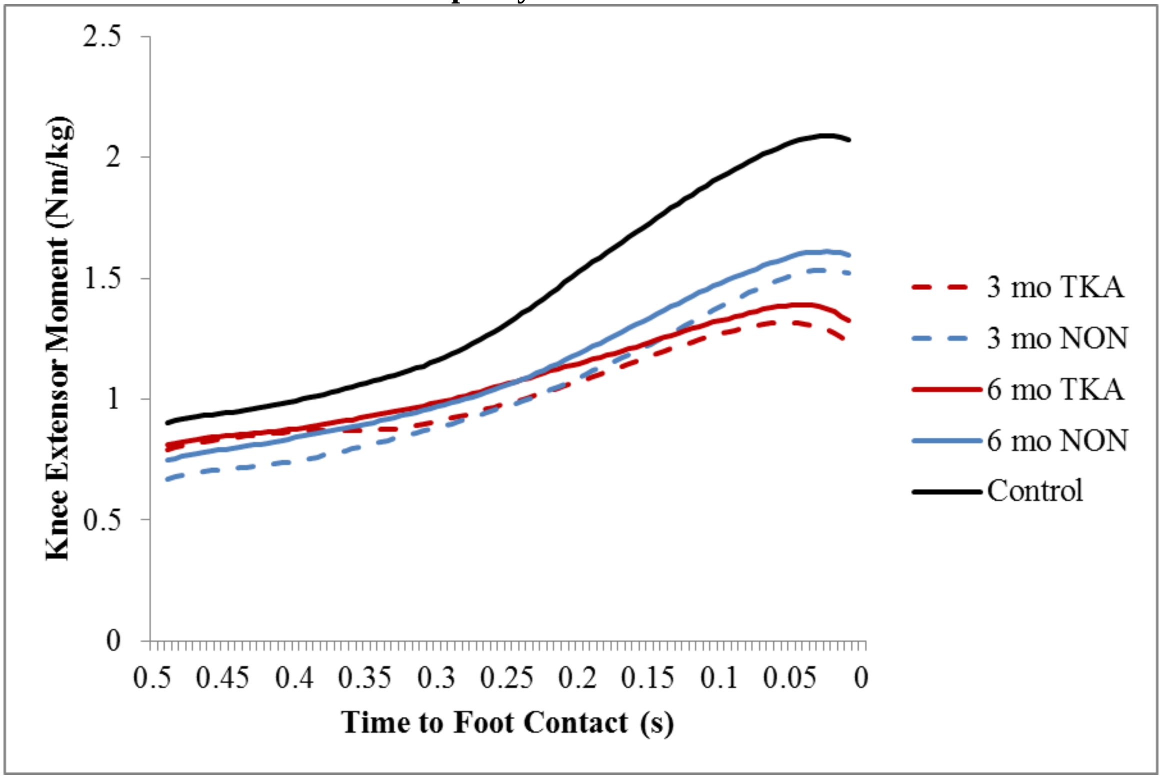
TKA: operative limb
NON: non-operative limb
mo: month

Figure 4.24: Sagittal Plane Hip Kinematics of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



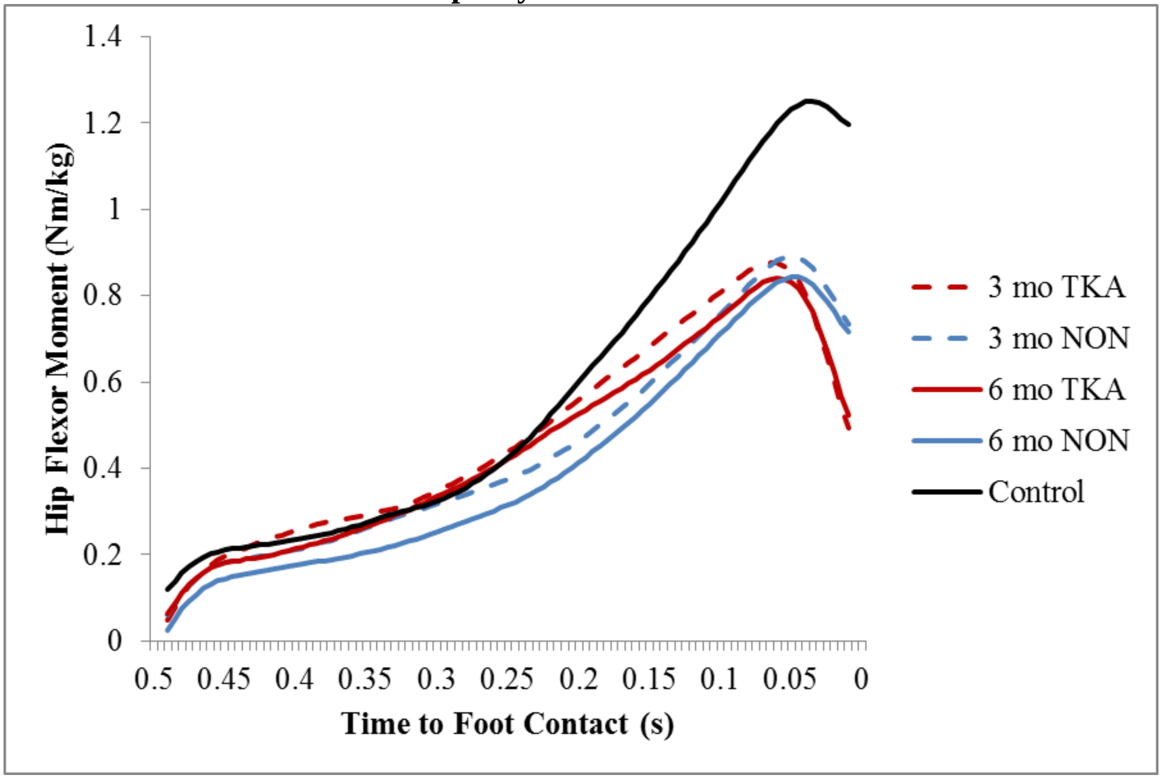
TKA: operative limb
NON: non-operative limb
mo: month

Figure 4.25: Knee Extensor Moment of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



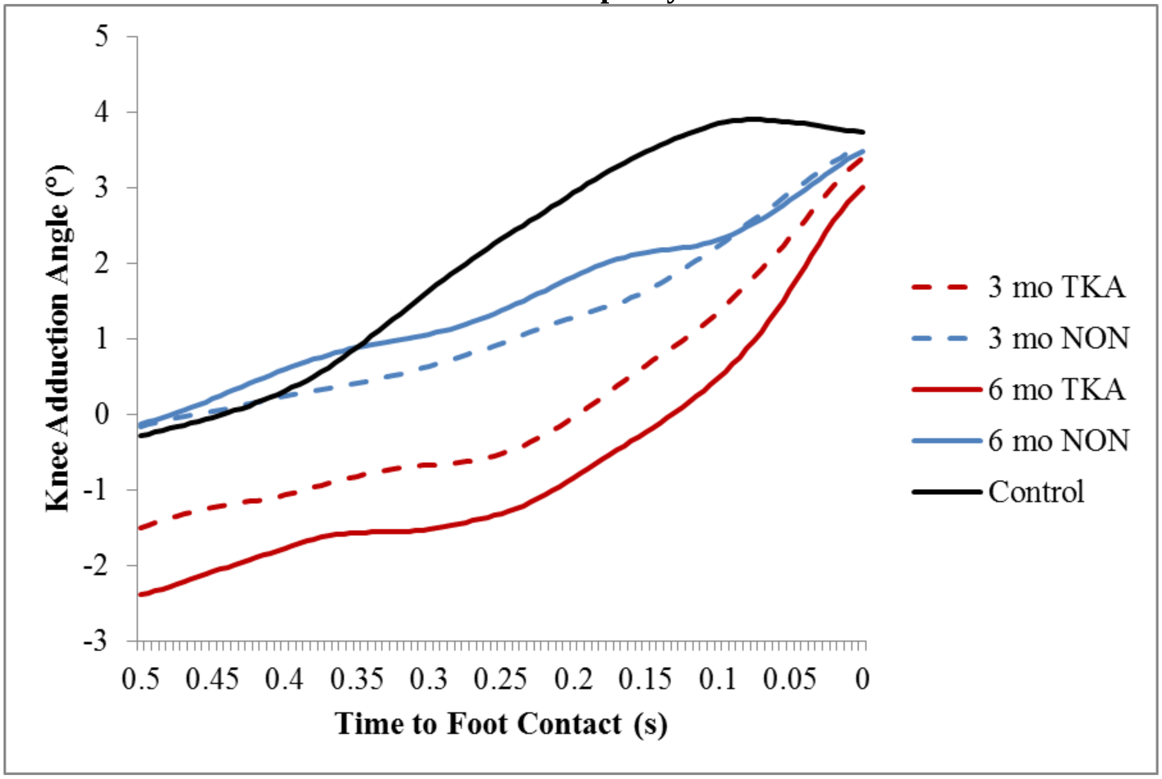
TKA: operative limb
NON: non-operative limb
mo: month

Figure 4.26: Hip Flexor Moment of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



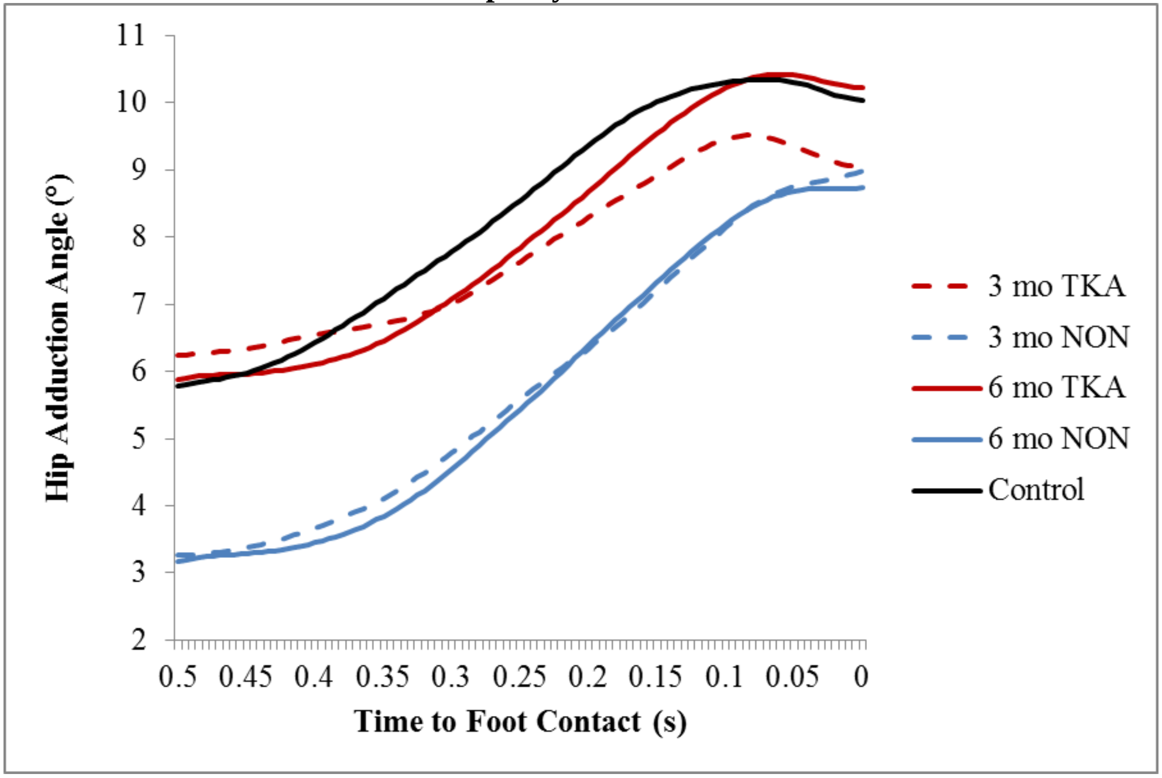
TKA: operative limb
NON: non-operative limb
mo: month

