Lower Extremity Biomechanics during Stair Ascent in Healthy and Total Knee Replacement Older Adults

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Tyler Whitney Standifird

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DEDICATION

This dissertation is first dedicated to Ashley, Lucas, and Beckham. Without Ashley's belief in me and constant support through 5 years of marriage I would have never made it this far. Also to Lucas and Beckham who greeted me with eagerness each day off the bus, you (with your mother) provided me with complete joy at the end of every day. Second to my parents Ron and Patty Standifird who for 30 years have celebrated every success of my life and who are the reason that the successes have outweighed the failures. Finally to my siblings Jason, Heather, Ryan, Kristin, and Brandon who provided a path to achievement that was well worn and easy to follow.

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ABSTRACT

Altered gait following total knee replacement (TKR) may increase risks for failure of joint replacements and subsequent joint replacements in both the replaced and non-replaced limb of TKR patients. Stair climbing is an activity of daily living that is more demanding than level walking and may be more robust at detecting altered gait biomechanics. Study One reviewed biomechanics during stair ambulation following TKR. Study Two compared lower extremity biomechanics during the first three steps of ascent and level walking in healthy adults. Study Three compared lower extremity biomechanics of the replaced and non-replaced limbs of TKR patients and a healthy control limb during stair ascent. Study Four utilized principal component analysis (PCA) to compare waveforms of knee biomechanical variables in TKR patients and healthy controls. Thirteen TKR participants and fifteen healthy control subjects participated. A motion analysis system and instrumented 3-step staircase were utilized to collect trials of stair ascent and level walking.

The findings of Study Two show that many sagittal plane variables for healthy subjects were smallest in level walking, larger on the first step and greatest on the second and third steps. In the frontal plane the knee was more adducted with greater abduction ROM in the step conditions. The findings of Study Three show that the loading response peak knee extension moment was greater in control and non-replaced knees compared with replaced of TKR. In addition, loading-response peak hip abduction moments were greater in the replaced and non-replaced limb compared to controls, while the push-off peak hip abduction moment was greater in replaced compared to controls. The findings of Study Four show that peak knee abduction and internal rotation moments were elevated in TKR compared to controls.

TKR patients have compensatory gait that results in deficits in the sagittal plane, with increased demands in the frontal and transverse plane at the knee and hip in the replaced limb in

addition to compensation by the non-replaced limb. Rehabilitation strategies should continue to focus on the quadriceps muscle, but should also focus heavily on other muscles surrounding the knee and hip joints for optimal recovery following TKR.

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CHAPTER I

INTRODUCTION

Background

The center for disease control (CDC) recently reported that 22.7% of US adults, or 52.5 million, report doctor diagnosed arthritis (13). Knee osteoarthritis (OA) is the most common form of arthritis and is projected to afflict 67 million (25% of the adult population) by the year 2030 (49). Total knee replacement (TKR) or total knee arthroplasty is a surgical treatment option for end-stage knee OA. In 2010, it was reported that the number of TKR surgeries was over 700,000 for the year (92) though the total number of TKR surgeries is increasing and expected to reach 3.5 million a year in the United States by 2030 (65). It was reported that the average cost for a TKR in the state of Wisconsin is $19,169 per procedure (82). Assuming similar costs across other states, it can be further extrapolated that the costs for TKR surgeries in the United States could approach 67 billion dollars a year by 2030. In addition, researchers have reported that the age of TKR patients is getting younger, with a substantial increase in patients younger than 60 years of age (106).

An understanding of the success of TKR surgery is imperative. The primary goals of TKR surgery are a reduction of pain, restoration of knee joint range of motion (ROM), improvement in joint alignment, and a restoration of the ability to perform common activities of daily living (1). Additionally, many patients desire a return to sport and/or leisure activities including walking, tennis, biking, swimming, and golf and many of these activities are listed as part of the knee society survey (115), a popular instrument utilized to assess patient outcomes following TKR. Previous research has reported that pain is significantly reduced following TKR (21, 46, 62) and that a majority of patients are satisfied with their knee replacements (93).

However, despite reports of significant reductions of knee pain and improvements in physical functions it was recently reported that some patients still have long-term pain following TKR (17). Patients have reported having at least some limitations in performing functional activities following a TKR surgery (94) in addition to decreased performance on clinical tests for TKR groups compared to healthy controls (19, 98). These results suggest that both alleviation of pain and restoration of locomotor ability may not be complete.

With more and younger individuals facing the need of a TKR in the future, understanding of recovery following surgery has become more important. Detailed lab-based biomechanical studies of gait related activities following TKR can offer an understanding of recovery following surgery. Biomechanics of overground walking following TKR has been studied extensively focusing on gait velocity (14, 83), sagittal plane knee range of motion (ROM) (14, 128), and frontal plane knee moments (14, 83), and review articles have summarized and depicted a more complete picture of overground gait biomechanics following TKR (75, 85). TKR should not only restore normal mechanics during level walking but also during more demanding daily activities such as stair climbing as younger TKR demands greater functional recovery.

Stair climbing is more demanding on lower extremity muscles and joints (91, 99) and is a common activity of daily living utilized frequently by both younger and older adults (122). Knee OA patients often have difficulty in climbing stairs (28). Furthermore, ability to climb stairs is included in all of the most common knee scoring tools (30, 52, 115) used to assess physical functions following a TKR. Deficiencies in biomechanics may become more apparent in more demanding activities of daily living (91, 100).

Although an increasing number of studies has examined the stair gait biomechanics after TKR, current literature is not in complete agreement on how TKR alters the biomechanics of variables measured during stair gait (16, 18, 23, 36). Some studies reported reductions in knee joint ROM for TKR patients compared to healthy subjects for knee (16, 18, 23, 36) while others reported no differences in knee ROM between TKR patients and healthy controls (16, 60, 128). Unlike level walking, no review articles have been developed to synthesize the current state of the literature regarding stair ambulation biomechanics following TKR. Hence, a systematic review is needed in order to provide useful information for clinicians and researchers. Varied study designs including subject population, replacement type, and instrumented staircase design are a few important factors to consider. Discrepancies in these factors can make it difficult to interpret and compare results and a detailed review would provide researchers with a clearer picture of stair ambulation biomechanics following TKR.

Differences in instrumented staircase designs can lead to varied results between studies analyzing stair ambulation biomechanics. Recent advances in instrumented staircase designs have made the collection of kinetic variables much more accessible for many labs. These staircases range from one instrumented step (73) to 16 (126). Though the step of interest in stair ambulation biomechanics is often a choice of researchers and varied primarily due to equipment constraints, little research has been carried out to understand how the choice of step alters research findings. Yu et al. (130) performed a study on the reproducibility lower extremity biomechanics during normal stair-climbing. They found that lower extremity joint angles and moments on the first step of a staircase led to the greatest variability, while the third step showed most consistent results. In addition, the authors suggested that the first step of the staircase is a transition or an initiation step from level walking to stair ambulation (130). However, it did not report differences in magnitudes of key biomechanical variables associated with different steps of interest. Thus, a better understanding of how step of interest influences biomechanical variables during stair climbing would make possible better synthesis of the current literature.

Deficiency in lower extremity biomechanics during walking and stair climbing could potentially lead to altered loading conditions and incur further injury to the contralateral knee or other lower extremity joints. Previous research has shown that a non-random evolution of joint replacement occurs following a total joint replacement, with the contralateral cognate joint the most common joint to undergo a subsequent replacement (116). Minimal research has been carried out to understand the effects of TKR on the contralateral limb during stair climbing. Two studies utilized the nonreplaced limb for comparisons to the TKR limb in the same subject, but did not make comparisons to a healthy control group (54, 60). In addition both of these studies only reported variables in the sagittal plane, with no information on frontal plane knee variables. It is well known that frontal plane knee moments are associated with the severity and progression of knee OA, thus an understanding of these variables in the contralateral limb is essential.

Biomechanical data sets are often large and require careful attention to ensure that the most meaningful data are determined and utilized for analysis. Most often, discrete points are extracted from variable curves of interests and compared between groups. The choice of what discrete points to pick for analysis is made by the researcher based on their biomechanical significance and is often based on previous research studies. These types of comparisons are time consuming and are limited that they can only provide meaningful information at discrete points during movement. In addition to discrete analyses, whole curve analysis can equip researchers with additional tools to analyze data. Principal component analysis (PCA) is one of these tools. The main goal of PCA is to extract and analyze the most important information from large data sets (2). Instead of analyzing only discrete data points, PCA can compare entire waveforms for overall patterns and magnitudes. Additionally, PCA can create principle components (PC), which can be useful in detecting and describing differences in large data sets.

Though not often utilized in biomechanical research, PCA has been used to study gait and running (27, 38) and at times in patient groups with knee OA (10, 31) and in TKR patients (45, 74), and has been shown to be an effective tool in the reduction and interpretation of gait waveform data (31). Deluzio et al. (31) analyzed waveform patterns of the knee flexion angle, flexion moment and adduction moment during overground walking in patients with knee OA and healthy controls. Each of these variables returned up to three PC, which exhibited differences in overall magnitudes, range of motions and phase shifts. They found that, the range of motion of the knee flexion angle (second PC), the amplitude (second PC) and early stance magnitude (first PC) of the knee flexion moment and the magnitude of the adduction moment during early stance (second PC) were sufficient to detect group differences. Other studies have also successfully utilized PC to detect differences between healthy controls and moderate and severe knee OA patients (10, 33).

Mandeville et al. (74) utilized PCA to analyze overground and stair gait in patients pre and post TKR. They were able to apply PCA to waveform curves in order to group patients according to recovery following surgery. The analysis led to three PCs at both testing periods. They reported that the frontal plane knee moment during overground walking (first PC) and the knee flexion angle (third PC) and total support moment (third PC) during stair ascent were sufficient to detect differences between TKR patients and healthy controls. To our knowledge, this is the only study containing PCA on TKR patients during stair ambulation.

Statement of the Problem

To our knowledge, no studies have attempted to review the current state of the literature on stair climbing in patients following TKR. Additionally, when considering stair climbing, no studies have explored the effects of step of interest on common biomechanical variables. Finally, no research has been carried out to understand the effects of TKR on both sagittal and frontal plane biomechanics of the replaced and nonreplaced limb during stair climbing. Therefore, the purposes of proposed studies are listed below:

Study One: The purpose was to conduct a systematic review of the literature on stair climbing biomechanics following TKR.

Study Two: The purpose was to compare lower extremity biomechanics on the first three steps of stair ascent and level walking in a group of healthy mid and old-age adults.

Study Three: The purpose was to compare sagittal and frontal plane lower extremity biomechanics of the replaced limb and the nonreplaced limb of TKR patients to healthy controls during stair ascent.

Study Four: The purpose was to utilize a principal component analysis to compare biomechanical waveform graphs during stair ascent between TKR patients and healthy controls.

Research Hypotheses

Study One

No specific hypothesis was needed as it was a systematic review of the current literature regarding stair biomechanics following Total Knee Replacement.

Study Two

1. It was hypothesized that lower extremity biomechanical variables on the first step would be different than those on the second and third step during stair ascent.

2. It was hypothesized that biomechanics during level walking would be different than those during all three steps of stair ascent.

Study Three

1. It was hypothesized that the knee sagittal variables would be similar in the replaced limb when compared to the non-replaced limb, but that both would be different compared to control limb
2. It was hypothesized that frontal plane knee variables would be different in the replaced limb compared to non-replaced limb and control limb, but similar between the replaced limb and control limb.
3. It was hypothesized that for the ankle and hip, sagittal plane variables would be similar for all limbs, but that frontal plane variables would be different between the non-replaced and control limb.

Study Four

1. We hypothesized that PCA would detect differences between TKR patients and controls for knee flexion angle, knee extension moment and see similarities for peak knee abduction angles and moments/
2. We hypothesized that PCA would be more robust in detecting differences at various time points on the waveform, such as contact, peaks at loading and push-off and midstance, in all planes of motion.
3. Due to the lack of studies, we hypothesized no differences of transverse knee angle and moment between the groups.

Delimitations

The exclusion criteria for healthy adults for studies two, three, and four included:

- Knee pain for at least 6 months during daily activities.
- Diagnosed with any type of lower extremity joint osteoarthritis (self-reported).
- Any lower extremity joint replacement.
- Any lower extremity joint arthroscopic surgery or intra-articular injection within past 3 months.
- Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) (self-reported).
- BMI greater than 35.
- Inability to ascend/descend stairs without the use of a handrail.
- Inability to walk without a walking aid.
- Neurologic disease (e.g. Parkinson's Disease, stroke patients) (self-reported).
- Any major lower extremity injuries/surgeries.
- Any visual conditions affecting gait or balance.
- Women who are pregnant or nursing.
- Any cardiovascular disease or primary risk factor which precludes participation in aerobic exercise as indicated by the Physical Activity Readiness Survey. If any participant marks "yes" on the survey they will be required to obtain written consent from their doctor indicating they are healthy enough to participate in the study.

The inclusion criteria included for healthy adults for studies two, three, and four:

- Men and women between the ages of 35 and 80.

The exclusion criteria for TKR for studies two, three, and four included:

- Any additional lower extremity joint replacement.

- Any lower extremity joint arthroscopic surgery or intra-articular injection within the past month.
- Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) (self-reported).
- BMI greater than 35.
- Inability to ascend/descend stairs without the use of a handrail.
- Neurologic disease (e.g. Parkinson's Disease, stroke patients) (self-reported).
- Any major lower extremity injuries/surgeries.
- Inability to walk without a walking aid.
- Any visual conditions affecting gait or balance.
- Women who are pregnant or nursing.
- Any cardiovascular disease or primary risk factor which precludes participation in aerobic exercise as indicated by the Physical Activity Readiness Survey. If any participant marks "yes" on the survey they will be required to obtain written consent from their doctor indicating they are healthy enough to participate in the study.

The inclusion criteria for TKR for studies two, three, and four included:

- Men and women between the ages of 35 and 80.
- Total knee replacement in one knee.
- Posterior Stabilized replacement design.
- At least 6-months from TKR.
- No more than 5-years from TKR

Limitations

- All tests were conducted in a laboratory setting.
- Skin marker placement in obese participants may not reflect accurate bony landmark location.
- Reflective markers used to track the feet during motion trials were placed on the shoe. Thus, foot motions within the shoe may not have been accurately captured.
- The nature of the staircase set-up required placement prior to subjects coming to the lab. Thus, level walking always followed stair conditions.

CHAPTER II

LITERATURE REVIEW

Introduction

The purpose of Study One was to conduct a systematic review on the biomechanical adaptations during stair ambulation that occur after a total knee replacement (TKR). The purpose of Study Two was to compare lower extremity biomechanics during stair ascent on the first three steps of an instrumented staircase in healthy older adults. The purpose of Study Three was to analyze lower extremity biomechanics for TKR patients affected knee and contralateral unaffected knee and to compare these findings to healthy age matched controls. This study also utilized functional tests in both TKR patients and healthy controls as a means to help quantify recovery and provide more useful information to clinicians. The purpose of Study Four was to utilize a multivariate statistical technique, principal component analysis, to compare stair ascent gait in TKR patients to healthy controls. This technique has been utilized previously in gait research to not only compare magnitudes of variables but also pattern changes in waveforms.

The primary goals of this chapter were to 1) outline common biomechanical characteristics associated with overground walking in TKR subjects, 2) summarize stair ambulation biomechanics in both healthy and TKR populations, 3) consider special methodological situations associated with stair ambulation biomechanics and TKR subject populations, and 4) address the benefit and usefulness of principal component analysis for biomechanical studies.

Biomechanical Variables Associated With Total Knee Replacement During Level Walking

It is important to understand how gait is altered following total knee replacement during overground walking. Overground walking is a basic movement that is necessary for the performance of many activities of daily living. Ground reaction force, temporal-spatial, kinematic and kinetic variables were included for analysis. Comparisons within TKR subjects for pre-surgery gait and the non-operated limb, in addition to between TKR and healthy controls were summarized in order to more fully understand the impact of TKR surgery on overground gait.

It has been shown that the status of pre-operative functions is a strong indicator of success for post-operative recovery of patients (131). Comparisons to pre-operative gait can offer an indication of individual recovery following surgery. Additional comparison to healthy age-matched controls can offer a better idea of the level of recovery following surgery. TKR related studies have focused on comparisons between pre- and post-surgery (45, 63, 97), between TKR patients and healthy age-matched controls (6, 14, 77, 86, 128), and between TKR patients and both pre-surgery status and healthy controls (68, 72, 73, 98, 117). Shakoor et al. (116) analyzed a hospital database of total joint replacement patients in order to understand the relationship between OA in one of the three major lower extremity joints to that in the other three lower extremity joints. They found that following a total joint replacement there is a non-random evolution of OA disease progression and joint replacement. The authors reported that the contralateral cognate joint was the most common joint to undergo a subsequent replacement (116). Comparison between the contralateral knee joint would offer information that could aid in the reduction of subsequent knee replacements.

Temporal-spatial gait variables

Temporal-spatial variables offer basic information about recovery of gait following TKR. The most common of these variables analyzed are gait velocity, stride length, and walking cadence. These variables are important indicators of basic ambulation functions in older adults. Walking is the most basic activity of daily living and is necessary for high quality of independent life. In addition, these variables are easy to collect and analyze in a clinical setting without the use of any expensive equipment. An understanding of how replacement surgery affects these variables is an important first step in assessing function recovery after surgery.

Gait velocity has been shown to be associated with survival in older adults (124) and is often reported in various gait studies (6, 14, 45, 63, 68, 72, 77, 97, 98, 117, 128). Pre-surgery gait velocity was shown to range from 0.89 m/s (72) up to 1.13 m/s (68). An increase in gait velocity was found after surgery when compared with pre-surgery velocity (45, 63, 72, 97). Increase in gait velocity varied from 0.1 m/s (97) to 0.17 m/s (45). Levinger et al. (68) reported no differences between pre-surgery to post-surgery gait velocities, while Ouellet et al. (98) found that gait velocity was reduced two months post-surgery. Two months was by far the shortest testing time from replacement surgery employed in these studies and most studies wait until 1-year out from surgery to test TKR patients. Most likely the two- month testing time is not enough time for patients to achieve sufficient recovery following surgery (98). It appears that gait velocity is significantly improved after recovery following replacement surgery when compared with pre-surgery velocity.

Though improvements in gait velocity after TKR are apparent, these restorations do not appear to reach healthy levels. Gait velocity post TKR was reported to be between 0.7 m/s (at two-months post-surgery) (98) and 1.31 m/s (6). Significant differences were reported between TKR patients and healthy controls (6, 14, 68, 72, 98), with differences ranging from 0.12 m/s (6) to 0.6 m/s (98). McClelland et al. (77) reported velocity differences between TKR patients and controls that approached significant levels with a difference of 0.12 m/s ($p = 0.08$). Other studies found no differences between TKR patients and healthy controls for gait velocity (117, 128). Wilson et al. (128) had the longest follow-up testing time and reported no differences in gait velocity between TKR patients and healthy controls. This suggests that more time may be needed for recovery following TKR surgery in order to restore gait velocity. It appears from the literature that though gait velocity is improved from pre-surgery levels, it does not approach those values of healthy older adults at the time of testing. More longitudinal studies with multiple follow-up testing times are needed to see if gait velocity is recovered as time from surgery increases.

Stride length and walking cadence (or stride frequency) are two additional spatial-temporal parameters that provide information on recovery following TKR. Stride length is a measure of distance covered during successive foot contact of the same foot. Stride length after TKR increased when compared to pre-surgery levels in studies reporting on this variable (45, 63, 72). Increases ranged from 0.04 m (63) to 0.11 m (45, 72). The study with only a two-month follow-up testing, found a reduced stride length after surgery (98), and Levinger et al. (68) reported no differences in stride length of TKR subjects from pre- to post-surgery. Similar to results of gait velocity, stride length was found to be significantly longer in healthy controls compared to TKR patients (6, 14, 68, 72, 77, 98). Two studies reported no differences between controls and TKR patients (117, 128). Cadence, or the number of steps taken in one minute, was greater in healthy controls when compared with TKR patients (14, 68, 77, 98). The same studies that reported no differences in gait velocity and stride length between TKR patients and controls, also reported no differences for cadence (117, 128). Similar to results of gait velocity, stride length appears to be improved when compared with pre-surgery levels, but improvements do not approach levels of healthy aged matched controls. Walking cadence also appears to be significantly reduced in TKR patients when compared with healthy controls.

Stride length and walking cadence together contribute to walking velocity. It has been shown that gait velocity is improved following TKR surgery (6, 14, 68, 72, 98), in addition to increased stride length following surgery (45, 63, 72). This suggests that TKR patients have longer stride lengths after surgery, directly contributing to the improvements in gait velocity following surgery.

Though temporal-spatial variables offer some information on functionality in patients following TKR, more advanced measurements can provide more detailed information on important biomechanical variables. Ground reaction force, joint kinematics, and joint kinetics are biomechanical variables that can be measured during overground walking. They provide key information about more detailed function during walking tasks.

Ground Reaction Force

Ground reaction force (GRF) is a measure of force application applied by the ground to an individual during stance and can be a useful measure of overall external loading to the body during a given task. Often it is reported as a percentage of body weight (BW). Relatively few studies have included analysis on GRF variables (63, 84). Milner et al. (86) compared peak vertical GRF and loading rates between the operated limb and non-operated limb following TKR surgery. They reported that peak vertical GRF values were similar between the operated (1.07 BW) and non-operated limb (1.09 BW). Loading rates between limbs were also similar. TKR patients appeared to walk with reduced velocity (1.25 m/s) compared to healthy controls (1.42 m/s), but no statistical tests were done on gait velocity. It should be noted that comparisons were made between the operated and non-operated limb during the same walking trial, so it can be assumed that for these comparisons velocity was similar between steps. This study had a very heterogeneous sample of TKR patients. Subjects had a variety of replacement types, were tested at varying times from surgery (4 – 96 months), and were operated on by different surgeons. These factors make interpretations of the results difficult.

A more recent study (63) compared pre-surgery GRF variables to two-year post-surgery levels for both the operated and non-operated limb. They found that the contralateral limb had a greater peak vertical GRF value (1.06 BW) when compared with the operated limb (1.03 BW) prior to surgery. This difference was still apparent after TKR, the non-operated limb had a greater peak vertical GRF value (1.09 BW) compared with the operated limb (1.05 BW). Both limbs showed a significant increase in peak vertical GRF post-surgery when compared with pre-surgery values. Loading rates were similar between operated and non-operated limbs, but after replacement, the loading rates of both limbs were greater than those reported prior to surgery.

Ground reaction force variables are directly correlated with walking velocity and so as velocity increases, these variables would be expected to also increase. GRF variables should be reported with walking velocity in order to better understand the source of differences. The existence of asymmetry between peak vertical GRF between the operated and non-operated limb is interesting. It would be expected that knee OA patients awaiting TKR would favor, or share greater loading on the more healthy leg during gait. It is surprising that two years after surgery, the TKR patients are still loading the non-operated limb at a greater level. This may partially explain why nearly 40% of patients who undergo a TKR have the opposite knee replaced within ten years (81). Mores studies should report GRF variables, with gait velocity, in order to understand asymmetry in loading between limbs.

Sagittal Plane Joint Kinematics

Sagittal plane joint kinematic variables including knee flexion at contact, maximum knee flexion during stance and swing, and total knee flexion range of motion (ROM) were some of the most common variables examined in TKR related studies and are important for TKR patients. Passive knee flexion ROM is one of the primary clinical measurements assessed following surgery. It is often used as a measure that dictates progression from hospital, to inpatient physical therapy, and finally to outpatient therapy. Biomechanical analysis of gait can provide additional understanding of joint ROM by providing information on dynamic ROM.

Knee flexion at contact was similar between TKR patients and healthy controls (14, 68, 77).Comparisons between TKR patients and healthy controls for maximum knee flexion during stance and swing appear to be very consistent between studies. Most studies reported that TKR patients had reduced knee flexion during stance when compared with healthy controls (72, 77, 98, 128). On average, TKR patients had 6 degrees less knee flexion during stance when compared to healthy controls. Levinger et al. (68) and Smith et al. (117) were the only groups that reported similar maximum knee flexion angles between TKR patients and healthy controls. During the swing phase, some studies reported that TKR patients had reduced knee flexion when compared with healthy controls (14, 77, 128). TKR patients exhibited, on average, 50 degrees of maximum knee flexion during swing, compared to 60 degrees of maximum flexion in healthy controls. Similar to knee flexion during stance, some studies reported no differences for knee flexion during swing between TKR patients and healthy controls (68, 117). Levinger et al. (68) reported reduced knee extension during mid-stance for TKR patients when compared to healthy controls. Differences were almost 10 degrees prior to surgery and seven degrees post-surgery. These findings suggest that there are no differences of knee contact angle between TKR patients and healthy controls, but TKR patients have less knee flexion than healthy subjects during stance and swing phases. Knee ROM in the sagittal plane is often measured as the difference between knee contact angle and maximum knee flexion angle, or the difference between maximum knee extension angle and maximum flexion angle. Knee flexion range of motion (ROM) is reduced in TKR patients when compared with healthy controls. Decreased flexion ROM in TKR patients compared with healthy controls was reported, with absolute differences of 8 degrees (14) and 9 degrees (128). Levinger et al. (68) reported TKR patients had an 8 degree reduction in the same variable, a difference that approached significant levels ($p = .07$). When combining the results of sagittal knee ROM with other sagittal plane variables it becomes apparent that the source of the differences in ROM come from midstance knee angles and not knee angles at foot contact. Some studies have suggested that TKR patients employ a stiff knee gait, or quad avoidance, pattern following surgery (85), often measured by the amount of knee flexion during weight acceptance. This appears to be true for the TKR patients in these studies.

Walking is an activity of daily living that does not require a large knee flexion ROM. As a result, even though TKR patients walk with a reduced knee flexion ROM they are still able to complete the walking task successfully. More demanding tasks such as stair climbing, deep knee bending, and raising from a chair that require larger knee flexion ROM may still be difficult for TKR patients. This reduced dynamic knee ROM during walking may partially explain some of these difficulties.

Smith et al. (117) reported similar knee kinematic patterns between TKR patients and healthy controls, findings that were contradictory to other research studies. They also found that TKR patients and control groups walked with nearly identical walking velocities, an uncommon finding in TKR research. This suggests that their cohort of TKR patients may have been at a higher level of function and recovery than those who are still walking at reduced velocities. It is no surprise that these TKR patients would have knee kinematics during stance and swing that were similar to healthy controls. Walking velocity should be reported with kinematic variables in order to better understand potential sources of differences between groups.

Comparisons between pre- and post-surgery within TKR patients offer additional information on gait recovery following surgery. Levinger et al. (68) reported that there were no differences between pre-surgery and post-surgery values in knee flexion at contact, peak knee flexion during stance and swing, and peak knee extension during stance. Not surprisingly, when they made comparisons for sagittal knee ROM they also reported that there were no differences between TKR patients' pre and post-surgery. Hatfield et al. (45) used principal component analysis (PCA) to analyze knee flexion during the stance phase of gait and reported that patients had more knee flexion during stance phase after surgery compared to pre-surgery. Other studies that reported knee flexion during stance found that peak knee flexion was reduced after surgery when compared with pre-surgery values. (72, 98). Reductions in peak knee flexion following surgery were 3 degrees (72) and 9 degrees (98). While at first glance these results appear to be completely contradictory, a more careful analysis may help explain different findings. The two studies that reported reductions in knee flexion after surgery analyzed subjects at 6-months (72) and 2-months (98), while the other two both analyzed TKR subjects 1-year post surgery (45, 68). The longer time from surgery appeared to result in restoration of peak knee flexion during stance compared to pre-surgery levels. In addition, the use of PCA analysis by Hatfield et al. (45) provides a more robust statistical procedure for detecting differences. PCA analysis is used to analyze and compare entire sets of data as opposed to a few discrete points in a data set. This more advanced statistical tool may allow the detection of more subtle differences in the knee joint flexion curve.

Sagittal Plane Joint Kinetics

Kinetic analysis of the knee joint during gait offers an additional piece of information in a movement analysis. Sagittal plane knee moments are an example of kinetic variables that are often measured during gait analysis. A moment is a product of a force and the perpendicular distance (moment arm) between that force and an axis of rotation. Moments are either reported as being external or internal, depending on the specific convention used. Often these values are normalize to either body mass (Nm/kg) or bodyweight and height (%BW*height).

Peak external knee extension moment was reported to be reduced in TKR patients when compared to healthy controls (14, 68, 98). Differences between groups were reported as 0.16 ± 0.30 Nm/kg (98) and 2.2 ± 2.7 %BW*height (14). Smith et al. (117) reported peak mid stance external flexion moment and found that it was smaller in TKR patients (0.22 Nm/kg) when compared with healthy controls (0.3 Nm/kg). Mandeville et al. (72) reported that the knee internal extension moment (external flexion moment) at weight acceptance was reduced by 1.9 %BW*height in TKR patients when compared with healthy controls. Ouellet et al. (98) analyzed subjects at 2-months post-surgery and found that TKR patients had a maximum flexion moment of 0.13 Nm/kg, significantly lower than the control value of 0.44 Nm/kg, they did not report when these moments occurred. Wilson et al. (128) had the longest follow-up testing time, on average 46 months post-surgery, and they found that maximum external flexion moment values were lower in TKR patients when compared with healthy controls. Other studies reported that maximum external flexion moment was similar in TKR patients when compared with healthy controls (14, 68).

Comparisons between pre and post-surgery joint moments offer additional information about recovery following surgery. Hatfield et al. (45) analyzed sagittal knee moment curves using PCA within subjects for pre-surgery and post-surgery gait. They reported that subjects had a more normal bimodal moment pattern in the curves following surgery when compared with pre-surgery moments. Ouellet et al. (98) reported both the maximum knee flexion and extension moment, but made no mention of if moments were internal or external and also did not state clearly when in the stance phase these moments occured. They reported that there were no differences in maximum knee extension moment between TKR patients' pre and post-surgery. They also found that post-surgery TKR patients have a 0.20±0.27 (Nm/kg) reduction in maximum knee flexion moment when compared with pre-surgery values. Levinger et al. (68) analyzed maximum external flexion moment occurring during early stance phase and maximum external extension moment occurring near midstance. They found that the maximum external extension moment at midstance was similar for TKR subjects' pre and post-surgery. For the maximum external flexion moment at early stance, TKR subjects had an increase of 0.93 %BW*height post-surgery. Once again, the testing time from replacement helps to explain these results. The two-month follow-up used by Ouellet et al. (98) was much less than the 1-year follow up by Levinger et al. (68) showing that once again, recovery following TKR is not complete at 2-months post-surgery. In addition, the lack of information regarding the specific details of moments by Ouellet et al. (98) make comparing between additional studies very difficult. Mandeville et al. (72) reported that within subject differences for internal extension moment at weight acceptance were decreased by 0.9 %BW*height pre-surgery to post-surgery. An additional study reported that no asymmetry between replaced and non-replaced limbs was apparent for sagittal moment patterns (84).