Figure 4.27: Frontal Plane Knee Kinematics of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



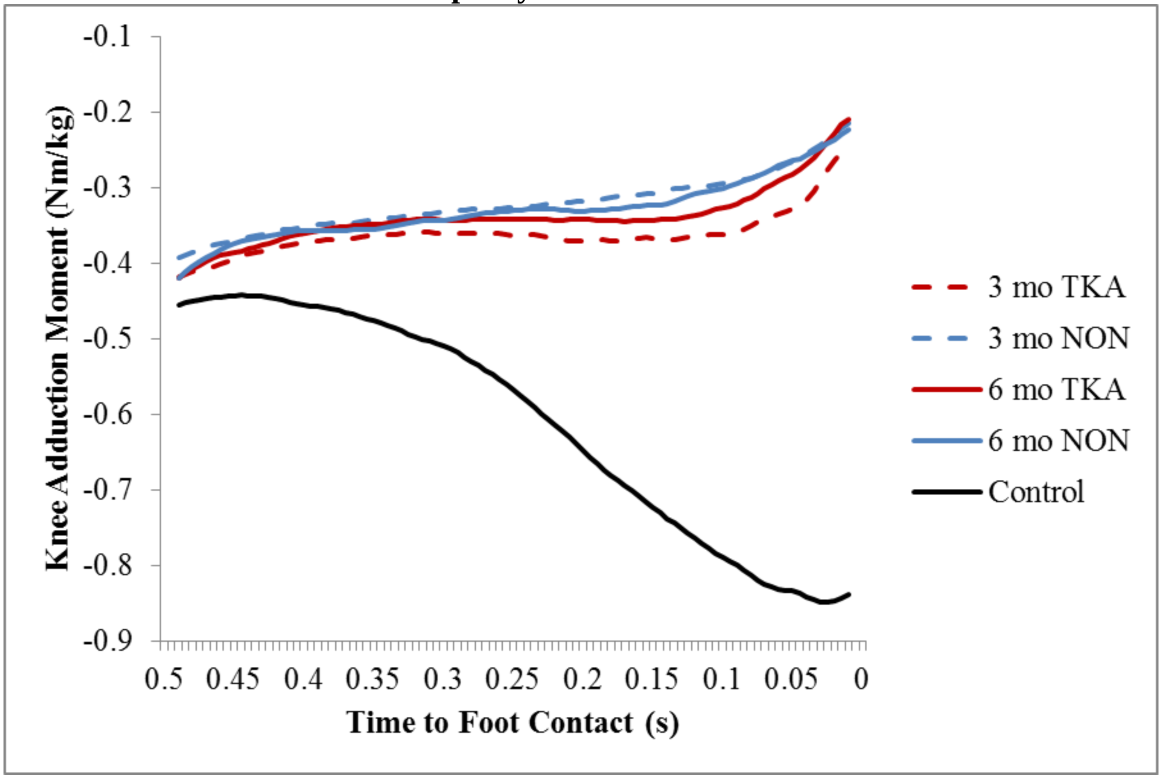
TKA: operative limb
NON: non-operative limb
mo: month

Figure 4.28: Frontal Plane Hip Kinematics of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



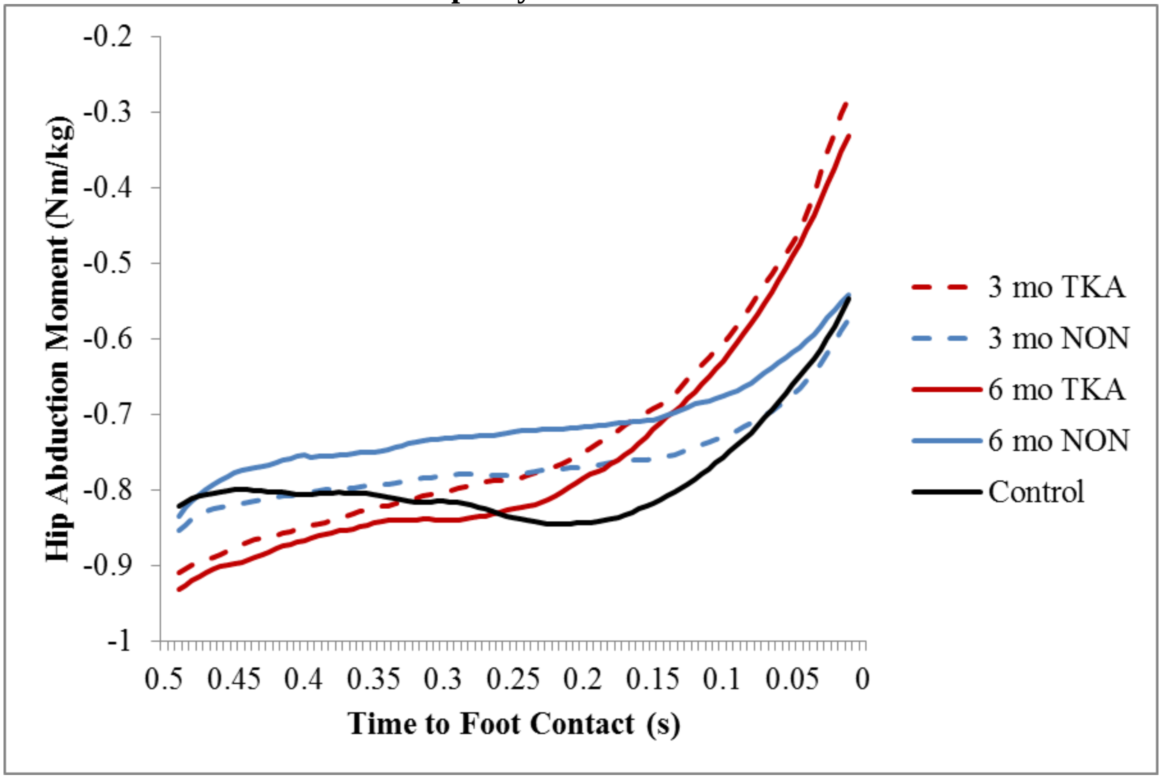
TKA: operative limb
NON: non-operative limb
mo: month

Figure 4.29: Knee Abduction Moment of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



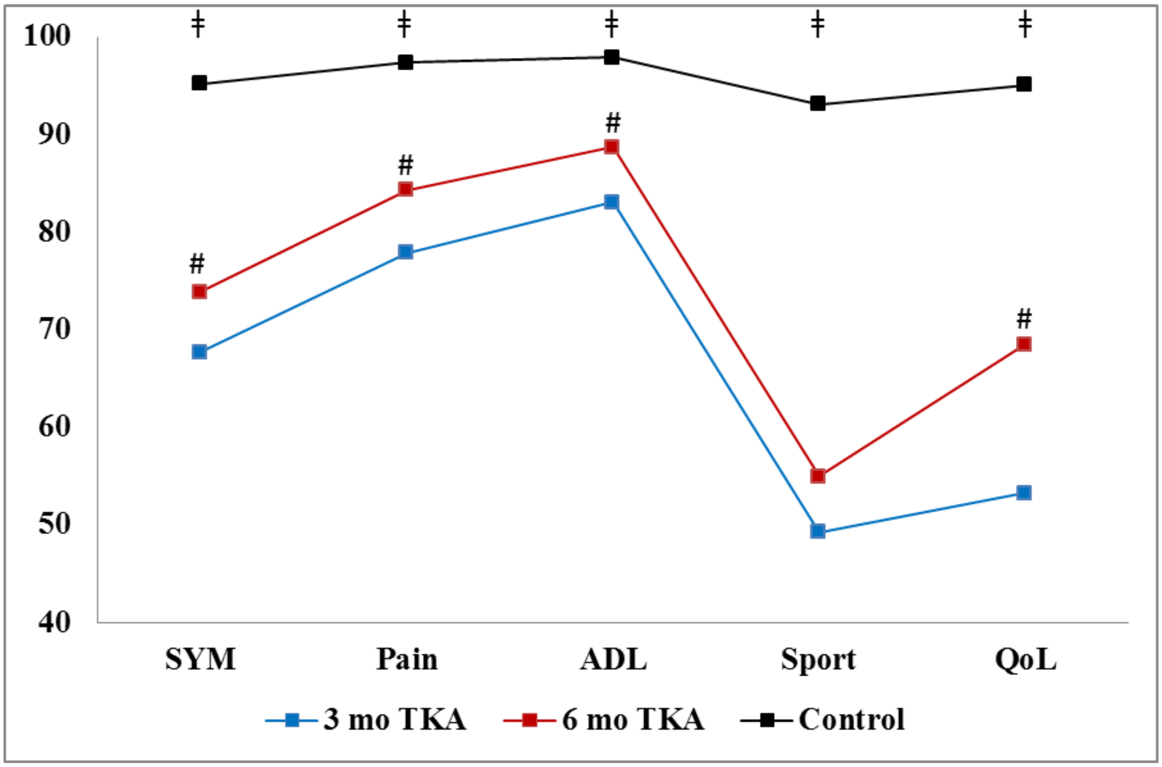
TKA: operative limb
NON: non-operative limb
mo: month

Figure 4.30: Hip Abduction Moment of the Stance Limb during Stair Descent in Patients after Total Knee Arthroplasty and Matched Controls



TKA: operative limb
NON: non-operative limb
mo: month

Figure 4.31: Line Plots Comparing Knee Injury and Osteoarthritis Outcome Questionnaire Scores in Patients after Total Knee Arthroplasty and Matched Controls



significant 3 mo vs 6 mo
ǂ significant vs Control

SYM: Symptoms subscale
Pain: Pain subscale
ADL: Activities of Daily Living subscale
Sport: Sports/Recreation subscale
QoL: Knee-related Quality of Life subscale
TKA: Total Knee Arthroplasty Group
mo: month

Chapter 5: The Role of Hip Muscle Strength and Functional Test Performance in Improving Patient-Reported Outcomes after Total Knee Arthroplasty

5.1 ABSTRACT

Purpose and Hypothesis: Patient-reported outcome measures are common clinical tools used to assess recovery after total knee arthroplasty (TKA). Patient-reported outcomes and measures of physical performance demonstrate weak relationships both early (< 1 month) and late (> 1 year) after TKA. However, previous studies have included only a limited number of physical performance measures and have yet to assess the intermediate periods of recovery (3 – 6 months post-surgery) when physical performance is often most improved. Thus, the purpose of this study is to evaluate the association between quadriceps and hip muscle peak strength and rate of torque development (RTD), five-time sit-to-stand (FTSTS), and Knee Injury and Osteoarthritis Outcome scores (KOOS) at 3 months and 6 months post-TKA and determine the association between the changes in the three measures from 3 to 6 months post-surgery. It was hypothesized that significant correlations would be observed between muscle strength measures and both FTSTS and KOOS scores at all time points, but no significant correlations would be observed between FTSTS and KOOS scores.

Methods: Twenty-one subjects participated in the study at 3 and 6 months post-TKA (7 male, 14 female, height: 1.68 ± 0.08 m, mass: 90.95 ± 21.04 kg, BMI: 32.27 ± 7.4 kg/m^2, Age: 60.6 ± 8.1 years). At both time points, the subjects performed isometric strength testing of hip abductors, hip external rotators, and quadriceps muscle groups to determine peak strength and RTD. Subjects also performed the FTSTS and completed the KOOS questionnaire. Improvement between time points was quantified by subtracting 3 month

values from 6 month values. Pearson product-moment correlations were used to assess relationships between measures at both time points and to determine the association between improvements in each measure.

<u>Results:</u> At 3 months post-surgery, peak hip external rotation strength, peak quadriceps strength, and FTSTS performance were significantly correlated with KOOS Pain and KOOS Sport subscales. FTSTS was significantly correlated with KOOS ADL subscale (R = -.632, p = .002) and peak hip abduction strength was significantly correlated with KOOS Pain subscale (R = .511, p = .021). At 6 months, only peak hip abduction strength was correlated with KOOS Symptoms subscale (R = .572, p = .013) and FTSTS significantly correlated with KOOS ADL (R = -.537, p = .018). Changes in KOOS Pain subscale were negatively correlated with peak hip abduction strength and RTD (R = -.595, p =.009; R = -.476, p = .046), while changes in KOOS ADL were positively correlated with quadriceps RTD (R = .524, p = .021).

<u>Conclusion:</u> Hip muscle strength and FTSTS performance were moderately correlated with KOOS Pain, ADL, and Sport subscales at 3 months post-surgery, with fewer relationships observed at 6 months and among improvements between time points. Maximizing hip muscle strength and FTSTS performance during the first 3 months of rehabilitation may result in improved patient-reported function after TKA.

5.2 INTRODUCTION

Osteoarthritis (OA) affects more than 20 million Americans, with the knee joint most commonly developing OA [165, 166]. Total knee arthroplasty (TKA) is the current gold-standard intervention for end-stage knee osteoarthritis and more than 3.48 million procedures are projected to be performed annually by the year 2030 [2]. Despite significant relief from OA-related pain after TKA, between 30-52% of patients report persistent difficulty with functional mobility after surgery and rehabilitation, resulting in reduced health and quality of life outcomes for many [6, 7, 105, 106].

Patient-reported questionnaires, such as the Knee Injury and Osteoarthritis Outcome Score (KOOS), are commonly utilized to evaluate patient-perceived function [88, 112]. These self-report questionnaires are appealing to researchers and clinicians due to their validity in patients after TKA, high internal consistency, limited time and cost demands, and lack of need for an in-person assessment[112]. Despite these advantages, there is growing evidence that patient-reported questionnaires fail to capture changes in physical performance after TKA [100, 153]. Since patient-reported questionnaires are reliant upon patient perception, these measures are particularly influenced by the patient's pre-operative abilities and presence of pain. Reduction in joint pain after TKA is associated with improvement in patient-reported abilities despite no apparent improvement in tests of physical performance [153, 167]. Thus, patient-reported questionnaires alone are not sufficient for determining recovery and functional status after TKA.

In response, it has been recommended to assess both subjective self-report and objective measures of physical function when evaluating patients after TKA [100, 153].

These objective measures included assessment of muscle strength and functional measures of strength such as the five-time sit-stand (FTSTS). Previous studies have noted the disconnect between patient-reported function and measures of physical performance both very early (1 month or less) and very late (≥ 1 year) after TKA [102, 168]. However, few studies have investigated the intermediate period (3-6 months) in which patients often maximize muscle strength, functional abilities, and outcomes stabilize [12, 100]. Much of the previous work has focused solely on peak isometric quadriceps strength, which may be a limited measure of muscle performance. Since functional activities are time-dependent tasks, an individual's ability to quickly produce muscle torque may be more related to their physical performance. As such, rate of torque development (RTD) has been revealed as potentially a more sensitive measure of recovery after TKA [18, 144]. Furthermore, since dynamic activities require adequate muscle strength throughout the lower extremity, recent evidence has noted improvements in functional ability with increased peak hip abduction strength [17, 62]. To date, no studies have investigated the relationships between quadriceps RTD and hip muscle peak strength or RTD on patient-reported function or physical performance measures. Hence, these additional muscle performance measures may further elucidate the influence of physical improvement with patient-perceived improvement.

The purpose of the this study is to evaluate the association between quadriceps and hip muscle peak strength and RTD, FTSTS, and KOOS scores at 3 months and 6 months post-TKA and determine the association between the changes in the three measures from 3 to 6 months post-surgery. It was hypothesized that significant correlations would be observed between muscle strength measures and both FTSTS and

KOOS scores at all time points, but no significant correlations would be observed between FTSTS and KOOS scores.

5.3 METHODS

Participants

All participants read and signed an informed consent document as approved by the University Institutional Review Board. For inclusion in the study, all participants were required to meet the following criteria: 1) between the ages of 40-90 years old at the time of the 3 month testing 2) undergone unilateral TKA within the past 3 months, 3) no prior surgery to the contralateral knee, low back, or either hip, ankle, or foot, 4) no presence of neurological or balance disorder that requires use of an assistive device for mobility, and 5) must be able to walk at least 10 minutes without an assistive device. Patients with contralateral knee osteoarthritis were not excluded from the study; however, if the contralateral knee was rated as more symptomatic than the TKA limb at 3 months post-surgery or the participant was scheduled for contralateral TKA within the next 3 months, the participant was excluded. All patients completed rehabilitation in community outpatient clinics as is the standard of care. All participants completed all assessments at both the 3 and 6 month post-surgery time points.

Muscle Strength

The following isometric strength tests of the operative limb were performed using a Biodex System 4 electromechanical dynamometer (Biodex Systems, Shirley, NY): hip abduction, hip external rotation, and knee extension. In sidelying, hip abduction was performed with the hip in a neutral position with the limb being tested in the superior position. The dynamometer arm was secured 5 cm proximal to the lateral tibiofemoral joint. Hip external rotation and knee extension were each assessed with the participant in sitting with the hips in neutral rotation, flexed to 85°, and knees flexed to 90°. The dynamometer arm was secured 5 cm proximal to the medial malleolus. A practice trial was performed for each muscle group. For the two hip strength tests, four experimental trials were collected and three experimental trials were collected for the quadriceps. Participants were asked to perform each trial with maximal effort and perform the motion "as hard as fast as possible".

Peak isometric strength and RTD were the outcomes of interest for strength testing. Custom MATLAB code (MathWorks Inc, Natick, MA) was used to calculate peak isometric strength and RTD. RTD was calculated by determining the mean slope of the first 200 milliseconds of the torque-time curve between the onset of the trial and peak torque. Peak strength and RTD were each normalized to body mass by dividing peak strength and RTD by the subject's mass in kilograms.

Five-Time Sit-to-Stand

Participants completed the FTSTS at each time point. Beginning seated in an armless chair with a 42.0 cm seat height, participants performed five consecutive sit-to-stands as quickly as possible. Performance was recorded in seconds and measured using a hand-held stopwatch. Time began upon the participant's back leaving the back rest of the chair and time ended when the patient returned to a sitting position after the fifth sit-to-stand. Use of the upper extremities was not permitted during any portion of the test. Two trials were allowed but only the fastest trial was used for data analysis.

Knee Injury and Osteoarthritis Outcome Score

At each time point, participants completed the KOOS questionnaire, a 42 item questionnaire divided into five individually-scored subscales: Symptoms (Sym), Pain, function in activities of daily living (ADL), function in sport and recreation (Sport), and knee-related quality of life (QoL). Scores on each subscale range from 0 (worst) to 100 (best). The test-retest reliability of the KOOS has been established for use after TKA, allowing for comparison among time points during recovery [112].

Statistical Analysis

Means for peak strength and RTD of hip abduction, hip external rotation, and quadriceps strength testing, FTSTS, and KOOS scores were created for the 3 month and 6 month testing time points. Changes between 3 and 6 months were calculated by subtracting 3 month data from 6 month data for each variable of interest. Using Pearson product-moment correlations, relationships between muscle strength, FTSTS, and KOOS scores were assessed for 3 and 6 month time points and the change between time points. Statistical significance was defined as $p \leq 0.05$.

5.4 RESULTS

TKA Participants

A total of 21 participants after TKA completed the study. Mean height 1.68 ± 0.08 m, mass 90.95 ± 21.04 kg, body mass index 32.27 ± 7.4 kg/m^2, age 60.6 ± 8.1 years.

Summary of Muscle Strength, FTSTS, and KOOS performance.

All measures of muscle strength improved between 3 and 6 months with the exception of hip external rotation and hip abduction RTD (Table 5.1). Performance on the FTSTS and all subscales of the KOOS significantly improved as well (Table 5.1).

Percentage improvements between 3 and 6 month time points are shown in Figures 5.1A and 5.1B.

Correlations: 3 month

At 3 months post-surgery, no significant correlations were observed between muscle strength (peak or RTD) and the FTSTS, KOOS Sym, KOOS ADL, or KOOS QoL subscales. Measures of peak strength in hip abduction, hip external rotation, and quadriceps were significantly positively correlated with the KOOS Pain subscale. Additionally, peak quadriceps and hip external rotation strength were significantly positively correlated with KOOS Sport subscale. FTSTS was significantly negatively correlated with KOOS Pain, KOOS ADL, and KOOS Sport subscales (Table 5.2). Lastly, KOOS Pain and KOOS ADL subscales were strongly correlated (Table 5.3).

Correlations: 6 month

At 6 months post-surgery, no significant correlations were observed between muscle strength measures and the FTSTS, KOOS Pain, KOOS ADL, KOOS Sport, or KOOS QoL subscales. Peak hip abduction strength was significantly positively correlated with KOOS Sym subscale. FTSTS performance was significantly negatively correlated with KOOS ADL, but no other subscales at 6 months post-surgery (Table 5.4). KOOS Pain and KOOS ADL subscales were also strongly correlated at 6 months post-TKA (Table 5.3)

Correlations: Improvements from 3 to 6 month

No significant correlations were observed between muscle strength measures and FTSTS, KOOS Sym, KOOS Sport, and KOOS QoL subscales. Negative correlations were observed between improvements in hip abduction peak and RTD and KOOS Pain subscales. A positive correlation was observed between quadriceps RTD and KOOS ADL. No significant relationships were observed between change in FTSTS performance and change in KOOS subscales between 3 and 6 months (Table 5.5)

5.5 DISCUSSION

Our initial hypotheses were partially supported as significant correlations were observed between muscle strength measures and KOOS scores. However, in contrast to our hypotheses, no significant correlations were observed between muscle strength measures and FTSTS performance. Furthermore, significant correlations were found between FTSTS performance and KOOS scores. A greater number of significant correlations were observed at 3 months post-surgery than at 6-months, with few significant relationships observed between improvements in these measures from 3 to 6 months after surgery. Findings from this investigation suggest that although patient-reported questionnaires and physical performance tests assess different constructs, there may be some convergence with the FTSTS and KOOS at approximately 3 months post-surgery.

To the author’s knowledge, this is the first evaluation of hip abduction and external rotation muscle strength and RTD on FTSTS performance and KOOS scores in patients after TKA. Hip abduction strength has been associated with improved functional performance as measured by the stair climbing test (SCT), FTSTS, figure-8 walk, timed up-and-go (TUG), and 6-minute walk tests (6MWT) [17, 62]. In older adults, FTSTS performance is used a functional measure of lower limb strength [20, 155, 156]. The results of this study demonstrate no significant relationships between muscle strength and FTSTS performance. The conflicting results related to muscle strength and functional performance may be due to differing task demands. The FTSTS requires both limbs to perform simultaneously and concurrently while the SCT, TUG, 6MWT, and other walking tests involve alternating cycles of swing and support. As a result, there is no period of single limb support or advancement during the FTSTS. Thus, deficits in the operative limb may be partially masked while patients place greater demand on their contralateral limb. Christiansen et al. note asymmetries in weight bearing during FTSTS in patients awaiting TKA and at 1 month post-surgery [49]. More symmetrical weight bearing between limbs during the FTSTS was correlated to quadriceps strength symmetry, 6MWT, and SCT, but not to FTSTS performance. While weight bearing symmetry was not assessed during assessment of FTSTS in non-clinical populations, minimal relationship with quadriceps strength suggests that other factors, such as pain, are contributing to FTSTS performance. In order to consider the contribution of pain on muscle strength and FTSTS performance, analyzing relationships with KOOS subscales may provide insight into potential relationships between these measures.