The findings of kinetics following TKR surgery are in much less agreement than the kinematics from the literature. This may in part be due to the varied methods between studies. As outlined earlier, some studies give detailed information regarding the nature of the knee joint moments, providing specific details about if the moments are internal or external and when they occur. Other studies are much less clear on these specifics and as a result make comparisons between studies very difficult. It is apparent that time from replacement does play a key role in recovery for sagittal plane knee joint kinetics. The two studies that tested subjects less than 6-months after replacement surgery reported that sagittal moments were significantly different between TKR patients and healthy controls (72, 98). Future studies should carefully select time from surgery and recovery level based on the research question. More studies are needed on comparisons between TKR patients pre and post-surgery would improve our understanding of recovery.

Frontal Plane Joint Kinematics

Frontal plane joint kinematics and kinetics are also important to consider in gait biomechanics for TKR patients. A majority of TKR surgeries are carried out on subjects as a result of end stage knee OA, and the most common location of knee OA is the medial joint compartment. It is well understood that frontal plane kinematics and kinetics play a role in the progression and severity of medial compartment knee OA. Specifically, the internal abduction (external adduction) moment has been shown to be a surrogate for medial knee joint compartment loading. Comparisons of frontal plane movement patterns play a key role in understanding the success of TKR surgery.

Peak knee adduction during stance was restored to normal healthy levels following TKR surgery, as research shows no differences between healthy controls and TKR patients (73, 77). TKR patients had on average 4.1 degrees of peak adduction during stance, while healthy controls averaged 3.9 degrees. Orishimo et al. (97) did not compare TKR patients to healthy controls, but did report that at 6-months post-surgery the peak adduction angle in TKR patients was 3.6 degrees, similar to other values reported for TKR patients (73, 77). From these studies, it appears that peak knee adduction angle is similar between TKR patients and healthy controls. Correction of static plane frontal knee alignment is one of the goals of TKR and it has been shown that TKR surgery is successful at achieving this goal (97). Knee alignment plays a crucial role in knee joint loading in the frontal plane. It is encouraging that the correction of static knee alignment does appear to carry over to the dynamic task of walking. Understanding how improved knee alignment alters knee moments, and subsequent loading, in the frontal plane is also an important aspect of gait analysis.

Some studies compared adduction angle between the operated limb, the non-operated limb of TKR patients, and healthy controls. Milner et al. (86) reported no differences between peak knee adduction angle for the operated limb (1.8º), non-operated limb (4.3º) and healthy controls (2.4º). Alnahdi et al. (6) found significantly less adduction at peak knee adduction moment in the operated limb (0.9º) when compared with the non-operated limb (3.28º), though neither value was different from healthy controls (2.5º). Both studies suggest, once again, that alignment appears to be improved following TKR surgery. A more neutral alignment is the goal of surgery and that appears to be achieved in these studies during the stance phase of walking.

Peak knee adduction angles within subjects prior to and post-surgery were also compared in the literature (73, 97). Orishimo et al. (97) found that the peak knee adduction angle was reduced from 9.7 degrees prior to surgery to 3.6 degrees at 6-months post-surgery. Mandeville et al. (73) reported that TKR patients had 4 degrees less varus knee angles at peak vertical GRF after surgery when compared to pre-surgery levels. Once again the corrected static knee alignment from pre-surgery to post-surgery also looks to be apparent in dynamic situations.

Frontal Plane Joint Kinetics

The external knee adduction moment (internal abduction moment) has been reported to be a surrogate measure for medial compartment knee joint loading. Typical external knee adduction moment curves exhibit a bimodal pattern and comparisons are often made for both peak values. Normal curves have a higher first peak value compared to the second peak. Increased medial knee joint loading may contribute to accelerated wear on the joint replacement. Longevity of replacement is critical, especially considering the decreasing age of first time joint replacement recipients.

Peak external knee adduction moments in subjects following TKR to healthy control subjects have been studied (14, 117). Smith et al. (117) found no differences in peak external adduction moment between TKR patients (0.39 Nm/kg) and healthy controls (0.46 Nm/kg). In contrast, Benedetti et al. (14) reported that TKR patients had reduced first and second peak knee adduction moments when compared with controls. The first peak was reduced by 1.4 %BW*height, and the second peak was reduced by 1.0 %BW*height. Other studies reported that the operated limb had lower peak external knee adduction moment when compared with the non-operated limb (6, 86). Reductions were 0.7 Nm/kg (6) and 0.012 fat free mass/height (86). No differences were reported between the replaced limb and healthy control subjects (6, 86). These findings suggest that peak external knee adduction moment is similar between TKR patients following surgery and healthy subjects.

Some other studies compared external knee adduction moment pre- and post-surgery. Orishimo et al. (97) reported that subjects prior to TKR had a peak external knee adduction moment of 3.2 %BW*height that was reduced to 84% of pre-surgery levels (2.7 %BW*height) at 6-months post-surgery. At 1-year post surgery, this value went back to 3.0 %BW*height, which was, however, not significantly different from either time point. Mandeville et al. (73) measured the internal abduction moment occurring at the peak vertical GRF. TKR patients internal abduction moment was reduced from 4.07 %BW*height pre-surgery to 3.01 %BW*height at 6-months post-surgery. Internal abduction moment for healthy controls was 2.8 %BW*height, which was significantly different than those reported in TKR patients pre-surgery. Hatfield et al. (45), using PCA, reported that post-surgery TKR patients had decreased magnitude of external knee adduction moment during stance when compared with pre-surgery levels. When comparing results within subjects, external knee adduction moment is reduced following TKR surgery.

Knee external adduction moments appear to have more consistent results for overground walking. Patients with a TKR had external knee adduction moments that were similar to those reported for healthy adults. Only Benedetti et al. (14) found differences between groups, and reported reduction in the external knee adduction moment in TKR compared to healthy subjects, which would signal reduced loading of the medial compartment. These findings are consistent with those reported for frontal plane knee kinematics. The external knee adduction moment is a product of the magnitude of the GRF and the moment arm in the frontal plane. TKR patients had peak knee adduction angles that were similar to healthy controls. This angle directly alters the length of the frontal plane moment arm as well as the frontal plane moments. Unfortunately none of the studies reported the actual length of this moment arm during walking or how it differed between TKR patients and healthy controls. Additionally, external adduction moment was reduced as a result of surgery in TKR patients. Once again, these findings are not surprising considering the changes in frontal plane knee kinematics following TKR surgery. Two studies reported that peak knee varus or adduction angles during walking were significantly reduced following surgery (73, 97). This would bring the knee closer to the GRF vector, reducing the length of the frontal plane moment arm. A reduction in this moment arm would result in a subsequent decrease in the external knee adduction moment, a common finding in these studies.

In summary, the purpose of this section was to provide a review of overground gait biomechanics following total knee replacement. Emphasis was placed upon how TKR subjects compared to healthy controls and to their pre-surgery levels. Temporal-spatial parameters, ground reaction force, knee kinematics, and knee kinetics were analyzed. Temporal-spatial variables such as gait velocity, step-length, and cadence were all improved following TKR, though these improvements were not restored to healthy age-matched control levels. In the sagittal plane, peak flexion angle and flexion ROM were reduced in TKR patients compared to healthy controls. Peak knee extension moments were mostly found to be reduced in TKR patients compared to healthy controls, though this variable did contain some inconsistencies between studies. Inconsistencies may be present due to varied methods including: how variables were reported and picked, recovery of TKR patients, and walking velocity. In the frontal plane, the peak adduction angle was reduced significantly following TKR surgery and values were comparable to healthy adults. External knee adduction moment, or internal abduction moment, were also reduced in TKR patients following surgery. These reductions in frontal plane moment values are most likely a result of improvements in alignment following TKR. It is important to note that the testing time from TKR plays a crucial role in recovery for these patients. Studies at various stages following surgery can provide a continuum of information on recovery. Studies with longer time from surgery may provide information about complete recovery, while shorter time from surgery provides beneficial information about patient difficulties immediately following surgery. When proper time for recovery is allowed, total knee replacement surgery improves many aspects of overground gait, though there are still deficiencies when compared to gait of healthy subjects.

Stair Negotiation

It is well accepted that stair ambulation is a more demanding and difficult task when compared with level walking. In the compendium of physical activities, slow pace stair climbing required two times the metabolic cost of slow walking (4). In addition to increased physiological demands, stair ascent and descent are more demanding on the lower extremity muscles and joints (91). These increased demands are especially important when considering older or clinical populations. It was reported that stair ambulation was one of the top five most difficult tasks in individuals over the age of 60 (127). Additionally, patients with knee OA often complain of difficulty in climbing stairs (28) and the ability to climb stairs is included in all of the most common knee scoring tools (30, 52, 115). Though older adults experience more difficulty with stair climbing, they utilize stairs as frequently as younger adults (122). Therefore, an understanding of stair ambulation biomechanics is necessary for both healthy older adults and clinical populations. The following sections will review literature on stair ambulation biomechanics in healthy adults, and total knee replacements.

Stair Ambulation in Healthy Adults

When compared with level walking, it is clear that stair ambulation, whether ascent or descent, leads to differences in many common biomechanical variables including stride length, stride frequency and velocity. Stair ambulation does not allow alterations in step length as easily as overground walking. The dimensions of the staircase often limit the ability of the subject to alter step length variability. As a result, few studies report on step-length variables. Nadeau et al. (91) showed that during stair ambulation, adults over the age of 40 have a reduced stride length and stride frequency and a decreased forward velocity when compared with overground walking (91). In addition to these variables, they also found that subjects spent greater amount of time in swing phase than level walking. This may be due to the swing leg being required to swing over the current stance step and to the subsequent step on the stair case. Proptopapadaki et al. (104) reported a slower velocity during stair ascent (0.49 m/s) compared with stair descent (0.56 m/s), but had no comparisons to overground walking. Spatial-temporal- variables are not as commonly studied during stair ambulation tasks; instead emphasis is placed upon other kinematic and kinetic variables in attempts to quantify the physical demands of stair ambulation.

Ground reaction force variables are commonly measured during stair ambulation tasks. This has been made possible by the development of force measuring staircases. Later on in this section, information will be presented on the methodological considerations necessary with these staircase designs. Studies have showed that during stair ambulation, values of the first peak vertical GRF are greatest during stair descent (44, 104). These values have been reported to be nearly 1.5 BW (44). The second peak vertical GRF, or the propulsive peak, was shown to be elevated in stair ascent compared to both stair descent and overground walking (104). Thus GRF values are elevated during stair ambulation tasks, especially during stair descent.

Joint kinematics is an additional variable reported in stair ambulation literature. During the early stance phase of stair ascent, the ankle is already dorsiflexed, whereas in level walking the ankle gradually enters dorsiflexion as the gait cycle progresses (91). The maximum level of dorsiflexion at the ankle has been shown to be greater during stair ascent compared with overground walking (91, 104). The knee has greater flexion at contact during stair ascent (65º) compared with level walking (1º) and the maximum knee flexion is also elevated in stair ascent (93º) compared with level walking (67º) (91). In addition, greater knee ROM is experienced during stair walking (53, 91, 104), compared with level walking. Jevsevar et al. (53) reported that healthy adult knees experienced 30 degrees greater flexion ROM during stair ascent when compared with level walking. In the frontal plane, Nadeau et al. (91) reported the mean peak knee adduction angle increasing from 4.6 degrees during level walking to 10.4 degrees during stair ascent and an increase in peak ankle adduction during stair ascent compared to level walking. At the hip there were no differences for frontal plane kinematics.

Joint kinetics provides additional insight into the demands placed on the lower extremity and have been examined during stair ambulation tasks. During stair ascent it has been reported that the peak knee extension moment is greater compared to level walking (7, 91, 104). These differences have been reported to range from 0.18 Nm/kg (104) to 0.52 Nm/kg (91). Andriacchi et al. (7) reported that the maximum external knee flexion moment was three times greater in stair ascent than level walking. An additional study (70) reported peak sagittal knee moments to be 11.9 Nm/%BW, a value that was significantly greater than level walking (7.4 Nm/%BW). It is clear that sagittal plane knee moments are elevated in stair ascent when compared with level walking.

In the frontal plane, much less research has been carried out to assess joint kinetics in healthy adults during stair ambulation. Nadeau et al. (91) reported that the first peak knee abduction moment was greater during stair ascent (0.78 Nm/kg) compared with level walking (0.61 Nm/kg). It was also reported that the highest knee adduction moments were found during stair descent (4.67 %BW*Height) (70). Thus the frontal plane knee joint kinetics also appears to be elevated during stair ambulation compared with level walking.

At the hip, the maximum hip flexion moment has been shown to be elevated during stair ascent (0.76 Nm/kg) compared with level walking (0.52 Nm/kg) (91). Additionally, during stair descent, the maximum hip flexion moment was reported to be 1.5 times greater than level walking (7). In the frontal plane, the greatest adduction moments were reported during stair descent (8.4% BW*Height) when compared with standing, walking, arising from a chair, and bending over (70). Nadeau et al. (91) further suggested that the hip abductor muscles play a large role during stair ascent in order to elevate the pelvis and raise the swing leg to the next step. Thus at the hip, it appears that stair ambulation tasks lead to elevated joint moments compared to level walking.

Joint contact forces are important to consider and offer additional insights into actual joint loading. GRF variables are beneficial at presenting the overall loading to the body system as a whole, but fail to capture joint specific loading. In 1969, Morrison (90) reported that the peak bone on bone reaction force was 4.25 times body weight when walking up stairs. A separate study suggested that the highest peak compressive forces were experience during stair descent among activities of daily living (70), reporting knee forces as high as 1.23 times BW and hip forces 1.1 times BW. Other studies have attempted to provide more information regarding joint specific loading, via various modeling techniques. Costigan et al. (28) modeled the lower extremity in order to provide information on joint loading at the knee. They reported that peak patella-femoral contact force was eight times greater during stair ascent than level walking.. Through these studies it can be seen that joint specific loading is elevated during stair ambulation compared with level walking.

Stair Ambulation in TKR Patients

Although an increasing number of studies has examined the stair gait biomechanics after TKR, current literature is not in complete agreement on how TKR alters the biomechanics of variables measured during gait (16, 18, 23, 36).