Although muscle strength was not related to FTSTS performance, stronger relationships were observed between muscle strength and KOOS scores. Hip strength measures were related to KOOS Sym, Pain, and Sport subscales. Additionally, the relationships between KOOS and hip strength were stronger than KOOS and quadriceps strength. The findings suggest that patients with stronger hip abductors, external rotators, and quadriceps have improved KOOS scores in these subscales at either 3 or 6 months post-surgery. A limitation of correlation analyses is that they do not assess causation. Thus, whether increased strength leads to improvement in KOOS scores or better patient-perceived function allows for greater strength measures is unclear and both explanations are plausible. Regarding KOOS Sym and Pain subscales, greater strength may allow for multiple movement strategies that reduce knee joint loading, improving function and resulting in less pain. Conversely, knee joint pain and symptoms may inhibit muscle performance during strength testing. A different mechanism may be inferred regarding the KOOS Sport subscale. Individuals with stronger hip and quadriceps muscles may be more capable of performing sporting tasks, making make them more likely to do so and perceive less difficulty. Alternatively, participation in higher level activities involving sporting tasks may lead to greater exposure to physical activity and provide a stimulus for improved muscle strength. Peak quadriceps strength is commonly assessed after TKA and has shown minimal relationship with KOOS ADL subscale score 1 month post-surgery and a low, but significant, relationship at 12 months post-surgery [153]. Other studies have included quadriceps strength assessment along with KOOS questionnaires and physical performance tests, but do not report the results of any correlations between these measures and quadriceps strength [100, 102]. Interestingly, although not significant, the correlation values of this study are similar to those reported previously for peak quadriceps strength and KOOS ADL subscale (.217 vs .26) [153]. Furthermore, improvement in quadriceps RTD between 3 and 6 months was significantly positively correlated with improvements in KOOS ADL scores. Rate of torque development has been suggested as a more functional measure of muscle performance because ADLs such as walking, sit-to-stand, and stair climbing require adequate muscle torque at critical times during the tasks. As patients' ability to rapidly generate torque improves, so too does their perceived ability to perform ADL tasks. The identification of significant relationships between muscle performance measures during the intermediate time points utilized in this study suggest that muscle strength may contribute to improved outcomes during this period.

Short-term follow up studies after TKA (~1 month) have demonstrated that patient-report questionnaires overestimate functional ability [100, 153]. In fact, an inverse relationship is noted with dramatic decreases in muscle strength and physical performance observed despite patients reporting significant improvement in their abilities [169]. After the initial precipitous decline in physical function, improvements in both self-report and objective physical function between 1 and 3 months post-surgery are noted with less improvement noted between 3 and 6 months post-surgery [100]. The findings of this study demonstrate between 7.1 – 32.8% improvements in all measures from 3 to 6 months, only one of which represent a clinically meaningful change (KOOS QoL) [88]. Thus, the period between 1-6 months post-surgery may be a time in which the trajectories of recovery for all measures are parallel and patient-perceived function is more greatly influenced by physical performance. In other words, reductions in pain drive improvements self-reported function during the first post-operative month, but improvements in physical function are better perceived by the patient between 1-6 months.

To this point, measures of muscle strength and FTSTS are moderately related to KOOS scores at 3 months post-TKA, most notably in the Pain, ADL, and Sports subscales. In each subscale, FTSTS performance showed the strongest relationship, followed by peak hip isometric muscle strength and quadriceps muscle strength. At 6 months, significant correlations were observed between only peak hip abduction strength and KOOS Symptoms subscale and FTSTS and KOOS ADL subscale. Furthermore, correlations between improvements in each measure revealed few relationships, which is likely due to small to moderate improvements between time points. Given relatively modest improvements in all outcomes between 3 and 6 months post-TKA, maximizing patient muscle strength and functional performance during the first 3 months of recovery is essential. Since formal rehabilitation is often completed within the first 3 months after TKA, opportunities for further physical performance enhancements are dependent upon the patient's own initiative and efforts. Minimal improvement in physical measures may explain why KOOS scores become less reflective of patient abilities in the long-term [112]. Previous work has noted gradual improvement in KOOS scores with increasing time from surgery despite indication that physical performance is unchanged [153]. This is likely due to the influence of patient perception on KOOS scores with patients modulating their expectations as they become more accustomed to their ability after TKA. This may result in additional increases in KOOS scores without any further increase in physical abilities.

Given that self-report questionnaires and physical performance tests reportedly assess different constructs, finding moderate correlations between FTSTS test performance and KOOS Pain and Sport subscales at 3 months and with KOOS ADL subscale at both 3 and 6 post-surgery were unexpected. Specific to the ADL subscale, one previous investigation did not observe significant relationships between FTSTS and KOOS ADL subscales [62]. However, this study included patients an average of 13.6 months post-surgery resulting in possible ceiling effects for KOOS ADL [112]. Moderate relationships between FTSTS and KOOS subscales at 3 months indicate that this test may serve as a valuable objective metric for readiness for discharge from physical therapy.

The unique results of this study may also be attributed to the essential nature of a sit-to-stand task in performing ADLs. Difficulties with this task are commonly reported after TKA and the FTSTS may more directly measure this task than other functional tests [6]. Additionally, it is important to consider other factors including knee joint pain as a potential contributor to poor FTSTS performance. Strong correlations are present between KOOS Pain and KOOS ADL subscales, as consistent with previous studies, indicating that patients may perceive their ability to perform ADLs are improved largely due to reduction in pain [100]. However, it is important to note that FTSTS performance was also significantly correlated with KOOS ADL, but not KOOS Pain, at 6 months post-TKA. As such, since the FTSTS assesses sit to stand, which is a key component of many ADLs, it may have better construct validity with the ADL subscale.

A limitation of this investigation is the lack of pre-operative data for which to compare 3 and 6 month patient-report and physical performance outcomes. These data would potentially allow for larger differences to be observed in each measure. Also, additional factors related to patient expectation from surgery, fear of pain or injury, patient satisfaction at time of assessment, and other personality factors that may influence outcomes were not included in this study. It should also be noted that several relationships are trending towards significance. It may be that as the sample size of this study increases, additional significant relationships will be revealed.

In summary, FTSTS and muscle strength measures are related to patient-reported function at 3 months post-TKA but these relationships lessen with time. Maximizing hip muscle strength and FTSTS performance prior to 3 months after TKA may help to improve patient-reported outcomes, but specific thresholds have yet to be established.

Thus, while both subjective and objective measures are needed to assess recovery longitudinally after TKA, hip strength and FTSTS may influence subjective outcomes near the end of rehabilitation.

5.6 CONCLUSION

Small to moderate improvements were observed in muscle strength, FTSTS performance, and KOOS scores between 3 and 6 months after TKA. Hip muscle strength and FTSTS performance were moderately correlated with KOOS Pain, ADL, and Sport subscales at 3 months post-surgery, with fewer relationships observed at 6 months and among improvements between time points. Maximizing hip muscle strength and FTSTS performance during the first 3 months after TKA may result in improved patient-reported function after TKA.

Table 5.1: Summary of Physical Performance and Self-Report Measures

	3 month	6 month
Hip Abd Peak	0.58 ± 0.3	0.68 ± 0.34
Hip Abd RTD	1.93 ± 1.15	2.31 ± 1.34
Hip ER Peak	0.29 ± 0.11	0.32 ± 0.14
Hip ER RTD	0.72 ± 0.41	0.82 ± 0.48
Quad Peak	0.86 ± 0.34	1.0 ± 0.5
Quad RTD	2.43 ± 1.28	2.96 ± 1.73
FTSTS	12.32 ± 2.96	10.48 ± 2.77
KOOS Sym	67.1 ± 9.8	73.1 ± 12.6
KOOS Pain	76.9 ± 8.5	83.6 ± 10.3
KOOS ADL	82.1 ± 8.6	88.0 ± 8.8
KOOS Sport	47.3 ± 22.9	53.9 ± 23.4
KOOS QoL	50.3 ± 19.6	66.8 ± 20.5

Abd: abduction
Peak: peak isometric strength (Nm/kg)
RTD: rate of torque development (Nm/kg*s)
ER: external rotation
Quad: quadriceps
FTSTS: Five-time Sit-to-Stand test (seconds)
KOOS: Knee Injury and Osteoarthritis Outcome Score
Sym: Symptoms subscale
Pain: Pain subscale
ADL: Activities of Daily Living subscale
Sport: Sports/Recreation subscale
QoL: Knee-related Quality of Life subscale

Table 5.2: Correlation Matrix for 3 Month Variables

	KOOS Sym	KOOS Pain	KOOS ADL	KOOS Sport	KOOS QoL	FTSTS
Hip Abd RTD	.421 (.065)	.295 (.207)	.025 (.918)	.304 (.192)	.202 (.392)	-.083 (.727)
Hip Abd Peak	.443 (.051)	**.511*** (.021)	.287 (.220)	.443 (.051)	.375 (.104)	-.255 (.279)
Hip ER RTD	.126 (.587)	.179 (.437)	-.012 (.960)	.337 (.135)	.109 (.640)	-.251 (.272)
Hip ER Peak	.283 (.214)	**.482*** (.027)	.176 (.445)	**.527*** (.014)	.307 (.176)	-.364 (.105)
Quad RTD	.326 (.149)	.333 (.141)	-.059 (.800)	.288 (.205)	.023 (.923)	-.152 (.511)
Quad Peak	.369 (.100)	**.441*** (.045)	.217 (.346)	**.504*** (.020)	.191 (.407)	-.320 (.157)
FTSTS	-.245 (.285)	**-.519*** (.016)	**-.632*** (.002)	**-.543*** (.011)	-.415 (.061)	n/a

Abd: abduction
Peak: peak isometric strength
RTD: rate of torque development
ER: external rotation
Quad: quadriceps
FTSTS: Five-time Sit-to-Stand test
KOOS: Knee Injury and Osteoarthritis Outcome Score
Sym: Symptoms subscale
Pain: Pain subscale
ADL: Activities of Daily Living subscale
Sport: Sports/Recreation subscale
QoL: Knee-related Quality of Life subscale

Table 5.3: Correlation between KOOS Pain and KOOS ADL Subscales

	3 month	6 month
KOOS Pain:KOOS ADL	**.624*** (.016)	**.729*** (.000)

KOOS: Knee Injury and Osteoarthritis Outcome Score
Pain: Pain subscale
ADL: Activities of Daily Living subscale

Table 5.4: Correlation Matrix for 6 Month Variables

	KOOS Sym	KOOS Pain	KOOS ADL	KOOS Sport	KOOS QoL	FTSTS
Hip Abd RTD	.41 (.091)	.164 (.515)	.083 (.744)	.413 (.088)	.291 (.242)	-.033 (.898)
Hip Abd Peak	**.572*** (.013)	.173 (.492)	.247 (.324)	.357 (.146)	.406 (.095)	-.458 (.056)
Hip ER RTD	.197 (.418)	.199 (.414)	.095 (.700)	.251 (.301)	.324 (.176)	-.051 (.835)
Hip ER Peak	.215 (.377)	.048 (.846)	.011 (.966)	.161 (.511)	.282 (.243)	-.123 (.614)
Quad RTD	.307 (.201)	.110 (.655)	.153 (.533)	.340 (.154)	.162 (.507)	-.303 (.207)
Quad Peak	.362 (.128)	.176 (.472)	.233 (.336)	.428 (.067)	.278 (.250)	-.330 (.168)
FTSTS	-.428 (.068)	-.213 (.382)	**-.537*** (.018)	-.207 (.395)	-.415 (.077)	n/a

Abd: abduction
Peak: peak isometric strength
RTD: rate of torque development
ER: external rotation
Quad: quadriceps
FTSTS: Five-time Sit-to-Stand test
KOOS: Knee Injury and Osteoarthritis Outcome Score
Sym: Symptoms subscale
Pain: Pain subscale
ADL: Activities of Daily Living subscale
Sport: Sports/Recreation subscale
QoL: Knee-related Quality of Life subscale