During stair ascent, knee flexion angle at foot contact is reduced in TKR patients when compared with healthy controls, with differences ranging from 8.7º to 17.7º (16, 23, 36, 72, 103). Maximum knee flexion angles are commonly reported during the swing phase of stair ascent. Most of the research has shown that the maximum knee flexion angle during swing is reduced in TKR patients compared to healthy (23, 36, 103, 114). Berti et al. (16) found no differences in maximum knee flexion during swing between TKR and control groups, though they reported differences of almost 10º. It appears that during stair ascent, TKR patients have less flexed knees at both initial foot contact and at peak during the swing phase. These two variables are closely related to the total knee ROM often measured during stair ambulation. The knee flexion ROM was also reduced in TKR patients compared to healthy controls (16, 18, 23, 36, 60, 128). Berti et al. (16) reported that these reductions were nearly 17º in TKR patients with a non-resurfaced patella, while Fantozzi et al. (36) found that those with a mobile bearing design had reductions in knee flexion ROM of 10º. However, two early studies did not find any differences in knee flexion ROM when comparing TKR to healthy controls (128) and to the contralateral non-replaced leg (60). From these results, the knee kinematics in the sagittal plane is altered as a result of a TKR.

Sagittal plane knee joint moments are important to consider in addition to knee joint kinematics. It is well documented that TKR patients have reductions in quadriceps strength following a TKR. Mizner et al. (89) reported that patients had over a 60% decrease in quadriceps muscle strength one month following TKR surgery, due to decreased voluntary activation and reduced muscle cross-sectional area. Another study found that knee extensor muscles were over 40% weaker, in addition to a 34% reduction in knee flexors (56). These deficits have been shown to persist up even beyond 6 years post-surgery (50). Rehabilitation measures are taken to restore knee strength, but recovery has not shown to be complete. Quadriceps muscle function contributes directly to the production of the maximum internal extension moment required to produce extension about the knee joint. Studies have shown that the maximum internal extension moment is reduced in TKR patients (2.08 – 3.3 %BW*HT) when compared with healthy controls (5.10 – 6.50 %BW*HT) (16, 23, 36, 72). Some studies have reported that these reductions are larger than 50% of %BW*HT (23, 36). In contrast, other studies found no differences in the maximum internal extension moment (18, 114, 128). Stair ascent velocity plays a role in the magnitude of joint moments. For example if the same subject were to ascend stairs at varying velocities, the magnitude of the maximum knee extension moment would differ as a result of varied velocity. Studies that report reductions in maximum knee extension moment, also report a reduction in walking velocity in TKR patients (16, 23, 36, 72). As a result it is difficult to determine if the reductions in knee moment values are a result of reduced velocity or muscular deficits in TKR patients. However, a reduction in ascent speed may be related to a decrease strength and or pain following TKR surgery. Those studies that reported no differences between TKR and controls for maximum knee extension moment did not report on ascent velocities between the two groups. This highlights the need for future research to include information regarding ascent velocity in order to interpret the results correctly.

Frontal plane variables are also included in research regarding stair ambulation following TKR. As mentioned earlier in this chapter, the frontal plane knee joint moments have been shown to be linked to the severity and progression of knee OA and lower limb joint alignment plays a key role in the magnitude of the frontal plane knee moment. A majority of TKR surgeries are performed as a treatment for end-stage knee OA and so understanding how TKR affects frontal plane moments is essential. Studies reporting on the value of the maximum frontal plane moment, either internal abduction or external adduction, reported that TKR patients with a posterior stabilized design have values either equal to or reduced compared to healthy subjects (23, 36, 73, 114). In contrast to these studies Berti et al. (16) reported that those with non-resurfaced patella designs had elevated maximum external knee adduction moments (3.8 %BW*HT) compared to healthy controls (2.7 %BW*HT). An additional study also reported that patients with a mobile bearing replacement design had reduced knee adduction moment (1.8 %BW*HT) compared to healthy controls (2.7 %BW*HT) (36) TKR surgeries appear to restore frontal plane kinetics to levels at least equal to healthy control subjects. These values are very promising to show that TKR surgery appears to restore more normal knee function in the frontal plane during stair ascent, these improvements may be related to corrections to the lower limb alignment.

Stair descent is much less researched in TKR populations. Among the few studies that have analyzed stair descent none have reported descent velocity (18, 23, 114). The absence of descent velocity and the inconsistencies between research studies show the need for more research to be carried out in order to understand how patients descent stairs following a TKR.

Knee flexion/extension ROM was shown to be reduced in TKR patients in some studies during stair descent (18, 128). However, when considering the same variable, Catani et al. (23) found no differences between the TKR group and healthy controls whereas Kelman et al. (60) reported no differences between the TKR knee and a healthy knee in the same subject. The inability of current research to come to consistent conclusions regarding this straightforward variable during stair descent, highlight the need for more research in this area. The most recent studies on stair descent following TKR made no comparisons to a healthy control group or patients pre-surgery (54, 76). Though these studies provide useful information, the lack of comparisons between healthy control subjects make it difficult to assess the recovery level of the TKR patients in the study. Future studies, should include healthy controls, pre-surgery comparisons, knee OA patients, or other clinical populations to better assess recovery following TKR surgery.

Kinetic variables have been included as well in some of these studies. It is interesting to note that only the earliest study reported any differences in the maximum external flexion moment between TKR (13.1 %BW*LL) and healthy subjects (16.3 %BW*LL) during stair descent (128). The more recent studies, reported similar values between the two groups (18, 23, 54, 114). In the frontal plane, Saari at al. (114) found no differences in the maximum internal abduction moment between TKR and controls. Catani et al. (23) was the only other study that compared frontal plane moments and reported no differences between TKR patients and healthy controls for the maximum external knee adduction moment.

Research on stair descent in TKR patients following surgery is sparse in the literature. There are few studies that analyzed frontal plane knee moments and no studies that report on descent velocity, an important variable for kinetic interpretations. It is easy to see that more research is needed to better understand stair descent following TKR surgery. Future studies should include velocity measurements, frontal plane knee variables, and should utilize additional groups for comparison purposes.

Methodological Considerations

Methodological Considerations for Stair Ambulation

Stair ambulation can be carried out in varied methods based on the needs of the individual and the task at hand. Most stair case designs require the inclusion of a handrail that can be utilized for propulsion or balance during stair ascent and descent. In addition, individuals can choose to ascend stairs with different foot placement strategies including step-over-step and step-by-step methods. In addition to varied methods of stair climbing techniques, the advent of instrumented staircases creates additional problems that must be carefully considered by researchers.

Light handrail use is common for many individual as a means to ensure balance during stair ambulation. Reeves et al. (107) conducted a study on the effect of light handrail use on biomechanics of stair negotiation in older participants. During stair ascent they reported no differences between any of the temporal-spatial parameters including: stair ascent velocity, stride length and walking cadence with light handrail use compared to no handrail use. The GRF variables were all similar, except that the first peak mediolateral value was smaller when subjects utilized the handrail. This reduction may indicate that the use of the handrail led to less lower extremity requirement for providing frontal plane stability (107). When considering peak hip flexion, peak knee flexion and peak dorsiflexion, no differences were observed between ascending stairs with a handrail and without. The maximum first peak knee joint extension moment was higher when utilizing the handrail (1.12 Nm/kg) compared with the non-handrail condition (0.9 Nm/kg). From this study, ascending stairs with the use of a handrail leads to differences in lower extremity biomechanics compared to ascending stair without the use of a handrail.

During stair descent, the use of a handrail led to more marked changes in biomechanical variables of the lower extremity. This is not surprising, since during stair descent the use of the handrail would aid an individual in reducing their vertical and horizontal velocity towards the steps. This was exemplified by the reduction in first peak vertical GRF during handrail use (1.15 N/kg) compared to no handrail use (1.32 N/kg) (107). This result was coupled with a reduced second peak knee extension moment (0.47 Nm/kg compared to 0.8 Nm/kg), with a concomitant increase in second peak ankle plantarflexion moment (1.43 Nm/kg compared to 1.07 Nm/kg) . This shows that a redistribution of lower extremity moments when utilizing the handrail. It is apparent that, similar to stair ascent, stair descent biomechanics are different when using a handrail.

Foot placement strategies such as the step-over-step (SOS) and the step-by-step (SBS) lead to varied biomechanical patterns during stair ambulation. The SOS method is the traditional method of stair ambulation that requires an individual to swing the trailing leg over the step contacted by the lead leg and onto the next step of the stair case. The SBS pattern is carried out by placing both right and left feet on each step of the stair case. This pattern can be effectively employed by subjects who lack muscular strength, coordination, or balance necessary to accomplish stair walking via the SOS method. Reid et al. (109) carried out a study keying in on the knee biomechanical differences in the SOS and SBS method. For the SBS condition they compared both the lead leg (SBSL) and the trailing leg (SBST). They found that during stair ascent the peak anteroposterior (AP) GRF forces were greatest in the SOS task followed by the SBSL and the SBST. The external knee flexion moment of the SOS and SBSL were similar and much greater than those measured during SBST condition. During stair descent the initial AP peak GRF was greater in the SOS condition compared to the SBSL and the SBST. However the second peak AP peak GRF, or propulsive peak force, was similar in the SOS and SBST conditions and were greater than the SBSL condition. The first peak external knee flexion moment was greatest in the SOS condition (0.5 Nm/kg), but the second peak flexion moment was similar between the SOS (1.5 Nm/kg) and SBST (1.11 Nm/kg) condition and were significantly greater than the SBSL (0.18 Nm/kg) condition (109). Not surprisingly, varied stair ambulation strategies lead to differences in knee biomechanics.

From these studies it is clear that varied strategies for stair ambulation can lead to biomechanical differences in the lower extremity. This is important to consider when performing research regarding stair biomechanics and especially when working with older and clinical populations. Many times the strength and coordination deficits experiences by older adults and clinical populations will require modified stair climbing strategies. Though there is a need for studies looking at all of these varied methods, it is important that subject groups should all perform stair ambulation in a similar fashion. This allows for the most appropriate comparisons to be made between subject groups.

Instrumented staircases have been utilized extensively in stair ambulation literature. Prior to the advent of the instrumented staircase, biomechanical research on stair ambulation was limited to joint kinematics. Research labs with an instrumented staircase can collect and analyze kinetic data in addition to kinematics. This provides much greater insight into the biomechanics of stair ambulation. Instrumented staircase designs are varied between labs and can range from one instrumented step (73) to sixteen (126). Very little research has been carried out regarding the importance of considering methods regarding how the step of interest, i.e. which step is analyzed, influences research findings. As such it is important to understand how step of interest can influence biomechanics of stair ambulation.

Yu et al. (130) conducted a research study aiming to understand the reproducibility of lower extremity kinematics and kinetics during stair ambulation. They reported that the kinematics and kinetics of stair ascent on the first step were the most variable, while the data on the third step were the least variable. This same trend followed during stair descent as the last step was the most variable and the third to last step was the least variable. They suggested that when considering stair ascent tasks, the first step should be considered as a transition or initiation step from level walking to stair walking, though many stair ambulation studies still utilize the first step as the step of interest(18, 54, 60, 72, 73, 114, 128). Though Yu et al. (130) provided meaningful information related to variability on different steps of stair ambulation, they did not report actual magnitudes of lower extremity biomechanical variables. Thus, research is needed to understand how magnitudes of ankle, knee, and hip kinematic and kinetic variables are influenced by different steps during stair ambulation.

Methodological Considerations for TKR Subjects

Total knee replacement subjects are varied on many different levels including: replacement design, rehabilitation, recovery, and pre-surgery functionality. These components should be considered when attempting to perform research with TKR populations. Very few gait labs have the benefit of being linked with orthopaedic hospitals that provide and endless supply of TKR patients. As such, researchers must weigh the difficulty of subject recruitment with the goal of the research project, in order to appropriately choose a sample of TKR patients.

Patients with different types of replacements may respond differently in stair ambulation and comparisons between these may offer insight as to what specific design may restore knee mechanics during stair ambulation to normal levels. When possible, the TKR design should be controlled to ensure consistency between subjects. Several studies analyze differences between two different types of TKR designs (16, 18, 23, 36, 54, 103, 114). For example, maximum external knee adduction moments (internal abduction knee moment) were reduced during stair ascent in a mobile bearing replacement design compared to a posterior stabilized design and healthy controls, suggesting that the mobile bearing approach decreased medial compartment joint loading (23, 36). The resurfaced patella design appears to better restore movements to healthy control levels compared with the non-resurfaced patella for both sagittal knee ROM and maximum knee internal abduction moment (16). These are just a few examples of the benefits of research controlling the design in replacements. As newer designs are developed and utilized, research should continue to be carried out to gauge the progress of replacement designs. Some studies do not mention the specific designs for TKR patients (98), while others state that patients were recruited regardless of TKR design (84, 86). Studies with more broad inclusion criteria allows for larger subject populations, but since design has shown to be influential on gait mechanics, it makes it difficult to interpret findings correctly.

Like many orthopedic surgeries, rehabilitation is often prescribed following surgery. In addition, prehabilitation, or an improvement in functional capacity of an individual through physical activity in order to withstand a stressful event (34)is prescribed (80, 111, 112). In recent years, research has been carried out to understand how new trends in exercise and rehabilitation can improve outcomes for TKR patients (11, 66, 67). Some of the current areas of research regarding rehabilitation include: when to start the rehabilitation program (66), how long the programs should last (3, 87), the benefits of higher intensity rehabilitation (11) and varying types of rehabilitation including electrical stimulation (67, 123) or balance (102). These studies measured the efficacy of these programs by length of hospital stay, clinical function, strength gains, and pain outcomes. None of these rehabilitation studies analyzed how varying strategies for rehabilitation alter biomechanics of overground or stair walking. In addition, studies analyzing stair gait biomechanics rarely mention the rehabilitation of their patient population. Mandeville et al. (72) reported that patients received standard weight bearing rehabilitation and Pollo et al. (103) stated that patients were considered fully rehabilitated. Clearly there is a gap in the research that needs to be addressed. This could begin with biomechanical studies reporting as much information on rehabilitation as possible, even if it is varied between subjects. This would provide at least some information on how rehabilitation may affect gait biomechanics following TKR. Future studies could employ a random method for assigning varied rehabilitation protocols and compare gait biomechanics between different rehabilitation groups.

Time from replacement surgery and functional recovery are two additional methodological considerations for TKR patients. Time from replacement surgery is varied between studies. In those looking at stair ambulation, time from surgery ranged from surgery in as soon as two months (98) to as long as 98 months (range 72 – 134 months) (18). Within studies, the three earliest studies had the largest range of time from surgery for TKR patients. Range of follow-up for subjects was 55(60), 62 (18), and 76 months (128). Tighter control on time from surgery may lead to more consistent patient populations, though physical recovery may not always be correlated with time from surgery. Studies conducted with varied time from surgery in addition to patient recovery are needed in order to understand the continuum of recovery following TKR.

Basic assessments of physical function, in addition to time from surgery, may depict a more complete picture of patient recovery. Some TKR patients may be fully recovered after only 6-months (72, 73), while some may take longer than 2 years (16). Basic assessments, most often in the form of simple functional tests that could be carried out in clinical settings, should be utilized more in biomechanical testing on clinical populations. Some of these tests may include passive knee ROM, timed-up-and-go, stair ascent/descent, 6-m walk, sit-to-stand, chair rise and others (20, 39, 101, 102). These tests can offer information regarding recovery that is independent of time from surgery. Unfortunately very few research studies pair functional with biomechanical tests as a means to quantify recovery in TKR patients. Ouellet et al. (98) was one study that utilized functional tests to see how patients improved from pre to post-surgery. They performed timed-up-and-go and a 6-minute walk test on TKR patients, and compared results to a healthy population. In addition to reporting on detailed biomechanical variables, they were also able to provide information on how basic functionality in their TKR patients compared to the control group. These types of studies should be more common in gait research following TKR in order to understand functional recovery.