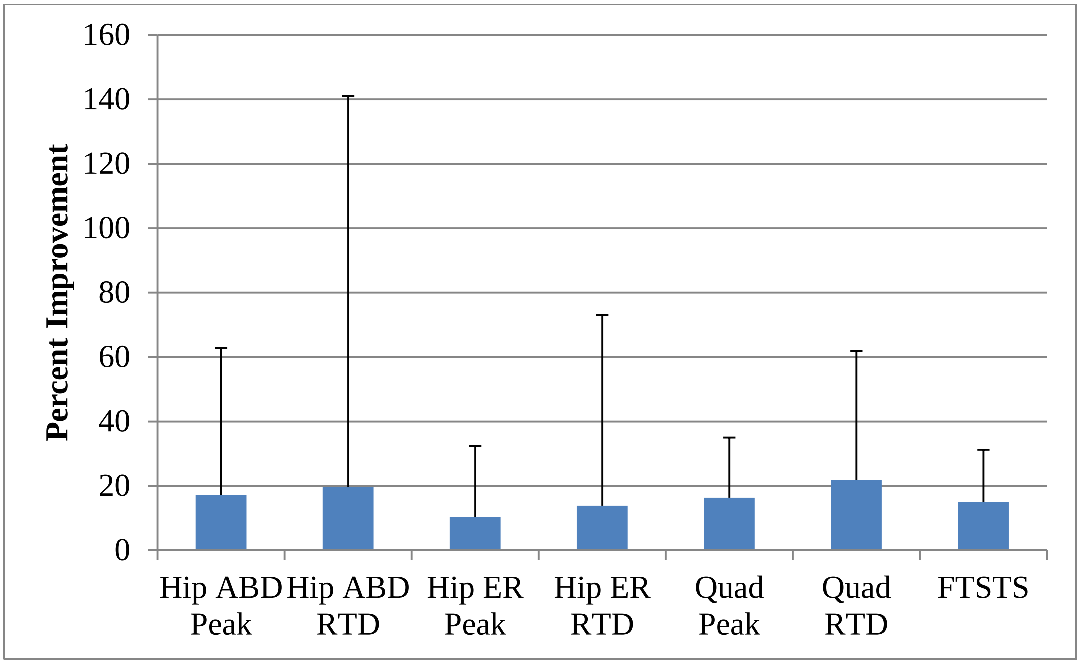
Table 5.5: Correlation Matrix for 3 to 6 Month Improvement

	KOOS Sym	KOOS Pain	KOOS ADL	KOOS Sport	KOOS QoL	FTSTS
Hip Abd RTD	-.002 (.994)	**-.476*** (.046)	-.399 (.101)	.033 (.895)	-.409 (.092)	.185 (.461)
Hip Abd Peak	-.34 (.168)	**-.595*** (.009)	-.167 (.509)	-.141 (.577)	-.370 (.130)	-.060 (.812)
Hip ER RTD	.201 (.410)	-.082 (.739)	-.006 (.980)	.031 (.899)	.178 (.467)	-.273 (.257)
Hip ER Peak	-.141 (.564)	-.134 (.584)	.122 (.619)	-.184 (.450)	.086 (.728)	-.232 (.339)
Quad RTD	-.133 (.586)	.194 (.426)	**.524*** (.021)	.391 (.098)	-.074 (.765)	-.453 (.051)
Quad Peak	-.296 (.219)	.096 (.697)	.260 (.282)	.059 (.812)	.086 (.726)	-.412 (.080)
FTSTS	.059 (.811)	-.153 (.531)	-.241 (.319)	-.153 (.532)	-.317 (.186)	n/a

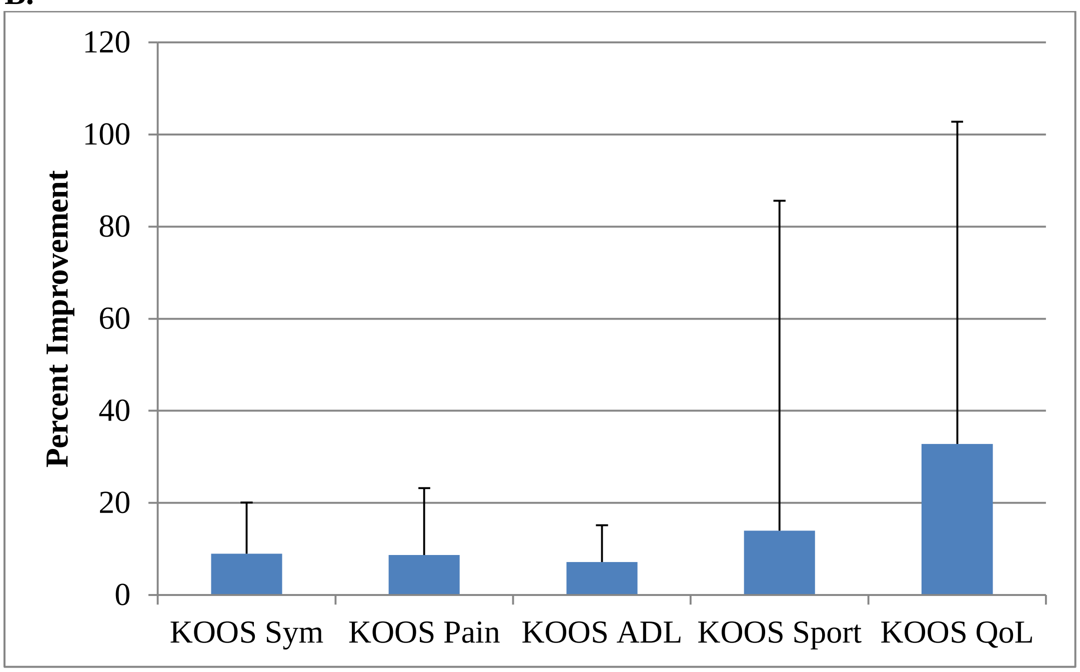
Abd: abduction
Peak: peak isometric strength
RTD: rate of torque development
ER: external rotation
Quad: quadriceps
FTSTS: Five-time Sit-to-Stand test
KOOS: Knee Injury and Osteoarthritis Outcome Score
Sym: Symptoms subscale
Pain: Pain subscale
ADL: Activities of Daily Living subscale
Sport: Sports/Recreation subscale
QoL: Knee-related Quality of Life subscale

Figure 5.1: Bar graphs of Percent Improvement from 3 to 6 months post-surgery in A) physical performance tests and B) KOOS Scores

A.



B.



Chapter 6. Identifying Clinical Predictors of Knee Flexion Mechanics during Walking after Total Knee Arthroplasty.

6.1 ABSTRACT

Purpose and Hypothesis: Despite significant rehabilitation, deficits in knee flexion excursion during walking are known to persist after total knee arthroplasty (TKA). Techniques to directly assess walking mechanics in a clinical setting are limited by concerns regarding time, cost, and validity. For this reason, determining the ability of clinical tests to predict gait mechanics would fill a critical clinical gap. Thus, the purpose of this study is to determine the utility of clinical assessments performed 3 months after TKA in predicting knee flexion motion during walking at 6 months after TKA. It was hypothesized that measures of physical performance, but not patient-reported function, would predict gait mechanics in individuals after TKA.

Methods: Thirty-nine individuals completed the study protocol, 21 in the TKA group (7 male, 14 female, height: 1.68 ± 0.08 m, mass: 90.95 ± 21.04 kg, BMI: 32.27 ± 7.4 kg/m^2, Age: 60.6 ± 8.1 years) and 18 matched control subjects (7 male, 11 female, height: 1.69 ± 0.10 m, mass: 83.69 ± 20.2 kg, BMI: 29.2 ± 5.5 kg/m^2, age: 61.2 ± 8.8 years). At 3 months post-operatively, participants performed isometric strength testing to determine peak strength and rate of torque development (RTD) of hip abductor, hip external rotator, and quadriceps muscle groups as well as completed the FTSTS and KOOS. At 6 months post-operatively, participants underwent three-dimension motion analysis while walking on an instrumented treadmill. Pearson product-moment correlations and stepwise multiple linear regression were used to assess the relationship and predictive properties of 3 month to 6 month measures.

Results: Three significant regression models were identified. Model 1 included solely quadriceps RTD (Adj R^2 0.357, p = .000). Model 2 included quadriceps RTD in addition to hip external rotation RTD (Adj R^2 0.435, p = .000), while Model 3 included quadriceps RTD, hip external rotation RTD, and FTSTS (Adj R^2 0.488, p = .001).

Conclusion: Faster quadriceps RTD, slower hip external rotation RTD, and faster FTSTS performance at 3 months post-surgery is predictive of greater knee flexion excursion during walking at 6 months post-surgery.

6.2 INTRODUCTION

Total knee arthroplasty (TKA) is the most common treatment for end-stage knee osteoarthritis with over 600,000 procedures performed annually in the United States [1]. Although TKA is successful in reducing pain due to osteoarthritis, significant muscle weakness, poor functional mobility, and gait asymmetries persist after surgery and rehabilitation [5-7, 107]. As a means of helping clinicians improve care after TKA, numerous methods have been developed to assess patient self-reported function and physical performance [45, 57, 112]. Despite these options, clinicians continue to lack time-efficient and inexpensive methods to quantitatively assess gait mechanics. As persistent gait asymmetries are known contributors to poor functional mobility after TKA, limited gait assessment methods represent a significant clinical problem [15].

Post-acute rehabilitation for TKA includes, on average, 19 visits to outpatient rehabilitation during the first 8-12 weeks after surgery [3]. During this period, regular assessments of hip and knee muscle strength, functional performance, and patient-reported function are conducted with significant progress typically achieved before discharge from supervised care [100, 170]. Despite expectations of continued improvements, poor gait mechanics often persist including reductions in knee flexion motion during stance phase [79, 107]. If clinical tests could be evaluated for their ability to determine which patients will have persistent gait impairments, then additional interventions could be introduced before a patient is discharged from care.

Direct assessment of gait mechanics in a clinical setting is limited by the significant time and financial demands of three-dimensional motion analysis systems. Two-dimensional video gait analysis suffers from potential for perspective error, unknown validity, and also requires additional clinic time and space that currently impedes mass implementation of this tool. Without the ability to formally assess gait mechanics, clinicians may defer to qualitative gait assessment or their best clinical judgement to determine which patients are likely to recovery more normal gait mechanics and which may require additional intervention. Commonly performed clinical assessments leading up to discharge from rehabilitation after TKA include hip and knee muscle strength, five-time sit-to-stand (FTSTS) performance, and the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire [45, 57, 112]. Recently, improved hip muscle strength has been indicated as a possible compensatory mechanism for quadriceps weakness, but the influence on knee mechanics during walking is unknown [17, 62]. Furthermore, in addition to measures of peak muscle strength, rate of torque development (RTD) or how quickly a muscle generates torque, has been proposed as a more sensitive measure of muscle performance and may better reflect muscular demands during dynamic activities [18, 144]. Rate of torque development, in addition to peak hip and knee muscle strength, FTSTS, and KOOS scores are potentially well suited for use as clinical predictors of knee mechanics because they have fewer time and equipment demands than instrumented gait analyses and can be safely assessed throughout the early and intermediate stages of outpatient rehabilitation.

Thus, the purpose of this study is to determine the utility of clinical assessments (hip and knee peak strength and RTD, FTSTS, and KOOS scores) performed 3 months after TKA in predicting knee flexion motion during walking at 6 months after TKA. In doing so, this project will serve as an initial step towards developing objective criteria for discharge and inform clinicians of the role these clinical assessments have in evaluating gait mechanics after TKA. It was hypothesized that measures of physical performance (strength, RTD, and FTSTS), but not patient-reported function (KOOS), would predict gait mechanics in individuals after TKA.

6.3 METHODS

Study Design and Participants

Participants were recruited as previously described in Chapter 4 (pg. 62). Participants with TKA were included if they met the following criteria: 1) between the ages of 40-90 years old, 2) undergone unilateral TKA within the past 3 months, 3) no prior surgery to the contralateral knee, low back, or either hip, ankle, or foot, 4) no neurological or balance disorder that requires use of an assistive device for mobility, and 5) able to walk at least 10 minutes without an assistive device. All control participants were required to be free of previous surgery and current injury in lower back and lower extremity joints, and match a TKA participant in sex, age, body mass index, and physical activity level as measured by the Physical Activity Scale for the Elderly (PASE). At 3 months post-TKA, participants completed muscle strength and RTD testing, FTSTS, and KOOS assessments. At 6 months post-TKA, participants underwent three-dimensional instrumented gait analysis. Control participants performed all testing procedures in a single session.