Principle Component Analysis

Typical gait biomechanics studies can lead to an exuberant amount of data. These data must be carefully inspected and analyzed as a part of the scientific process. One of the most difficult aspects of biomechanical research is pulling from large data sets the most meaningful information. Many times discrete data points on curves are selected and compared both within and between subject populations (16, 36, 98). Previous research has provided useful information regarding which of these discrete points are the most important for different clinical populations. Studies utilizing statistical tools to compare these discrete points are both plentiful and meaningful (14, 16, 23, 80, 84). These studies allow researchers to quickly and efficiently present useful information regarding their subject populations. Though these types of studies are the most common, they are not the only way to analyze biomechanical data.

Principal component analysis (PCA) is a popular multivariate statistical technique that has been around since the early 1900's (2). The main goal of a PCA is to extract the most important information from data, compress the size of the data by keeping only the most important information, simplify the description of the data set, and finally analyze the structure of the observation and the variables (2). These goals all coincide well with the nature of large scales biomechanical data sets and thus it is easy to see their usefulness in biomechanical research. It has been shown that PCA can be an effective tool in the reduction and interpretation of gait waveform data (31).

PCA utilizes a variety of multivariate statistical procedures with the end goal being the creation of linear combinations of original variables called principal components (PC). Waveform data in biomechanical data sets are typically represented in time series fashion and thus can be represented in matrix form (Figure 1).

$$X = \begin{vmatrix} x_{11} & x_{12} & . & . & . & x_{1p} \\ x_{21} & x_{22} & . & . & . & x_{2p} \\ . & . & . & & & . \\ . & . & & . & & . \\ . & . & & & . & . \\ x_{n1} & x_{n2} & . & . & . & x_{pp} \end{vmatrix}$$

Figure 1. Sample matrix for PCA (61)

Each row represents a time series waveform for one subject and each column represents the values at one instant on the waveform (61). Each of the waveforms is temporally normalized to correspond to 100% of the gait cycle, resulting in 101 time points for the waveform. For example, a data set with 20 subjects for knee extension moment would contain a matrix with 20 rows (20 subjects) and 101 columns, (101 time normalized data points for the knee extension moment). A set of mathematical transformations are performed in order to come up with the set of linear combinations of PC that are associated with the data set. These PCs are paired with eigenvectors and become the measure of how much of the total variability in the data set in contained in a specific PC (2). These PCs and eigenvectors provide researchers with the ability to analyze and compare whole curves, instead of simply comparing discrete variables on the curves.

Typically a number of PCs are reported as being significant to the research question. The use of scree plots is a common method utilized to understand which PCs are significant (25, 55, 61). Scree plots are obtained by plotting the eigenvalues according to their size and looking for a point in the graph when the slope changes from steep to flat. The scree, or elbow, test is to keep only those components which are before this change in the graph, typically occurring near a value of 1.0. The Kaiser method is another common method for determining the number of significant components, often utilized by many of the statistical software packages (58). This method suggests that meaningful components are those which have an eigenvalue greater than 1.0, though this hard fast rule may lead to overestimation of significant components. Deluzio et al. (61) suggest that the number of PCs retained could be based upon the percentage of variation explained by the retained PCs, typically between 90% and 95%. These components are often listed in order of their ability to explain variation in the data set and can explain things such as pattern differences in waveforms, and timing of peaks in addition to peak magnitudes. In addition, scores from the retained PCs can be easily used to compared and detect between group differences using t-tests and other statistical tests (10, 32, 33, 61). PCA potentially provides an additional statistical technique to detect and describe differences in large data sets.

Though not often utilized in biomechanical research, PCA has been used to study basic gait parameters (27), injured runners (38), and mechanics of cutting (96). In addition, PCA has been used at times to study gait in those with knee OA and in TKR patients (45, 74).

Deluzio has provided information regarding the use of PCA during gait assessments in those with pathological conditions (33), including knee OA (31). In one early study, Deluzio et al. (33) collected data on 29 asymptomatic elder subjects and a group of osteoarthritic patients both pre and post unicompartmental replacement surgery. The main goal was to develop a

Principal Component Model (PCM) to highlight the ability of PCA to analyze waveform data. They presented three cases to show the strength of PCA and PCM to detect differences between the healthy and osteoarthritic patients.

The first case was presented to highlight the ability of PCA to detect magnitude differences between waveform graphs (Figure 2). Though the shape of the pre unicompartmental knee replacement surgery, post-surgery and normal curves are similar, it is clear that a magnitude difference does exist. The PCM of the knee flexion angle contained two PCs, The first PC captures the differences between knee flexion during the stance phase, while the second PC reflects those differences during the swing phase (33).

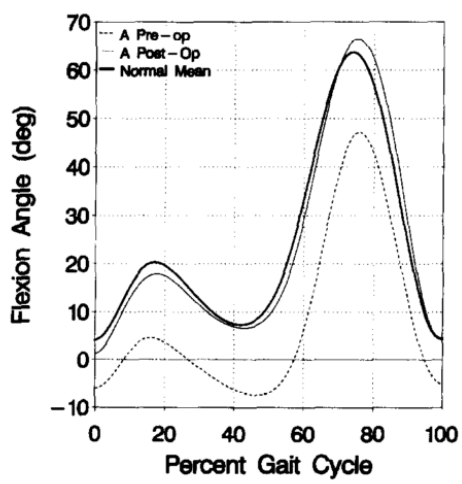


Figure 2. Knee flexion angle magnitude (33).

The second case was presented to highlight the use of residuals from the principle components to detect differences from normal in the knee adduction moment for timing components as well as magnitude (Figure 3). This PCM also identified the first two PC to explain variations from the normal waveform. The first PC detected the higher magnitude of the adduction moment in the replacement patients compared to healthy controls. Large residuals, or differences between the actual waveform and the predicted by the PCM, were also noted at 60-70% of the gait cycle to identify the longer time spent in the stance phase (PC2), while the second PC also contained heavy loading earlier in the stance phase, showing the increased time to reach peak adduction moment for the patient compared to healthy subjects (33)

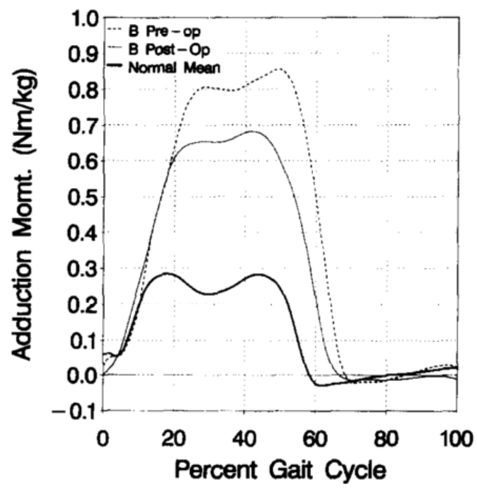


Figure 3. Knee adduction moment magnitude and timing (33).

The third case was used to highlight the use of PCM to detect subtle differences in waveform shape (Figure 4). The flexion moment curve is always within one standard deviation of the mean, but it can be seen that there are differences in the pattern. This PCM revealed that the patient's peak flexion moment is different than the normal pre-operatively, with the PC residuals being large around 60% of the gait cycle to show the lack of a biphasic moment pattern (33). These three cases provide specific examples of the benefits of PCA in detecting magnitude, timing, and shape differences between waveforms.

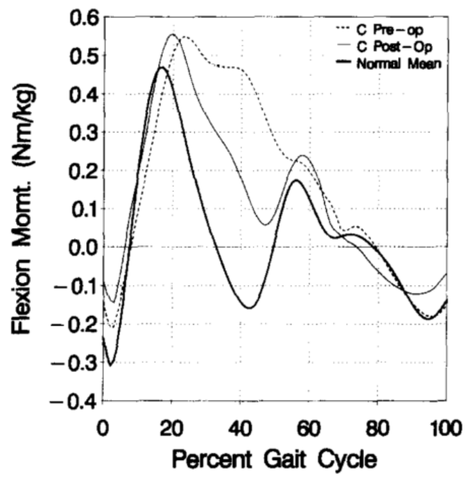


Figure 4. Knee flexion moment pattern differences (33)

Astephen et al. (10) utilized PCA to identify the most important combinations of biomechanical factors that could distinguish between moderate and severe knee OA patients. They analyzed flexion/extension angle, and the net moments in all three planes of motion at the hip, knee and ankle. They also analyzed EMG waveforms of the quadriceps, hamstring, and gastrocnemius muscles using the same approach. They reported 3 PC, which contained five measures that distinguished between healthy patients and those with moderate OA. Those with moderate OA had greater rectus femoris EMG activity throughout the gait cycle (PC1), smaller knee flexion moment and hip external rotation in early stance (PC2), and greater knee internal rotation moment in late stance and elevated mid-stance hip adduction moment (PC3) compared to healthy controls. Differences between those with moderate and severe OA were also reported in a similar fashion. Severe OA patients had lower knee flexion angle in stance and swing and lower hip internal rotation in stance (PC1), lower ankle internal rotation moment and hip flexion moment (PC2), and greater medial gastrocnemius EMG activity in early stance (PC3) compared to healthy controls. This study highlights two of the benefits of a PCA for gait waveform data. First is the ability to distinguish group differences via the reduction of large data sets to a few essential components. The second is the ability to detect timing of peaks in waveforms across the gait cycle.

Hatfield et al. (45) carried out a similar research study using PCA to quantify differences between TKR patients prior to and post replacement surgery. They averaged five overground walking trials 1-week prior to and 1-year post surgery and used PCA to capture the major amplitude and shape of hip, knee, and ankle angles in all 3 planes of movement. The first PC of the knee adduction moment was reduced following surgery, showing a reduction in the overall medial compartment loading even with an increased walking velocity. For knee flexion, the first PC increased following surgery, indicating an overall increase in knee flexion during gait. The first PC for knee rotation was not different pre and post-surgery, indicating no differences for the internal knee rotation moment. This study utilized on a TKR population, once again shows the ability of PCA to detect differences in patterns and overall shape in addition to magnitude.

Mandeville et al. (74) used PCA to determine those aspect of clinical and gait measures during level walking and stair ascent that were the best predictors of membership. They reported that all components of the WOMAC (knee pain, stiffness and activities of daily living) and the level walking frontal plane knee moment loaded highly on the first PC. For the second PC, loading was high for walking velocity and stride length during level walking. The third PC, loaded heavily on stair ascent knee flexion angle and total support moment. The researchers suggested that those variables contained in the first PC were associated with knee dysfunction, while the second PC included those associated with gait dysfunction, and finally the third PC variables were related to stair ascent dysfunction. This study, similar to Hatfield et al. (45) utilized PCA in a similar fashion to reduce data to those most important for distinguishing group differences following TKR. This study appears to be the only one that has utilized PCA during stair ambulation following TKR.

This section outlines the benefits of PCA in reducing and analyzing large scale biomechanical data sets. As discussed previously, PCA can be beneficial for comparing magnitude differences in waveforms, variations in timing of peak values, and pattern differences in curves. Furthermore, it can be used to reduce data to those variables that are most important to group differences. Though the benefits of PCA are clear, this technique is relatively underused in analyzing stair biomechanics following TKR. Thus studies with PCA as a statistical tool may be beneficial for providing more and detailed information regarding recovery following TKR.

Closing Statement

The current literature review highlights some of the current research regarding both overground and stair gait biomechanics following TKR. Though research is growing in this population, especially for overground gait, more efforts are needed to understand gait biomechanics during stair ascent and descent in TKR populations. Potential methodological issues for both TKR patients and stair ambulation biomechanics should be carefully considered in order to ensure accurate and valid data are collected. Finally, additional statistical testing, paired with traditional methods, may help depict a more complete picture of recovery following TKR surgery in gait and stair ambulation.

CHAPTER III

MATERIALS AND METHODS

Study One

Databases and Searches

Studies were identified by searching electronic databases. The English publications from PubMed and Web of Science were searched. No restrictions were placed upon publication dates when the searches were performed for articles. The search terms that were used to retrieve articles included total knee replacement, total knee arthroplasty, TKR, TKA, biomechanics, kinematics, gait, stair, step, ascent, descent and climbing in solo and/or combination (Table 1).

Table 1. Search Strategy

Search Number	Terminology
1	Total Knee Replacement
2	TKR
3	Total Knee Arthroplasty
4	TKA
5	1 or 2 or 3 or 4 and gait
6	1 or 2 or 3 or 4 and stair
7	1 or 2 or 3 or 4 and step
8	1 or 2 or 3 or 4 and biomechanics
9	1 or 2 or 3 or 4 and kinematics
10	1 or 2 or 3 or 4 and biomechanics or kinematics and gait
11	1 or 2 or 3 or 4 and biomechanics or kinematics and stair
12	1 or 2 or 3 or 4 and biomechanics or kinematics and step
13	1 or 2 or 3 or 4 and ascent or descent
14	1 or 2 or 3 or 4 and climbing
15	1 or 2 or 3 or 4 and ascent or descent or climbing
16	1 or 2 or 3 or 4 and stair and ascent or descent or climbing

Study Selection and Quality Assessment

In order to be included in the review, studies were required to analyze stair ambulation using motion analysis techniques, present original data and have at least two steps in the staircase though no other requirements were necessary for stair design. Studies using only a one-step staircase were considered a step-up task and were not included in this review as biomechanical characteristics of a step-up task may be different from a more traditional stair ascent task. Participants could be any age, gender and size. Recovery following TKR surgeries varies greatly between subjects and the exact recovery time is not currently understood. As a result, as long as subjects could climb stairs, no exclusions were made for time from surgery. Primary outcome measures were knee kinematics and kinetics in the sagittal and frontal planes. These included knee flexion at contact, maximum knee flexion angle, knee flexion/extension ROM, maximum knee flexion/extension moments and maximum knee ab/adduction moments. To be included, studies had to report on one of these outcome variables.

Eligibility of studies was performed by one of the authors. Research articles were screened by use of title and abstract in order to assess if requirements for inclusion were met. If the study appeared to meet the criteria for inclusion or if it was unclear if it should be included, full text articles were retrieved and reviewed in order to determine inclusion. After reviewing titles and abstracts, full text of 33 articles were reviewed for inclusion in the review (Figure 5).

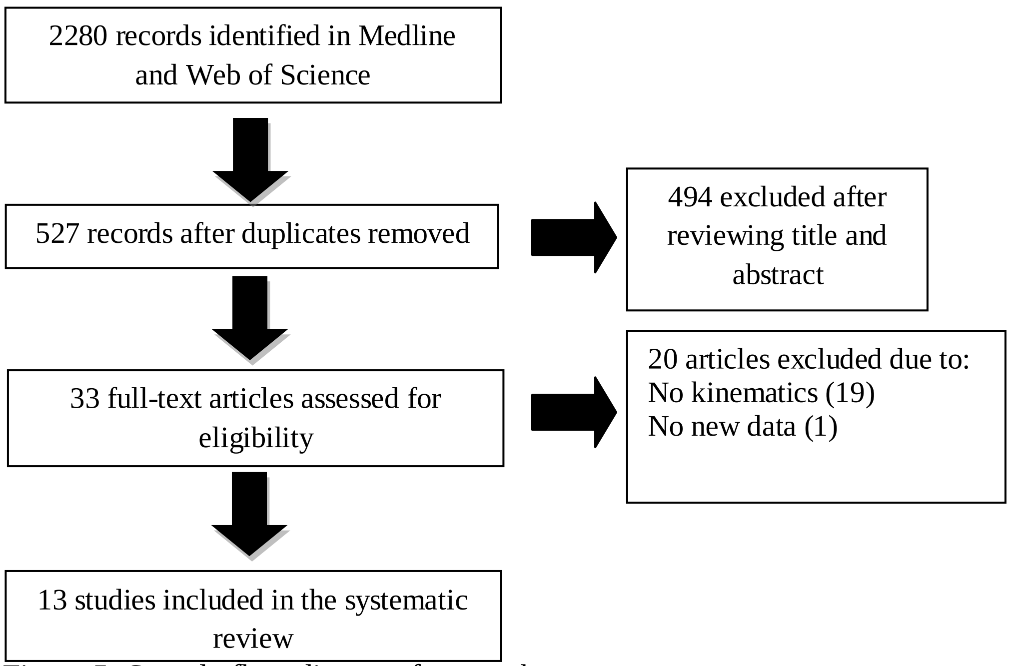


Figure 5: Sample flow diagram for search

Study Two, Three and Four

Participants

Healthy mid- and old-age adults were recruited through flyers, email recruitment and word of mouth. The subjects who met the exclusion criteria (Table 2) were asked to participate in Study Two, Three and Four.

In Study Three and Four, TKR subjects were referred to the primary investigators via phone interviews carried out by Tennessee Orthopaedic Clinic. TKR procedures were all performed by the same surgeon and with a standard posterior stabilized design. TKR subjects who met the specific criteria for participation (Table 3) were invited to participate in the research study.

Table 2. Inclusion and Exclusion Criteria for the Healthy Subjects.

Exclusion Criteria:	Inclusion Criteria:
- Knee pain for at least 6 months during daily activities. - Diagnosed with any type of lower extremity joint osteoarthritis (self-reported). - Any lower extremity joint replacement. - Any lower extremity joint arthroscopic surgery or intra-articular injection within past 3 months. - Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) (self-reported). - BMI greater than 35. - Inability to ascend/descend stairs without the use of a handrail. - Inability to walk without a walking aid. - Neurologic disease (e.g. Parkinson's Disease, stroke patients) (self-reported). - Any major lower extremity injuries/surgeries. - Any visual conditions affecting gait or balance. - Women who are pregnant or nursing. - Any cardiovascular disease or primary risk factor which precludes participation in aerobic exercise as indicated by the Physical Activity Readiness Survey.	- Men and women between the ages of 35 and 80.

Table 3. Inclusion and Exclusion Criteria for the TKR Subjects.

Exclusion Criteria:	Inclusion Criteria:
- Any additional lower extremity joint replacement. - Any lower extremity joint arthroscopic surgery or intra-articular injection within the past month. - Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) (self-reported). - BMI greater than 35. - Inability to ascend/descend stairs without the use of a handrail. - Neurologic disease (e.g. Parkinson’s Disease, stroke patients) (self-reported). - Any major lower extremity injuries/surgeries. - Inability to walk without a walking aid. - Any visual conditions affecting gait or balance. - Women who are pregnant or nursing. - Any cardiovascular disease or primary risk factor which precludes participation in aerobic exercise as indicated by the Physical Activity Readiness Survey.	- Men and women between the ages of 35 and 80. - Total knee replacement in one knee. - At least 6-months from TKR. - No more than 5-years from TKR

An *a priori* power analysis, using existing data, showed that a minimum of 10 participants were needed for each group in order to obtain an alpha of 0.05 and beta of 0.80. All patients signed an informed consent document approved by the Institutional Review Boards at The University of Tennessee, Knoxville.

Instrumentation

A nine-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain three-dimensional (3D) kinematics during testing. Participants wore a standardized laboratory running shoe (Noveto, Adidas, USA) during the experiment. Reflective anatomical markers were placed on 2nd toe, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and acromion processes. Clusters of four reflective tracking markers on semi-rigid thermoplastic shells were placed on lateral shank, lateral thigh, lateral pelvis and posterior-inferior trunk. Four discrete tracking markers were placed on the heel counter of the shoe. An instrumented 3-step staircase (FP-stairs, American Mechanical Technology Inc., Watertown, MA, USA) was used in the study (99, 100). The FP-Stairs bolted independently to two force platforms (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA) were used to measure the GRF and the moments of forces during stair walking (Figure 2). The two additional customized wooden steps (4th and 5th steps) were used in conjunction of the instrumented staircase in order to ensure a continuous motion after the three instrumented steps. Each step had a rise of 17.8 cm, a width of 60.0 cm, and depth of 29.9 cm. A handrail was available on the right side of the stairs during stair ascent in case of loss of balance by the subjects. Speed during stair climbing was monitored by two sets of photo cells (63501 IR, Lafayette Instrument Inc., IN, USA) mounted on 1st and 4th step and electronic timers (54035A, Lafayette Instrument Inc., IN, USA).

Figure 6. Complete setup of 5-step staircase for experimental data collections

Experimental Procedures

TKR patients were asked to complete the Knee Society Survey (115), a questionnaire aimed to assess recovery following replacement surgery, and a brief questionnaire detailing knee replacement type, surgeon and rehabilitation. Both healthy and TKR patients completed a physical activity readiness survey and provided basic demographic information. Following completion of the surveys and questionnaires, subjects performed a 3-minute warm up walking on a treadmill at a self-selected speed. After the warm up, all subjects were asked to perform a battery of clinical tests including: passive knee ROM, timed up-and-go (TUG), and stair ascent/descent test. Subjects performed one practice trial and two timed trials for both the TUG and the stair ascent/descent test. Subjects were then fitted with markers as previously described and were asked to perform practice stair ascent trials at a self-selected speed. Once subjects were comfortable on the steps (about three trials each for ascent and descent) the participant was asked to ascend stairs at their respective speed range (mean ± 5%) obtained in the practice trials. All subjects performed three – five trials in each of four test conditions, condition one with the right foot contacting the first step, condition two with the left foot contacting the first step, and conditions three and four of overground walking with the right and left foot contacting the force plate, respectively. The order of the stair ascent conditions was randomized. The overground walking conditions were also randomized, though these conditions always followed the stair ascent conditions. The participants were required to ascend the stairs in a step over manner and without utilizing the handrail. Subjects were required to repeat a trial if they contacted a step with both feet, touched the handrail or were not able to achieve the pre-determined speed range. A visual analog pain scale was used to asses pain in both knees for healthy and TKR patients prior to the start of the warm-up, at the completion of the clinical tests, and of stair ascent and overground walking conditions.

Data Analyses

Visual3D biomechanical analysis software suite (C-Motion, Inc., Germantown, MD, USA) was used to compute the 3D kinematic and kinetic variables. A right-hand rule with a Cardan rotational sequence (X-y-z) was used for the 3D angular computations and a right hand rule was used to define the conventions of angular kinematic and kinetic variables. Positive values indicate toe-out angle, ankle dorsiflexion and ROM, knee extension angle and ROM, hip flexion angle and ROM, ankle inversion angle, knee adduction angle and ROM, and hip adduction angle and ROM. For kinetic variables, positive values indicate ankle dorsiflexion and inversion moments, knee extension and adduction moments, and hip flexion and adduction moments. Kinematic and GRF data were both filtered using a fourth-order Butterworth low-pass filter with the same cut-off frequency of 8 Hz (64, 95, 99). Two customized computer programs was utilized to determine variables of interest and organize data for statistical analyses. GRF variables were normalized to subject's body weight (BW) and joint moments were normalized to subject's mass (Nm/kg).

Statistical Analyses

In Study Two, statistical analyses were carried out for only the healthy subjects. A one-way repeated measures analysis of variance (ANOVA) was performed to detect differences between four test conditions: first step, second step, and third step in stair ascent, and level walking of the right side (19.0, IBM SPSS, Chicago, IL). When the ANOVA revealed a main effect, post-hoc comparisons with Bonferroni adjustments were utilized to compare means between conditions. The alpha level was set at 0.05 *a priori*.

In Study Three, a mixed model ANOVA (SAS 9.3, SAS Institute Inc. Car, NC) was performed to detect differences between the replaced limb, non-replaced limb of TKA patients and the right limb of control patients on the second step of stair ascent (69) Because two of the conditions were measured on the same participant, it was necessary to consider the effect of correlations on the residuals between the replaced and non-replaced limb of TKA patients. Statistical models were run on the data, with and without correlation, and correlation was included between the replaced and the non-replaced limb when the log likelihood test was significant (a reduction of at least 5 points between the two statistical models) (69). When the ANOVA revealed a significant main effect, post-hoc comparisons with Bonferroni adjustments were utilized to compare means between conditions ($p<0.05$). In addition, differences of demographics between participants were determined using the independent sample t-test.

In Study Four, PCA analysis was utilized to detect variations in knee angle and moment waveforms during the stance phase of stair ascent. The main purpose of PCA is to extract the information that is the most important to the data (2, 31, 108). Waveforms of the selected variables were temporally normalized to correspond to 100% of the stance phase on the second step of stair ascent. Following time normalization, each variable was ensemble averaged for each participant, resulting in one waveform for each subject per variable. Six data matrices were constructed, one for each variable of interest, with rows representing time series waveforms for each subject, and columns representing values at each instant on the waveform (61). MATLAB (R2014v, MathWorks, Natick, MA, USA) software was utilized to run six separate PCAs. Output variables from PCA included: normalized eigenvectors as an estimate of the covariance matrix of the data matrix (principal component coefficients), the variation explained by each PC, and the PC scores for each subject calculated as the contribution of each PC loading to each subject's waveform (10). Percent variation explained by each PC was then inspected to decide which PCs should be included for further analysis. In order to determine which PCs to retain, scree plots were analyzed and at least 90% of the variation in the data was explained by the retained PCs (25, 61). The eigenvectors were then plotted across the time normalized gait data and utilized for interpretation of the retained PCs (61). PC scores were returned for all subjects and comparisons of scores between groups were made using an independent sample t-test ($p<0.05$). In addition, differences of participant demographics were determined using the independent sample t-test.

CHAPTER IV

STAIR AMBULATION BIOMECHANICS FOLLOWING TOTAL KNEE REPLACEMENT: A SYSTEMATIC REVIEW

Abstract

The purpose of this review was to summarize the biomechanical adaptations during stair ambulation that occur after total knee replacement (TKR). Articles were identified by searching PubMed and Web of Science. During stair ascent, knee flexion angle at heel strike and walking velocity were reduced in TKR subjects compared to controls. Results of other variables were not consistent between studies. During stair descent only one study found any differences for knee moments in the sagittal and frontal plane between TKR subjects and controls. Other results during stair descent were not consistent between studies. Differences in methods can partially explain discrepancies between studies in this review. More studies with consistent and improved methods are needed in order to provide better understanding of stair ambulation following TKR.

Key Words: knee arthroplasty, stair ascent, stair descent, gait biomechanics

Running Title: Stair Ambulation of Total Knee Replacement

Introduction

Total knee replacement (TKR) or total knee arthroplasty is a surgical treatment option for end-stage knee osteoarthritis (OA) to alleviate pain and restore physical functions of daily activities. The total number of knee replacement surgeries is expected to reach 3.5 million a year in the United States by 2030 (65).

Previous research has reported that pain is significantly reduced following TKR (21, 46, 62) and that a majority of patients are satisfied with their knee replacements (93). However, despite reports of significant reductions of knee pain and improvements in knee physical functions, some studies have shown that some patients still have long-term pain following TKR (17). Additionally, patients report having at least some limitations in performing functional activities following a TKR surgery (94). Studies have also noted a decrease in performance on clinical tests for TKR groups compared to healthy controls (19, 98). These results suggest that both alleviation of pain and restoration of locomotor ability may not be complete.

Total knee replacement should not only restore normal mechanics during common daily activities such as level walking but also during more demanding activities. Stair ascent and descent are more demanding on the lower extremity muscles and joints (91) and TKR patients potentially encounter stairs on a daily basis. Knee OA patients often complain of difficulty in climbing stairs (28). Furthermore, ability to climb stairs is included in all of the most common knee scoring tools (30, 52, 115). Deficiencies in biomechanics may be more apparent in more demanding activities of daily living. Therefore, a better understanding of stair walking biomechanics following TKR is an important aspect of TKR research.

Although an increasing number of studies has examined the stair gait biomechanics after TKR, current literature is not in complete agreement on how TKR alters the biomechanics of variables measured during gait (16, 18, 23, 36). When considering stair ambulation, some studies reported differences between TKR and healthy subjects for knee ROM (16, 18, 23, 36) while others reported no differences in knee ROM between TKR patients and healthy controls (16, 60, 128). It is not clear if the past studies have employed similar pieces of equipment such as staircase designs and step of interest on the staircase, making it difficult to interpret and compare results. No review articles exist in the literature on biomechanical findings of stair climbing after TKR. Hence, a systematic review is needed in order to help address some of the discrepancies in the literature and provide useful information for clinicians and future research. Therefore the aim of this paper was to provide a comprehensive review of literature on methods and results of research studies on biomechanical characteristics during stair ascent and descent following TKR.

Methods

Databases and Searches

Studies were identified by searching electronic databases. The English publications from PubMed and Web of Science were searched on May 2, 2013. No restrictions were placed upon publication dates when the searches were performed for articles. The search terms that were used to retrieve articles included total knee replacement, total knee arthroplasty, TKR, TKA, biomechanics, kinematics, gait, stair, step, ascent, descent and climbing in solo and/or combination (Table 4).

Study Selection and Quality Assessment

In order to be included in the review, studies were required to analyze stair ambulation using motion analysis techniques, present original data and have at least two steps in the staircase though no other requirements were necessary for stair design. Studies using only a one-step staircase were considered a step-up task and were not included in this review as biomechanical characteristics of a step-up task may be different from a more traditional stair ascent task. Participants could be any age, gender and size. Recovery following TKR surgeries varies greatly between subjects and the exact recovery time is not currently understood. As a result, as long as subjects could climb stairs, no exclusions were made for time from surgery. Primary outcome measures were knee kinematics and kinetics in the sagittal and frontal planes. These included knee flexion at contact, maximum knee flexion angle, knee flexion/extension ROM, maximum knee flexion/extension moments and maximum knee ab/adduction moments. To be included, studies had to report on one of these outcome variables.

Eligibility of studies was performed by one of the authors. Research articles were screened by use of title and abstract in order to assess if requirements for inclusion were met. If the study appeared to meet the criteria for inclusion or if it was unclear if it should be included, full text articles were retrieved and reviewed in order to determine inclusion. After reviewing titles and abstracts, full text of 33 articles were reviewed for inclusion in the review (Figure 7).

Results

The search of PubMed and Web of Science provided a total of 2280 citations, among which 1753 were duplicated studies and were removed. Titles and abstracts of the remaining 527 articles were reviewed and 494 clearly did not meet the inclusion criteria (Figure 7). Full text articles of the 33 remaining studies were accessed. Review of these studies resulted in the exclusion of 20 additional articles where 19 were eliminated because they did not use motion analysis techniques and one paper was excluded because it did not contain novel data. As a result, a total of 13 studies were included in the review (Table 5).