3 Month Assessments

Muscle Strength and Rate of Torque Development

All participants completed isometric strength testing of hip abduction, hip external rotation, and quadriceps of each limb using a Biodex System 4 (Biodex Systems, Shirley, NY). Participants in the TKA group were assessed at 3 months post-surgery. Hip abduction was assessed with the hip joint in neutral alignment and the participant in sidelying. The dynamometer arm was secured 5 cm proximal to the lateral tibiofemoral joint. Participants were instructed to abduct their leg towards the ceiling. Hip external rotation and quadriceps were each assessed with the hip flexed to 85°, knee flexed to 90°, and hip in 0° rotation while the participant was seated. The dynamometer arm was secured 5 cm proximal the medial malleolus. During hip external rotation, participants were instructed to rotate their leg as if they were looking at the bottom of their shoe. For the quadriceps, participants were given verbal instruction to extend their knee as if to kick forward. One practice and three experimental trials were performed for quadriceps testing, while four experimental trials were conducted for hip abduction and hip external rotation. Verbal encouragement was provided during all strength testing and with patients asked to provide maximal effort and performed each task with as much force and as quickly as possible.

Peak strength values and rate of torque development (RTD) were determined for each trial and averaged for each variable for use in statistical analyses. All tests were performed bilaterally and the trials were normalized to body mass. Custom MATLAB code (MathWork Inc, Natick, MA) was used to calculate the mean slope of the torque-time curve over the first 200 milliseconds of the linear portion between the onset of the trial and peak torque [158].

Five-time Sit-to-Stand Test

All participants completed the five-time sit-to-stand test (FTSTS) with participants in the TKA group assessed at 3 months post-surgery. Beginning seated in an armless chair with a 42.0 cm seat height, participants were asked to complete five consecutive sit-to-stands as quickly as possible without using their upper extremities or an assistive device for assistance. Using a hand-held stopwatch to record time, timing began upon initiation of the task from sitting and was stopped upon returning to sitting after the 5^{th} sit-to-stand. Two trials were allowed, with the fastest trial used for data analysis.

Knee Injury and Osteoarthritis Outcome Score (KOOS)

All participants completed the Knee Injury and Osteoarthritis Outcome Score (KOOS), with the TKA participants assessed at 3 months post-surgery. Each individual subscale was scored separately on a scale of 0 to 100 with 0 indicating the worst possible function and 100 representing the best.

<u>6 Month Assessment</u>

Three-dimensional Gait Analysis

All participants underwent three-dimensional motion analysis at a self-selected speed on an instrumented treadmill as previously described in Chapter 4 (pg. 65). Data for the TKA participants were collected at 6 months post-surgery. During walking, marker trajectories were recorded using a 10-camera motion analysis system (Motion Analysis Corp, Santa Ana, CA) with a sampling rate of 200 Hz. Data filtering of marker position was performed with a fourth-order, low-pass, zero-lag Butterworth filter at 8 Hz and calculations of joint kinematics were performed using Visual 3D software (C-Motion, Germantown, MD). Angles were calculated using Cardan XYZ angles referencing the distal segment to the proximal. Custom MATLAB code was generated to extract sagittal plane knee kinematic data. Knee flexion excursion was calculated as the total amount of knee flexion motion occurring between initial contact and midstance.

Statistical Methods

Data were analyzed with SPSS Statistics 22 (IBM, Armonk, NY), Pearson product moment correlations coefficients were calculated to assess relationships between the 3 month assessments and 6 month knee flexion excursion. Statistical significance was defined as $P \leq 0.05$. Significant correlations in addition to age, height, mass, body mass index were then entered into a stepwise multiple linear regression to determine the predictive properties of 3 month assessments on 6 month knee flexion excursion of the operative limb.

6.4 RESULTS

Participant Characteristics

A total of 39 participants (21 TKA, 18 controls) completed the study. No significant differences in mean age, height, weight, body mass index (BMI), or PASE physical activity level between the TKA and control groups were present at the time of testing (Table 4.1).

Correlation

The mean and standard deviation for all variables are reported in Table 6.1. Significant positive relationships were found between 3 month hip external rotation RTD, hip external rotation peak strength, quadriceps RTD, and quadriceps peak strength of the operative limb and 6 month knee flexion excursion (Table 6.2A). In the nonoperative limb, significant positive relationships with 6 month knee flexion excursion were only found with quadriceps RTD and peak strength (Table 6.2B). All five KOOS subscales were positively associated with knee flexion excursion (Table 6.2C). Lastly, the FTSTS was significantly and negatively correlated with knee flexion excursion (Table 6.2C).

Regression Models

The stepwise multiple linear regression identified three significant models to predict knee flexion excursion (Table 6.3). Model 1 included only quadriceps RTD of the operative limb (b = 1.4 ± 0.68; p = 0.000). Model 2 included operative limb quadriceps RTD (b = 2.5 ± 1.13; p = 0.000) and hip external rotation RTD (b = -5.7 ± 5.01; p = 0.027). Model 3 included operative limb quadriceps RTD (b = 2.03 ± 1.17; p = 0.001), hip external rotation RTD (b = -5.0 ± 4.87; p = 0.045), and FTSTS performance (b = -0.6 ± 0.59; p = 0.048). The overall model fit for models 1, 2, and 3 for predicting knee flexion excursion, as measured by adjusted R^2, were 0.357, 0.435, and 0.488, respectively. Variance inflation factors were calculated to determine the severity of multicollinearity in the regression equations. For Model 2, the variance inflation factor was 3.3 for each variable. In Model 3, the highest variance inflation factor was 3.9 with quadriceps RTD. Each of these values is <10, indicating low concern for collinearity influencing the regression results.

6.5 DISCUSSION

The purpose of this study was to determine the utility of clinical assessments performed at 3 months in determine knee flexion excursion at 6 months post-TKA. The initial hypothesis was confirmed, objective measures, but not subjective patient-reported function (i.e. KOOS), were predictive of knee flexion excursion. Specifically, 3 month operative limb quadriceps RTD, hip external rotation RTD, and FTSTS performance were predictive of 6 month operative limb knee flexion excursion.

Quadriceps function is typically assessed through measures of peak strength after TKA with significant deficits noted during the first year after surgery [43]. These deficits have been associated with impaired physical function and more asymmetrical gait mechanics [15, 52]. Despite its utility and ease of implementation, measures of peak strength are not subject to the same time constraints as functional tasks like walking. For this reason, peak strength may not reflect function as accurately as time-constrained measures of strength, such as RTD. The results of the regression model from this study support this notion as quadriceps RTD, but not quadriceps peak strength, of the operative limb was included in all 3 predictive models with faster quadriceps RTD at 3 months post-TKA predicting greater knee flexion excursion at 6 months post-TKA. This suggests that quadriceps RTD is a better indicator of dynamic function than peak quadriceps strength. Furthermore, Model 1 identified quadriceps RTD alone as a significant predictor of knee flexion excursion and explained nearly 36% of the variance. Individuals after TKA are noted to have reduced peak knee flexion angle and knee flexion excursion during walking, a pattern that has been termed "quadriceps avoidance" gait [108]. By reducing the degree and total amount of knee flexion, this gait pattern reduces the required muscular demand of the quadriceps to control the knee joint during loading and weight acceptance. Individuals with poorer quadriceps function, as measured by slower quadriceps RTD, undergo less knee flexion excursion suggesting limitations in rapid torque generation of the quadriceps are contributing to reductions in knee joint motion during walking. Furthermore, the results of this study expand upon previous findings related to quadriceps function by demonstrating the relationship of quadriceps RTD near the time of discharge from rehabilitation to knee flexion mechanics at a future time point. Given the ubiquity of quadriceps RTD in each of the 3 prediction models, emphasis on maximizing gains in this measure should be emphasized during rehabilitation after TKA.

Similar patterns between RTD and peak strength were observed in operative limb hip external rotation as RTD, but not peak strength, was a significant predictor of knee flexion excursion and explained an additional 7.8% of the variance in knee flexion excursion. Interestingly, the predictor coefficient for hip external rotation RTD was negative, suggesting that faster hip external rotation RTD at 3 months predicted less knee flexion excursion at 6 months post-surgery. Testing hip external rotation in seated is proposed as a better method of assessing gluteus maximus function than hip extension testing [161]. To the author's knowledge, no previous studies have investigated the contribution of hip muscle performance on gait mechanics after TKA. The findings of the regression models suggest that those individuals with greater gluteus maximus function undergo less knee flexion excursion. Keeping in mind the contribution of quadriceps RTD, these results indicate that better gluteal function does not ameliorate impaired quadriceps function in achieving normal knee mechanics during walking. Rather, achieving or maintaining gluteal function during rehabilitation may reinforce utilization of a hip-dominant movement strategy at the expense of restoring normal knee mechanics during gait. Thus, patients may be more likely to utilize the muscle groups that function best. Better gluteal function allows individuals to walk successfully while transferring muscular demand from the knee to the hip. As a result, individuals with faster hip external rotation RTD are more capable of implementing a hip-dominant strategy and may have minimal catalyst to utilize their quadriceps or increase knee flexion excursion during walking.

The FTSTS was the final predictor of knee flexion excursion and explained an additional 5.3% of the variance in the model. FTSTS performance is associated with quadriceps strength and is often used as a surrogate measure of lower extremity strength [20, 155, 156]. One previous study noted that individuals who demonstrated an improvement in FTSTS performance from pre-operative to 1 year postoperative that exceeded the minimal detectable change (2.5 s), also demonstrated greater walking gait symmetry [66]. In combination with these findings, the results of the current study's regression model suggest that FTSTS performance may inform clinicians of a patient's knee biomechanics with faster FTSTS performance predicting greater knee flexion excursion. The timing demands of the FTSTS, requirements for greater knee flexion, in addition to the need for concentric and eccentric muscle contractions may contribute to this test being a predictor of knee mechanics during walking. However, additional study is warranted to determine potential meaningful thresholds for FTSTS performance.

Non-operative quadriceps strength and RTD were included in the regression model, but were not significant predictors of knee flexion excursion. Previous studies have noted that quadriceps strength of the non-operative limb is a strong predictor of post-operative functional abilities [54, 160]. One of these studies utilized pre-operative strength measures and neither assessed gait mechanics, which may explain why the non-operative quadriceps function did not significantly contribute to the predictive model in this study. Interestingly, hip abduction peak strength and RTD were not significantly correlated with knee flexion excursion and were, therefore, not included in the regression model. Growing evidence exists that greater hip abduction strength is associated with improvements in functional performance measures such as the stair climbing test and 6-minute walk test. However, these tests do not assess joint kinematics. Thus, hip abduction strength may have a role in physical performance but this does not appear to extend to knee flexion motion during walking. Lastly, KOOS scores were significantly correlated with knee flexion excursion but did not significantly contribute to the predictive model. This was as hypothesized and consistent with previous reports that subjective self-report measures of physical function are not predictive of gait mechanics[103]. The correlation values reported in this study are higher than previous studies, likely due to the inclusion of a control group with higher mean KOOS scores.

The predictive quality of these models is limited to the variables from which they were produced, as not all potentially influential factors were measured in this study. Possible variables unaccounted for include patient motivation, baseline function (self-reported and objectively assessed), and patient activity (type, duration, intensity) between 3 and 6 months post-surgery. Future work should seek to prospectively validate the utility of these assessments and develop specific thresholds that, when achieved, will predict optimal joint mechanics in the long-term. Furthermore, since quadriceps RTD impairments are shown to persist and impact gait mechanics, exploration of interventions to improve quadriceps RTD and normalize gait patterns are necessary.