General Information

The number of subjects of the included studies in the TKR group ranged from 8 (60) to 21 (36, 72, 73) (Table 5). All but three studies (54, 60, 76) had a control group that consisted of similar number of subjects compared to the TKR subjects. Seven studies further divided the TKR subjects based on the different replacement designs: with or without resurfaced patellae (16, 103), mobile bearing or posterior stabilized (23, 36), small preoperative deformity with posterior cruciate ligament (PCL) retaining or large preoperative deformity with PCL resecting (114) and PCL retaining or substituting (18, 54). The remaining studies tested subjects with a posterior stabilized replacement (72, 73, 128) or a PCL sparing design (60). One study made no mention of specifics about TKR design (98).

Most studies required that subjects had successful replacement surgeries (18, 36, 54, 60, 76, 103, 128), which were often defined as a good or excellent score on the knee society scoring system (52) or no qualitative sign of replacement loosening (16, 23). Common exclusion criteria for subjects used included neurological dysfunctions (72, 76, 98)and musculoskeletal pathologies (16, 23, 98), with some studies specifically excluding Parkinson’s (72, 114) and diabetes (72). A few studies have identified an additional orthopedic condition as reason for exclusion (54, 60, 76, 98, 103, 114). Subjects who had a joint replacement in addition to the TKR were excluded in two of the studies (18, 128). One study did not report any specific exclusion criteria (73).

Stair specifications were outlined for each study (Table 5). Stair design either consisted of four steps (16, 23, 36, 98, 103), three steps (18, 72, 73, 128) or two steps (54, 60, 76, 114) with varying heights and depths. Most studies collected force data on the first step (18, 54, 72, 73, 98, 114, 128).

Time from replacement surgery to biomechanical testing of stair gait varied significantly among the included studies (Table 5). The shortest time period from replacement surgery was 2-months (98) and the longest was 98 months from surgery (18). Most studies provided data on specific time from replacement, the overall average time from replacement for these studies was 26 months (18, 23, 36, 54, 60, 72, 73, 98, 103, 128).Three studies tested their subjects right before and at two months post-surgery (98) and at six months post-surgery (72, 73).

Sagittal Plane Stair Ascent

A total of 12 of the studies have examined sagittal plane variables during stair ascent (Table 6). The most commonly used variables were the knee flexion angle at contact, knee flexion ROM, maximum knee flexion and max knee flexion/extension moments.

Studies reported knee flexion angle at contact during stair ascent and all found a reduction of the knee flexion angle at contact in those with TKR compared to controls(16, 23, 36, 72, 103). For knee flexion ROM during the stance phase, (16, 18, 23, 36, 60, 128) (Table 6), some studies noted reductions of the ROM for TKR patients, when compared with controls (16, 18, 23, 36). However, other studies found no differences between the knee flexion/extension ROM in those with TKR when compared with control groups (16, 128), and the contralateral healthy limb (60).

Two studies reported the maximum knee flexion during stance, one for both swing and stance, and five of the studies reported the maximum flexion only during swing (Table 6)(16, 23, 36, 54, 76, 98, 103, 114). During the stance phase a reduction in maximum knee flexion was found for TKR groups compared with controls (98), while some studies did not make comparisons of maximum knee flexion during stance to a control group (54, 76). During swing phase the maximum knee flexion was found to be reduced in replacement groups when compared with controls (23, 36, 103, 114). Berti et al. (16)found no differences in max knee flexion during swing between TKR and control groups.

For the maximum sagittal plane moments (Table 6), a reduction of the maximum external flexion moment in the TKR group was reported compared to the control group in some studies (16, 23, 36, 72). In contrast, other studies found no differences in the moment (18, 114, 128). Two studies did not compare results with control groups (54, 76).

Frontal Plane Stair Ascent

Six studies reported frontal plane variables and the most common variables examined in the selected studies were the maximum external knee adduction moment or maximum internal knee abduction moment (Table 3)(16, 23, 36, 73, 76, 114), a variable that is often used as a surrogate for loading to medial compartment of knee joint.

A reduction in the maximum external knee adduction moment was found for TKR patients compared to controls (23, 36). In contrast, Berti et al. (16) reported an increase in the maximum external adduction moment of the TKR compared to the control group. Mandeville et al. (73) reported a reduction in the internal knee abduction moment at the first peak vertical ground reaction force (GRF) for those with TKR compared to controls, while Saari et al. (114) found no differences in the maximum internal abduction moment.

Speed Stair Ascent

Only four studies reported the velocities during stair ascent and velocity for TKR subjects was significantly slower compared to healthy controls (Table 6)(16, 23, 36, 72). The reviewed studies chose to allow subjects to walk at self-selected velocity (16, 23, 36, 72). TKR subjects ascended stairs at speeds between 0.28 to 0.52 m/s while control subjects at a speed between

0.39 to 0.71 m/s. Differences between TKR and control groups ranged from 0.06 m/s (16) to 0.19 m/s(72).

Stair Descent

Less information is available about stair descent biomechanics in the TKR population in the literature (18, 23, 54, 60, 76, 114, 128). Similar to stair ascent, the most common variables of sagittal and frontal planes reported include maximum knee flexion, sagittal range of motion, maximum flexion/extension moment, and maximum abduction/adduction moment (Table 7).

Sagittal Plane Stair Descent

Two studies found that the knee flexion/extension ROM was reduced in TKR compared to controls (Table 7) (18, 128). However, Catani et al. (23)found no differences between the TKR group and healthy controls and Kelman et al. (60) reported no differences between the TKR knee and a healthy knee in the same subject.

It was reported that the maximum knee extension during the swing phase was less in TKR groups compared to controls (23, 114). No differences were found for the maximum knee flexion between TKR patients and healthy controls (114).

For the maximum external flexion moment, only one study found significant differences between TKR and control groups (128). Other selected studies reported no differences between the two groups (18, 23, 54, 114).

Frontal Plane Stair Descent

Frontal plane knee moments were reported by only three of the included studies (23, 76, 114) (Table 4). No significant differences were reported between TKR and control subjects for the maximum internal knee abduction (114), or maximum external knee adduction moment (23).

The maximum external knee adduction moments were reported for only TKR patients in another study (76).

Speed Stair Descent

None of the selected studies reported speed during stair descent.

Discussion

Evidence from the reviewed studies suggests that the differences between TKR subjects and healthy controls are more apparent for stair ascent than descent and there exist some inconsistencies. This may be in part due to the varied methods used in the reviewed studies. During stair ascent, TKR patients showed reductions in knee flexion angle at contact, maximum knee flexion, total knee flexion ROM and ascent velocity compared to healthy controls. These results were among the most consistent results from nearly all of the reviewed studies regardless of knee replacement designs, surgeons and staircase designs (16, 18, 23, 36, 72, 98, 103, 114). It is apparent that for the more demanding task such as stair ascent, knee kinematics and ascent velocity are not restored to normal levels.

These findings are in agreement with many of the studies conducted on TKR patients during overground walking. Research on overground gait following TKR concluded that TKR patients had reductions in both maximum knee flexion, total flexion ROM, and walking velocity when compared with healthy controls (75, 85). The impact of these reductions of knee ROM and walking velocity are not well understood. Passive knee flexion ROM is often measured at various stages following TKR surgery and used as an assessment of progression in recovery. It was suggested that in order to perform activities of daily living, healthy older adults need 110 degrees of knee joint ROM (113).

For stair descent, only Wilson et al. (128) found a significant reduction in maximum external knee flexion moment for TKR subjects compared to controls. The other three studies showed no differences in maximum external knee flexion and maximum external knee adduction between groups (18, 23, 114). The lack of differences in joint moments during stair descent seems to suggest that TKR patients have recovered or the results are confounded by other factors which were not accounted for. Patient recovery and walking speed are two factors that would influence joint moments. Time from surgery may not be the best judge of recovery as patients may recover to different extents and at different times. Clinical assessments of physical function may be better indicators of patient recovery, yet no reviewed studies report any type of qualitative assessment of patients. Additionally, speed can significantly influence the sagittal-plane knee joint moment and was not reported in stair descent trials in any of the studies (18, 23, 114, 128).

Inconsistencies of findings in regards to joint moments during stair ascent and joint kinematics during stair descent were apparent. Additionally only a small number of the reviewed studies even analyzed gait during stair descent. Among the studies that investigated maximum sagittal-plane knee moment, some reported reductions in the maximum external knee flexion moment (or internal knee extension moment) (16, 23, 36, 72, 98) , while the others reported no differences between groups (18, 114, 128).

Patients with different types of replacements may respond differently in stair ambulation and comparisons between these may offer insight as to what specific design may restore knee mechanics during stair ambulation to normal levels. Several studies analyzed differences between two different types of TKR designs (16, 18, 23, 36, 54, 103, 114). For example, maximum external knee adduction moments (internal abduction knee moment) were reduced during stair ascent in a mobile bearing replacement design compared to a posterior stabilized design and healthy controls, suggesting that the mobile bearing approach decreased medial compartment joint loading (23, 36). The resurfaced patella design appears to better restore both sagittal knee ROM and maximum knee internal abduction moment to healthy control levels compared with the replacement with non-resurfaced patella(16).

There seems to be a considerable amount of difficulty in recruiting TKR subjects for gait analysis in the reviewed studies. As a result, the patient population is often varied between and within studies. Time from surgery in the reviewed studies varied from as soon as two months (98) to as long as 98 months (range 72 – 134 months) (18). Within studies, the three earliest studies had the largest range of time from surgery for TKR patients. Range of follow-up for subjects was 55(60), 62 (18), and 76 months (128), respectively. Tighter control on time from surgery may lead to more consistent patient populations, though physical recovery may not always be correlated with time from surgery. Basic assessments of physical function, in addition to time from surgery, may depict a more complete picture of patient recovery. Studies with the longest follow-up testing time reported no differences in kinematic (60, 128) or kinetic variables (18, 128) between TKR and control groups. This suggests that as time from replacement surgery increases, TKR subjects seem to have restored their functions and ascend stairs more like healthy controls. Wilson et al. (128) suggested that the increased follow-up testing time may explain why their patients were similar to normal healthy subjects. On the other hand, testing TKR subjects too soon after surgery may also present challenges. Mandeville et al. (72) stated the testing time at 6-months post TKR surgery as a potential limitation of their study. Clinical assessments of physical functions in TKR patients and gait biomechanics assessment paired with time from surgery, would offer great insight into patient recovery following surgery. Future TKR studies should place special attention on the testing time from replacement surgery. Specific research questions should drive the decision on when to test subjects following TKR.

Longitudinal studies in TKR gait biomechanics are rare in the literature, probably due to difficulties with subject recruitment and time constraints. A majority of the studies examined differences between post-surgery TKR patients and healthy controls. All but three of the reviewed studies (54, 60, 76) had a healthy control group. Comparisons of TKR patients with healthy older adults may not be the most appropriate as it has been shown that pre-operative conditions of TKR patients is a strong indicator of post-surgery recovery (131). Only three of the reviewed studies compared TKR patients to their pre-surgery levels (72, 73, 98). Comparisons to the pre-surgery arthritic knee, may be more valuable to the understanding of stair gait following TKR. Future studies should attempt to focus on comparisons of post-surgery data at various time points with pre-surgery data from same subjects or subjects with similar pre-surgery conditions. These types of studies would provide a better understanding of to what extent recovery following TKR could be achieved.

Stair design is another issue in the stair gait studies. A majority of the studies in this review used the first step as the step of interest (18, 54, 60, 72, 73, 114, 128). Kinematics and kinetics of stair ascent on the first step were shown to be the most variable, while the data of the third step were the least variable (130). The first step of staircase is considered a transition or initiation step from level walking to stair ambulation (130). In addition there exist differences in common biomechanical gait variables on the first step compared to the second or third step (133). Other stair case designs allow GRF to be collected on multiple steps (16, 24, 100)

Differences in patient populations and instrumented staircases are apparent in the reviewed studies which may play a role in the inconsistent findings found in this review. We recommend future studies include more homogenous subject populations, improved instrumented stair designs, correlation with clinical tests, and inclusion of rehabilitation information.

Studies analyzing detailed biomechanical aspects of stair gait following TKR are important, but they should also aid and improve clinical practices. Most clinics are equipped to only carry out simple tests on patients and rely on more advanced research labs for more quantitative gait analysis. Clinicians would benefit more from research that attempts to integrate results from biomechanical gait analysis with simple physical function tests. Only one study of the selected studies included such physical function tests (timed up-and-go and six-minute walk) in addition to their biomechanical analysis (98). Future studies should also attempt to correlate quantitative gait analysis with clinical tests which would provide clinicians with easily assessable tools to assess recover following TKR surgery.

Examination of rehabilitation and related issues in conjunctions with gait and stair ambulation biomechanics is also important. Rehabilitation after any orthopedic surgery is an important step in the recovery process and the progress in physical rehabilitation could directly influence the biomechanical outcome measures of gait and stair ambulation. Only two studies provided information on rehabilitation (72, 103). One study described patients as receiving a standard weight bearing rehabilitation (72) and the other stated that subjects were considered fully rehabilitated (103). Studies specifically investigating different rehabilitation protocols and adherence could lead to a better understanding of the role rehabilitation plays in functional recovery of stair ambulation following TKR.

Limitations of this review may include the incomplete retrieval of all studies and reporting bias in the selected variables. Additionally, studies using other methods to quantify locomotor deficits following TKR such as in vivo and fluoroscopy studies were excluded from the review. This type of research can give detailed and accurate information about the knee kinematics, but is limited in its scope due to radiation and access, and is limited to a smaller capture volume compared to 3D biomechanics gait analysis.

In summary, during stair ascent knee flexion at contact, peak flexion and flexion range of motion do not seem to be fully restored for patients following TKR. Kinetic variables during stair ascent are much more inconsistent among studies. The findings regarding kinematic variables of the knee joint during stair descent do not offer any consistent findings. In order to better understand the deficiencies following TKR, future research on stair ambulation following TKR is needed with more consistent methods including: replacement design, time from replacement surgery, stair specifications and rehabilitation strategies.

Chapter IV Appendix: Tables and Figures

Table 4. Examples of search strategy used.

Search Number	Terminology
1	Total Knee Replacement
2	TKR
3	Total Knee Arthroplasty
4	TKA
5	1 or 2 or 3 or 4 and gait
6	1 or 2 or 3 or 4 and stair
7	1 or 2 or 3 or 4 and step
8	1 or 2 or 3 or 4 and biomechanics
9	1 or 2 or 3 or 4 and kinematics
10	1 or 2 or 3 or 4 and biomechanics or kinematics and gait
11	1 or 2 or 3 or 4 and biomechanics or kinematics and stair
12	1 or 2 or 3 or 4 and biomechanics or kinematics and step
13	1 or 2 or 3 or 4 and ascent or descent
14	1 or 2 or 3 or 4 and climbing
15	1 or 2 or 3 or 4 and ascent or descent or climbing
16	1 or 2 or 3 or 4 and stair and ascent or descent or climbing

Table 5. General information of included studies.