6.6 CONCLUSION

This study has shown that operative limb quadriceps RTD, hip external rotation RTD, and FTSTS assessed at 3 months post-TKA are significant predictors of knee flexion excursion during walking at 6 months post-surgery. Maximizing quadriceps RTD and FTSTS performance while reducing reliance on hip strategies during rehabilitation will likely improve future knee joint motion during walking after TKA. The results of this study serve as an initial step towards identifying targets for objective criteria for discharge after TKA.

Table 6.1 Three and Six Month Variables of Interest

	Mean ± SD	
3 Month	TKA	NON
ABD RTD	2.3 ± 1.1	2.4 ± 0.9
ABD Peak	0.7 ± 0.3	0.7 ± 0.3
ER RTD	1.0 ± 0.6	1.23 ± 0.56
ER Peak	0.4 ± 0.1	0.4 ± 0.1
Quad RTD	4.1 ± 2.4	5.0 ± 2.0
Quad Peak	1.4 ± 0.7	1.7 ± 0.6
FTSTS (s)	10.2 ± 3.1	
KOOS_Sym	80.4 ± 15.9	
KOOS_Pain	86.9 ± 12.4	
KOOS_ADL	89.9 ± 10.2	
KOOS_Sport	69.5 ± 29.5	
KOOS_QOL	72.6 ± 26.5	
6 Month		
KFLEXC (°)	12.9 ± 5.7	

Abd: abduction
Peak: peak isometric strength (N/kg)
RTD: rate of torque development (N/kg*s)
ER: external rotation
TKA: operative limb
NON: non-operative limb
Quad: quadriceps
FTSTS: Five-time Sit-to-Stand test
KFLEXC: knee flexion excursion

Table 6.2 Correlation Matrices for 3 month A) Operative Limb Muscle Performance, B) Non-operative Limb Performance, c) FTSTS and KOOS scores to 6 month Knee Flexion Excursion

A.

	ABD RTD	ABD Peak	ER RTD	ER Peak	Quad RTD	Quad Peak
KFLEXC	.257 (.142)	.336 (.052)	.337* (.048)	.446* (.007)	.598* (.000)	.587* (.000)

B.

	ABD RTD	ABD Peak	ER RTD	ER Peak	Quad RTD	Quad Peak
KFLEXC	.211 (.231)	.299 (.085)	.233 (.178)	.324 (.058)	.529* (.001)	.494* (.003)

C.

	FTSTS	Sym	Pain	ADL	Sport	QoL
KFLEXC	-.503* (.002)	.571* (.000)	.514* (.002)	.520* (.001)	.539* (.001)	.483* (.003)

Abd: abduction
Peak: peak isometric strength (N/kg)
RTD: rate of torque development (N/kg*s)
ER: external rotation
Quad: quadriceps
KFLEXC: knee flexion excursion
FTSTS: Five-time Sit-to-Stand test
Sym: KOOS Symptoms subscale
Pain: KOOS Pain subscale
ADL: KOOS Activities of Daily Living subscale
Sport: KOOS Sports/Recreation subscale
QOL: KOOS Knee-related Quality of Life subscale

Table 6.3 Results of Regression Models Predicting 6 month Knee Flexion Excursion of the Operative Limb.

	Predictors	Adj R^2	% Change	Beta (95% CI)	P-value
Model 1	TKA Quad RTD	.357	-	1.4 (0.76 – 2.08)	.000
Model 2	TKA Quad RTD	.435	7.8	2.5 (1.37 – 3.63)	.000
	TKA Hip ER RTD			-5.7 (-10.8 - -0.69)	.027
Model 3	TKA Quad RTD	.488	5.3	2.03 (0.85 – 3.2)	.001
	TKA Hip ER RTD			-5.0 (-9.9 - -0.13)	.045
	FTSTS			-0.6 (-1.2 - -0.01)	.048

Quad: Quadriceps
TKA: Operative limb
ER: External Rotation
RTD: Rate of torque development
FTSTS: Five-time Sit-to-Stand Test
Adj: Adjusted
CI: Confidence Interval

Chapter 7: Summary & Future Directions

7.1 INTRODUCTION

The goal of this dissertation was to define recovery during the early post-rehabilitative period between 3 and 6 months after TKA in four domains: 1) hip abductor, hip external rotator, and quadriceps muscle performance, 2) five-time sit-to-stand performance (FTSTS), 3) KOOS questionnaire scores, and 4) biomechanics of walking and stair descent. Furthermore, this dissertation sought to explore relationships between these four domains of recovery and develop predictive models of post-rehabilitative gait mechanics in order to identify possible targets for intervention. With more than 50% of patients after TKA reporting difficulty with walking, these data will serve as initial steps towards developing additional objective criteria for discharge from outpatient rehabilitation. With this goal in mind, the specific aims of this dissertation were developed to establish early post-rehabilitative recovery and provide clinically relevant findings to improve rehabilitation practices for individuals after TKA. Below is a brief summary of each aim, key outcomes, and clinical implications. Lastly, study limitations and suggestions for future research are discussed.

7.2 SUMMARY

In Chapter 3, a systematic review of recovery in muscle strength, FTSTS, walking and stair descent mechanics, and KOOS scores at pre-operative, 3 months post, and 6 months post-operative time points. This review primarily highlights gaps in current evidence related to recovery of hip muscle strength, FTSTS performance, and stair descent mechanics in individuals after TKA. This review also synthesizes previous studies identifying persistent quadriceps strength and gait mechanics during level walking. The key outcomes from this review are that whether or not hip muscle strength is impaired after TKA is unknown as are the implications of either normal or potentially impaired hip muscle strength on function and biomechanics. Furthermore, the review did not identify any studies investigating stair descent and only 2 studies on stair ascent during the first 6 months following TKA. Since difficulty with stair negotiation, particularly stair descent, is commonly reported after TKA, lack of research on this essential daily task is a critical gap in the clinical literature. More evidence exists regarding deficits in quadriceps strength and impairments in knee joint biomechanics during walking suggesting that recovery in these measures is incomplete 6 months after TKA. Ultimately, it was concluded from this review that despite improvement in KOOS scores, persistent deficits are common in quadriceps muscle strength, FTSTS, and knee joint biomechanics during walking at 6 months after TKA. The gaps identified in this review serve as potential areas for future research which may improve rehabilitation and subsequent outcomes for individuals after TKA.

As an initial step in addressing the gaps identified in Chapter 3, Chapter 4 investigated post-rehabilitative recovery in quadriceps and hip muscle strength and rate of torque development (RTD), FTSTS performance, KOOS scores, and hip and knee joint biomechanics during walking and stair descent. It was found that deficits in quadriceps and hip external rotation peak strength and RTD were present at both 3 and 6 months after TKA. Hip abduction peak strength and RTD recovered and were not significantly different compared to control subjects at the 6 month time point. Modest improvements were observed in FTSTS performance and KOOS scores, but remained impaired compared to control subjects. Additionally, knee flexion excursion during walking and landing from stair descent remained impaired in the TKA limb compared to both the non-operative limb and control subjects. Furthermore, patients after TKA demonstrate greater hip strategy utilization during walking than controls, possibly as a compensation for impaired quadriceps muscle function. Minimal improvements were observed in the stance limb during stair descent after TKA, as deficits in knee extensor moment, hip flexor moment, and knee flexion angle suggest that the demands of eccentrically controlling body mass during descent exceed the muscular capacity of the TKA limb at both time points. This is the first longitudinal investigation of quadriceps RTD, hip muscle peak strength and RTD, and stair descent mechanics after TKA and the results indicate incomplete recovery both at the conclusion of rehabilitation and the early post-rehabilitative phase, with minimal meaningful improvement between time points. Knowing that these deficits are not resolved at the conclusion of rehabilitation and demonstrated minimal meaningful improvement after discharge from rehabilitation is clinically valuable. This informs clinicians and researchers that current rehabilitation practices do not restore full muscle strength, functional ability, and mechanics and also suggests that if gains are not made during rehabilitation, then additional meaningful gains are unlikely to occur after rehabilitation. Based on these outcomes, it is recommended that clinicians seek to maximize recovery during rehabilitation and develop additional interventions to more fully recover muscle strength and RTD, FTSTS performance, and restore normal gait and stair descent biomechanics.

Building upon the findings of Chapter 4, a better understanding of the relationships between muscle strength and RTD, FTSTS, and KOOS scores would further elucidate common patterns of recovery after TKA. Chapter 5 sought to explore relationships between these measures at 3months post-surgery, 6 months post-surgery, and the change in performance between 3 and 6 months. It was found that better peak hip muscle strength and FTSTS performance were correlated with improved KOOS scores at 3 months, but these relationships were weaker at 6 months post-surgery. Additionally, few significant relationships were observed in the changes in performance between 3 and 6 months, likely due to the minimal improvements observed between time points. The results from this chapter provide additional clinical value as muscle strength and FTSTS performance are related to improved patient-perceived function at 3 months post-TKA. This would suggest that during the later phases of rehabilitation, a patient's strength and physical abilities are strong contributors to how patients' perceive their recovery. Previous studies have noted that KOOS scores early after TKA are largely influenced by the amount of pain the patient reports. As pain improves during the first 3 months after surgery, the findings of Chapter 5 would suggest that muscle strength and physical function are more influential in determining patient-perceived function than pain. Thus, rehabilitation should focus on enhancing muscle strength and sit-to-stand abilities during the final stages of rehabilitation for TKA in order to maximize patient-perceived function. Going forward, future research could assess the influence of pain, muscle strength, and FTSTS performance at more frequent time intervals early after TKA in order to determine more specifically when strength and functional ability become larger contributors to KOOS scores.

To build further upon the findings of Chapter 4, Chapter 6 sought to develop predictive models of 6 month gait mechanics. By identifying the clinical measures taken at 3 months post-surgery that predict knee joint motion during walking at 6 months post-surgery, clinicians could focus on the most important underlying impairments and more easily gauge patient progress during rehabilitation. The findings of this chapter revealed three measures that were predictive of knee joint motion, including: quadriceps RTD, hip external rotation RTD, and FTSTS performance. Quadriceps RTD was the strongest single predictor and was present in all three predictive models. Faster quadriceps RTD at 3 months predicted more knee flexion excursion at 6 months. Thus, individuals with better quadriceps function near the time of discharge from therapy are predicted to have better knee joint motion during walking in the future. Additionally, faster hip external rotation RTD predicted worse knee flexion excursion during walking. Also, FTSTS was the third predictor, with faster FTSTS performance predicting more knee flexion excursion during walking. In addition to their novelty, these findings are clinically relevant. These predictive models suggest that quadriceps function, as measured by RTD, is the best predictor of future gait mechanics after TKA. Since deficits in quadriceps RTD are large and persistent, some individuals may adopt a hip-dominant strategy and place greater demand on the hip musculature to control loading during walking. As such, those individuals with better gluteal function, as measured by hip external rotation RTD, undergo less knee flexion excursion in the future because they are better able to successfully implement a hip-dominant strategy. Thus, in order for patients after TKA to achieve optimal knee flexion excursion, rehabilitation should seek to maximize quadriceps RTD and FTSTS performance, while minimizing the utilization of a hip-dominant strategy during walking.

7.3 LIMITATIONS AND FUTURE DIRECTIONS

The primary limitation of this dissertation is the lack of pre-operative measures for the TKA group. Without such measures it is difficult to determine if the deficits apparent at 3 and 6 months post-surgery were also present pre-operatively. It is also difficult to ascertain whether or not patients after TKA demonstrated improved performance compared to their pre-operative abilities. This limitation is partially overcome by the inclusion of a sex, age, body mass index, and physical activity level matched control group, but these individuals may represent a higher performance standard than individuals awaiting TKA.

Another limitation is the use of an instrumented treadmill for gait analysis. Previous studies have shown that kinematic variables are not significantly different during treadmill vs overground walking, but kinetic variables may be reduced during treadmill walking [164]. Since both groups ambulated on an instrumented treadmill, comparisons within and between groups for this study are valid. However, direct comparison of kinetic variables reported in this study to those collected during overground walking may need to account for the potential influence of the treadmill. A final noteworthy limitation of this study is the use of a single stair descent. A single stair does not allow for a step-over-step descent pattern that may be more typical when descending a full flight of stairs. Thus, the task observed in this study does not provide information on the transition from one step descent into another. This is an area in which additional research is needed. However, understanding the characteristics and impairments present during a single step provide a knowledge foundation for discrete aspects of the more complicated descent of a full flight of stairs.

Based on the outcomes of this project, future work should investigate the efficacy of novel interventions to improve quadriceps peak strength and RTD. Current rehabilitation tools do not appear to sufficiently restore quadriceps function and this impairment contributes to longer term knee joint deficiencies during gait. It would also be beneficial for future work to examine the effect of movement retraining in restoring a more quadriceps dominant gait pattern via increased knee flexion excursion or increased knee extensor moment. Alternatively, use of movement retraining to reduce the utilization of a hip dominant strategy throughout rehabilitation may prevent patients after TKA from reinforcing a compensatory movement strategy developed at an earlier time point. Lastly, given the persistent muscle weakness observed in the quadriceps and hip external rotators at 6 months post-TKA, investigations into the efficacy of a post-rehabilitative progressive strengthening program in restoring normal muscle performance and improving patient outcomes are justified.

Appendix: Knee Injury and Osteoarthritis Outcome Score

KOOS KNEE SURVEY

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

Name:

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

Symptoms

These questions should be answered thinking of your knee symptoms during the **last week**.

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your knee catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Stiffness

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

S6. How severe is your knee joint stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Pain

P1. How often do you experience knee pain?

Never	Monthly	Weekly	Daily	Always
☐	☐	☐	☐	☐

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

P2. Twisting/pivoting on your knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P3. Straightening knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P4. Bending knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, daily living

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

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A4. Standing

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A14. Sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

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

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2. Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4. Twisting/pivoting on your injured knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Quality of Life

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

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

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

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

Q3. How much are you troubled with lack of confidence in your knee?

Not at all	Mildly	Moderately	Severely	Extremely
☐	☐	☐	☐	☐

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

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161. Neumann DA. Kinesiology of the hip: a focus on muscular actions. The Journal of orthopaedic and sports physical therapy 40(2): 82, 2010
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164. Lee SJ, Hidler J. Biomechanics of overground vs. treadmill walking in healthy individuals. Journal of applied physiology (Bethesda, Md : 1985) 104(3): 747, 2008
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167. Stratford PW, Kennedy DM. Performance measures were necessary to obtain a complete picture of osteoarthritic patients. Journal of clinical epidemiology 59(2): 160, 2006
168. Jacobs CA, Christensen CP. Correlations between knee society function scores and functional force measures. Clinical orthopaedics and related research 467(9): 2414, 2009
169. Parent E, Moffet H. Preoperative predictors of locomotor ability two months after total knee arthroplasty for severe osteoarthritis. Arthritis Rheum 49(1): 36, 2003
170. Yoshida Y, Mizner RL, Ramsey DK, Snyder-Mackler L. Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. Clinical biomechanics (Bristol, Avon) 23(3): 320, 2008

VITA

PAUL WILDER KLINE

EDUCATIONAL BACKGROUND

DOCTOR OF PHYSICAL THERAPY
East Carolina University, Greenville, NC
Physical Therapy
College of Allied Health Sciences
Conferred: May 2013

BACHELOR OF SCIENCE
Furman University, Greenville, SC
Health & Exercise Science
Conferred: May 2010

PROFESSIONAL BACKGROUND

CLINICAL EXPERIENCE

Physical Therapist, University of Kentucky Running Injury Clinic, Lexington, KY
August 2013 – Present

Physical Therapist, Saint Joseph Hospital, Lexington, KY
November 2014 – Present

Physical Therapist, Kentucky Orthopedic Rehab Team, Lexington, KY
August 2013 – July 2015

TEACHING EXPERIENCE

Guest Lecturer, Division of Physical Therapy, University of Kentucky
PT 805 (Spring 2016, 2017)
PT 815 (Summer 2015, 2016)

HONORS & AWARDS

Student Travel Award
Biomechanics Interest Group, American College of Sports Medicine, 2016

Robinson Graduate Award for Research Creativity
College of Health Sciences, University of Kentucky, 2016

Excellence in Research, Finalist
Sports Section, American Physical Therapy Association, 2016

Excellence in Research, Finalist
Sports Section, American Physical Therapy Association, 2015

Student Leadership Award
Department of Physical Therapy, East Carolina University, 2013

Clinical Excellence Award
Department of Physical Therapy, East Carolina University, 2013

Academic Excellence Award
Department of Physical Therapy, East Carolina University, 2013

Unsung Hero Award
Office of the President, Furman University, 2010

Thomas Award (Outstanding Senior)
Department of Health & Exercise Science, Furman University, 2010

PUBLICATIONS

ACCEPTED MANUSCRIPTS

1. **Kline P.W.**, Johnson D.L., Ireland M.L., Noehren B. Clinical predictors of knee mechanics at return to sport following ACL reconstruction. *Med Sci Sports Exerc.* 2016 May;48(5):790-5.

2. **Kline P.W.**, Williams D.S. III. Effects of normal aging on lower extremity loading and coordination during running in males and females. *Int J Sports Phys Ther.* 2015 Nov;10(6):901-9.

3. **Kline P.W.**, Morgan K.D., Johnson D.L., Ireland M.L., Noehren B. Impaired quadriceps rate of torque development and knee mechanics after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med.* 2015 Oct;43(10):2553-8.

SUBMITTED MANUSCRIPTS

1. Lucas K.H., **Kline P.W.**, Ireland M.L., Noehren B. Hip and trunk muscle dysfunction: implications for ACL injury prevention. (In review at *Annals of Joint*).

2. **Kline P.W.**, Burnham J, Yonz M.C., Johnson D.L., Ireland M.L., Noehren B. The role of hip muscle strength in single leg hop performance after anterior cruciate ligament reconstruction: a cross sectional case-control study. (In review at *Knee Surgery, Sports Traumatology, Arthroscopy*).

PRESENTATIONS

1. Noehren B., **Kline P.W.**, Ireland M.L., Johnson D.L. (2017) Early Objective Clinical Testing Predicts Jump Landing Mechanics Following an ACL Reconstruction: Impact for the Clinician and Return to Play Testing. American Orthopaedic Society for Sports Medicine Annual Meeting, Toronto, ON, Canada (Accepted)

2. Noehren B., **Kline P.W.**, Ireland M.L., Johnson D.L. (2017) Kinesiophobia is *Strongly Associated with Altered Loading after an ACL Reconstruction: Implications for Re-injury Risk.* American Orthopaedic Society for Sports Medicine Annual Meeting, Toronto, ON, Canada (Accepted)

3. **Kline P.W.**, Marquez M.J., Ireland M.L., Johnson D.L., Noehren B. (2017) *Hip-Dominant Landing Strategy During the Second Landing of a Drop Vertical Jump After ACL Reconstruction.* American College of Sports Medicine Annual Meeting, Denver, CO. (Accepted)

4. Marquez M.J., **Kline P.W.**, Ireland M.L., Johnson D.L., Noehren B. (2017) *Comparison of Post-ACLR Kinematics Between Landings of a Drop Vertical Jump: Implications for Re-injury Risk.* American College of Sports Medicine Annual Meeting, Denver, CO. (Accepted)

5. Kline P.W. (2017) *Muscular and Physical Performance Determinants of Patient Reported Outcome Score after Unilateral Total Knee Arthroplasty.* The Association for Clinical and Translational Science: Translational Science 2017, Washington, DC.

6. Robertson K., McKinley R., **Kline P.W.**, Noehren B. (2017) *Pain Processing Alterations in Females with Chronic Patellofemoral Pain.* Combined Sections Meeting of the American Physical Therapy Association, San Antonio, TX.

7. McKinley R., Robertson K., **Kline P.W.**, Noehren B. (2017) *More Than Knee Pain: Females with Chronic Patellofemoral Pain Demonstrate Altered Psychosocial Responses.* Combined Sections Meeting of the American Physical Therapy Association, San Antonio, TX.

8. **Kline P.W.**, Jacobs C., Duncan S.T., Noehren B. (2017) *Between-limb Asymmetries during Stair Descent 3 Months after Total Knee Arthroplasty.* Combined Sections Meeting of the American Physical Therapy Association, San Antonio, TX.

9. **Kline P.W.**, Ireland M.L., Johnson D.L., Noehren B. (2017) *Does Handheld Dynamometry Accurately Measure Quadriceps Strength Symmetry after Anterior Cruciate Ligament Reconstruction? Implications For Rehabilitation Progression.* Combined Sections Meeting of the American Physical Therapy Association, San Antonio, TX.
10. **Kline P.W.**, Ireland M.L., Johnson D.L., Noehren B. (2016) *Early Clinical Tests are Predictive of Knee Biomechanics at Return to Sport Following Anterior Cruciate Ligament Reconstruction.* Combined Sections Meeting of the American Physical Therapy Association, Anaheim, CA.

11. **Kline P.W.**, Morgan K.D., Grim K., Ackerman K., Noehren B. (2016) *The Effects of Trunk Fatigue on Proximal Joint Kinematics and Coupling During Running.* American College of Sports Medicine Annual Meeting, Boston, MA.

12. Marquez M.J., **Kline P.W.**, Ireland M.L., Johnson D.L., Noehren B. (2016) *Kinematic Asymmetries During the Second Landing of a Drop Vertical Jump After ACL Reconstruction.* American College of Sports Medicine Annual Meeting, Boston, MA.

13. **Kline P.W.** (2016) *Association of 3 Month Muscular Performance with 6 Month Patient Reported Outcomes After TKA.* The Association for Clinical and Translational Science: Translational Science 2016, Washington, DC.

14. **Kline P.W.**, Schmitz A, Ireland M.L., & Noehren B. (2015) *Impaired Quadriceps Rate of Torque Development Alters Knee Mechanics after ACL Reconstruction.* Combined Sections Meeting of the American Physical Therapy Association, Indianapolis, IN.

15. **Kline P.W.** (2014) *Complicated Patient – Sports Edition*. Combined Sections Meeting of the American Physical Therapy Association, Las Vegas, NV.

16. **Kline P.W.,** Williams D.S. III, Welch L.M. (2014*) Effect of Sex and Age on Lower Extremity Joint Coupling and Loading During Running.* APTA Combined Sections Meeting of the American Physical Therapy Association, Las Vegas, NV.

17. **Kline P.W.**, Welch L.M., Williams D.S. III. (2013) *Effect of Flexible vs. Inflexible Static Hamstring Length on Sagittal Plane Mechanics in Male vs. Female Runners.* Combined Sections Meeting of the American Physical Therapy Association, San Diego, CA.

18. **Kline P.W.**, Wurzinger B.W., Segal R.L., Steinbaker C.R., Ratcliff O.M., Williams D.S. III. (2012) *Magnetic Resonance Analysis of Intrinsic Foot Musculature during Running Shod and Barefoot Conditions.* 56th American College of Sports Medicine Annual Meeting, San Francisco, CA.

FUNDING

Title: Factors contributing to protracted strength loss and function after total knee arthroplasty
Mechanism: TL1 Pre-doctoral Award (TL1TR00015)
Funding Agency: National Center for Advancing Translational Sciences & National Institutes of Health
Date: 06/2015 – 07/2017
Role: Pre-doctoral Trainee

PROFESSIONAL AFFILIATIONS/LICENSING

MEMBERSHIPS

1. American Physical Therapy Association (2010 – Present)
2. Kentucky Physical Therapy Association (2013 – Present)
3. American College of Sports Medicine (2015 – Present)

LICENSURE

Physical Therapist, Kentucky Board of Physical Therapy #KY006267

<u>PROFESSIONAL SERVICE ACTIVITIES</u>

MANUSCRIPT REVIEWER

1. American Journal of Sports Medicine
2. International Journal of Exercise Science
3. Journal of Sport Rehabilitation