Studies	Subjects	Replacement Design	Time Periods	Staircase Design	Step of Interest
Joglekar (2012)	TKR: 18	nine cruciate retaining (CR) and nine cruciate subsituting (PS)	30 months for CR 34 months for PS	2 steps 26.9 cm deep and 17.8 cm high	First
McClelland (2009)	TKR: 5 stair ascent, 8 stair descent	Genesis-II posterior stabilised prosthesis w/ pattela resurfacing	at least 1 year post surgery	2 steps	No mention
Mandeville (2008)	TKR: 21 CON: 21 age-matched	Standard Posterior Stabilized	pre-surgery (P1) and 6-months post surgery (P2)	3 steps 25 cm deep and 18 cm high	First
Mandeville (2007)	TKR:21 CON: 21	Posterior stabilized or cruciate retaining	pre-surgery (P1) and 6-months post surgery (P2)	3 steps 25 cm deep and 18 cm high	First
Berti (2006)	TKR: 20 CON: 20	posterior stablized fixed bearing ten with resurfaced patellas (R) and ten with non resurfaced (NR)	at least 24 months post surgery	4 steps 28 cm deep and 16 cm high	Second and Third with force no mention of which was used
Saari (2004)	TKR:20 descending, 17 ascending CON: 17 descending, 15 ascending	small pre-operative deformity (SPD) , large pre-operative deformity (LPD)	between 1-2 years post surgery	2 steps 18.5 cm high	First
Fantozzi (2003)	TKR: 21	11 PCL retaining and mobile bearing (MB), 10 posterior stabalized (PS)	at least one year post surgery	4 steps 28 cm deep and 16 cm high	No mention
Catani (2003)	TKR: 20 CON: 10 age matched controls	10 posterior stabalized (PS) and 10 mobile bearing (MB)	11 months post in group 1 and 20 months post in group 2	4 steps 28 cm deep and 16 cm high	Second and Third with force

Table 5. Continued.

Studies	Subjects	Replacement Design	Time Periods	Staircase Design	Step of Interest
Ouellet (2002)	TKR: 16 CON: 18 and 21	Not Included	pre (P1) and two months (P2) post surgery	4 steps with a slope of 34%	First, cycle as first to third
Pollo (2000)	TKR: 18 CON: 9	nine resurfaced patellas (R) and nine non resurfaced (NR)	17 months for the R group and 24 months for the NR group	4 steps 26 cm deep and 15 cm high	None
Bolanos (1998)	E:14 subjects C: 16 subjects	posterior cruciate retaining (CR) and cruciate substituting (CS)	average follow up of 98 months with a range of 72 to 134 months	3 steps 26 cm deep and 22 cm high	First
Wilson (1996)	E:16 CON:16	posterior stabilized	average of 46 months post surgery	3 steps 26 cm deep and 22 cm high	First
Kelman (1989)	TKR: 8	PCL-sparing	average 28 months low of 7 and high of 62	2 steps 17.78 cm high	First and Second, collected for both with leading and trailing leg

Table 6. Major variables and findings in stair ascent.

Studies	Saggital Knee Angle (Degrees)			Knee Moment (%BW*HT)		
	Flexion at Contact	Max Flexion (Stance/Swing)	Range of Motion	Max Flexion/Extension	Max Ab/Adduction	Velocity (m/s)
Joglekar (2012) Internal		**CR:** 34 **PS:** 39 (Stance) **CR:** 74 **PS:** 81 (Swing)		**CR:** .3 **PS:** .3 (Nm/kg)		
McClelland (2009) External		**TKR**: 57.4 (Stance)		**TKR**: 2.5	**TKR**: 3.0	
Mandeville (2008) Internal					**TKR:** P1 3.70 P2 3.13* **CON:** P1 4.07 P2 4.69 **(first PVGRF)**	
Mandeville (2007) Internal	**TKR:** P1 39.9* P2 33.6* **CON:** P1 50.5 P2 50.5 **(first PVGRF)**			**TKR:** P1 3.71 P2 2.08* **CON:** P1 5.10 P2 6.37 **(first PVGRF)**		**TKR-** P1:0.48 P2:0.52* **CON-** P1:0.66 P2:0.71
Berti (2006) External	**TKR R:** 51.0* **TKR NR:** 46.8* **CON:** 59.7	**TKR R:** 78.4 **TKR NR:** 75.2 **CON:** 85.5 (Swing)	**TKR R:** 48.4 **TKR NR:** 39.2*^ **CON:** 55.8	**TKR R:** 3.0* **TKR NR:** 3.3* **CON:** 5.3	**TKR R:** -2.8 **TKR NR:** -3.8*^ **CON:** -2.7	**TKR R:** 0.31* **TKR NR:** 0.33* **CON:** 0.39
Saari (2004) Internal		**TKR SPD:** 87* **TKR LPD:** 89 **CON:** 95 (Swing)		**TKR SPD:** 0.8 **TKR LPD:** 0.7 **CON:** 1.0 (Nm/kg)	**TKR SPD:** -0.4 **TKR LPD:** -0.3 **CON:** -0.3 (Nm/kg)	
Fantozzi (2003) External	**TKR MB:** 44.9* **TKR PS:** 50.0* **CON:** 67.7	**TKR MB:** 73.1* **TKR PS:** 77.9* **CON:** 88.8 (Swing)	**TKR MB:** 46.6*^ **TKR PS:** 51.5* **CON:** 56.7	**TKR MB:** 3.1* **TKR PS:** 2.9* **CON:** 6.5	**TKR MB:** -1.8*^ **TKR PS:** -2.7 **CON:** -2.7	**TKR MB:** 0.28*^ **TKR PS:** 0.36* **CON:** 0.44
Catanai (2003) External	**TKR MB:** 51.8* **TKR PS:** 46.7* **CON:** 67.9	**TKR MB:** 75.8* **TKR PS:** 76.6* **CON:** 88.8 (Swing)	**TKR MB:** 49.0* **TKR PS:** 49.0* **CON:** 56.7	**TKR MB:** 3.3* **TKR PS:** 3.3* **CON:** 6.4	**TKR MB:** -1.9*^ **TKR PS:** -2.9 **CON:** -2.7	**TKR MB:** 0.35* **TKR PS:** 0.37* **CON:** 0.44

Table 6. Continued.

Studies	Saggital Knee Angle (Degrees)			Knee Moment (%BW*HT)		
	Flexion at Contact	Max Flexion (Stance/Swing)	Range of Motion	Max Flexion/Extension	Max Ab/Adduction	Velocity (m/s)
Ouellet (2002)		**TKR:** P1-59.0 P2-54.0*^ **CON:** 62.0 (Stance)		**TKR:** P1 0.63* P2 0.33*^ **CON:** 0.90 (Nm/kg)		
Pollo (2000)	**TKR R:** 54.5 **TKR NR:** 51.6* **CON:** 60.2	**TKR R:** 80.2* **TKR NR:** 84.3 **CON:** 88.8 (Swing)				
Bolanos (1998) External			**TKR CR:** 85* **TKR CS:** 87* **CON:** 96	No differences reported		
Wilson (1996) External			**TKR:** 90 **CON:** 96	**TKR:** 5.9 **CON:** 8.2 (%BW*LL)		
Kelman (1989)			**TKR:** 77 **Healthy leg:** 82			

CON - control group, TKR - total knee replacement group, External - study reported external moments, Internal - study reported internal moments, BW - body weight, LL - leg length, PVGRF - peak vertical ground reaction force, MB - mobile bearing, PS - posterior stabilized, R - resurfaced patella, NR - non resurfaced patella, SPD - small preoperative deformity, LPD - large preoperative deformity, CR - cruciate retaining, CS – cruciate sacrificing, P1- measurement prior to replacement, P2 - measurement after knee replacement.
*denotes significant difference between CON group, ^denotes significant difference between TKR groups.

Table 7. Major variables and findings in stair descent.

Studies	Saggital Knee Angle (Degrees)				Knee Moment	
	Extension at Contact	Max Flexion (Stance/Swing)	Range of Motion	Max Knee Extension (Swing)	Max Flexion/ Extension	Max Ab/Adduction
McClelland (2009) External		TKR: 87.6 (Stance)			TKR: 4.7 (%BW*HT)	TKR: 3.3 (%BW*HT)
Saari (2004) Internal		TKR SPD: 93 TKR LPD: 94 CON: 99 (Swing)		TKR SPD: -4 TKR LPD: -1* CON: 3	TKR SPD: 1.1 TKR LPD: 1.2 CON: 1.1 (Nm/kg)	TKR SPD: 0.6 TKR LPD: 0.5 CON: 0.6 (Nm/kg)
Catanai (2003) External	TKR MB: 4.1* TKR PS: 2.6* CON: 10.9		TKR MB: 58.7 TKR PS: 57.9 CON: 61.9	TKR MB: 2.7* TKR PS: 3.5* CON: 7.8	TKR MB: 5.3 TKR PS: 4.4 CON: 5.0 (%BW*HT)	TKR MB: -2.5 TKR PS: -2.6 CON:-2.5 (%BW*HT)
Bolanos (1998) External			TKR CR: 84* TKR CS: 84* CON: 97		No differences reported	
Wilson (1996) External			TKR: 88* CON: 96		TKR: 13.1* CON: 16.3 (%BW*LL)	
Kelman (1989)			TKR: 77 Healthy leg: 82			
Joglekar (2012) Internal		CR: 55^ PS: 59 (Stance) CR: 60^ PS: 67 (Swing)			CR: .52 PS: .50 (Nm/kg)	

CON - control group, TKR - total knee replacement group, External - study reported external moments, Internal - study reported internal moments, BW - body weight, LL - leg length, MB - mobile bearing, PS - posterior stabilized, CR - cruciate retaining, CS - cruciate sacrificing, SPD - small preoperative deformity, LPD - large preoperative deformity. *denotes significant difference between CON group, ^denotes significant difference between TKR groups.

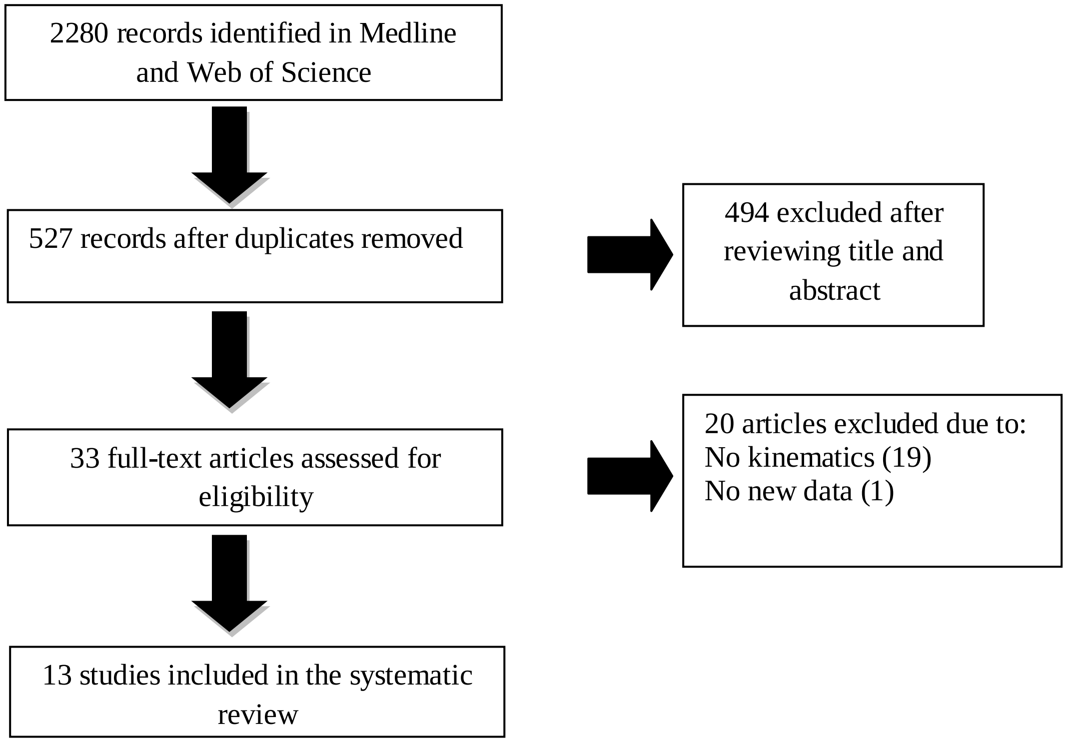


Figure 7. Flow diagram for search.

CHAPTER V

DIFFERENCES OF LOWER EXTREMITY BIOMECHANICS ON FIRST THREE STEPS DURING STAIR ASCENT AND LEVEL WALKING IN MID- AND OLD-AGE HEALTHY SUBJECTS

Abstract

Background: The step chosen for analysis often varies in stair ascent studies. It is unclear how gait biomechanical characteristics change among different steps and level walking, making result interpretations and comparisons difficult. The purpose of this study was to compare lower extremity biomechanics during the first three steps of stair ascent and level walking.

Methods: Twelve healthy adults (45-68 years) performed five trials of level walking and stair ascent.

Findings: In the sagittal plane, ankle contact angle and plantarflexion range of motion (ROM), knee contact angle, hip contact angle and extension ROM were all smaller in walking compared with all steps. Many of these ankle and knee variables were also smaller on the first step than the next two steps. The peak loading-response plantarflexion moment was greater in the second and third steps compared to the first while the peak push-off plantarflexion moment was greater greater in walking compared to all steps. The peak knee loading-response extension moment was almost two times greater in all step conditions compared to walking. In the frontal plane the knee was more adducted and had a greater abduction ROM in the step conditions compared to level walking. The peak knee and hip loading-response and push-off abduction moments were greatest in level walking while they were similar in the first and third steps.

Interpretation: These findings suggest that the first step is a transition step from walking to stair ascent and that steady state stair ascent is only reached on the second or third step.

Keyword: Stair ambulation, step of interest, knee extension moment, knee abduction moment, gait

Introduction

Stair climbing is a common activity of daily living utilized frequently by both younger and older adults (122). This task has been shown to be more demanding on lower extremity muscles and joints compared to level walking (91, 99). Research has been carried out to understand the biomechanical demands of stair climbing in many populations including: healthy young adults (28, 79, 104, 110, 126), healthy older adults (91, 99), patients with knee osteoarthritis (OA) (42, 59, 100), anterior cruciate ligament (ACL) reconstructions (40, 125), and those recovering from total knee replacement (TKR) surgery (47, 73). More demanding tasks such as stair climbing may bring to light some deficiencies otherwise not seen during less demanding activities, e.g. level walking.

Different staircases used in studies range from one instrumented step (73) to sixteen (126). The choice of step for analysis is determined by the staircase design, often varied between research labs. The inconsistencies among studies have made comparisons difficult. In a recent review of stair climbing biomechanics following TKR, it was pointed out how different staircase setups and methods, including step of interest, makes it difficult to compare results between studies (120). Yu et al. (130) performed a study on the reproducibility lower extremity biomechanics during stair-climbing of normal subjects and found greatest variability in lower extremity joint angles and moments on the first step of a staircase and most consistent results on the third step. In addition, they suggested that the first step of the staircase is a transition or an initiation step from level walking to stair ambulation (130).

It is important to understand how step of interest impacts biomechanical variables of stair ascent in order to make equitable comparisons of different studies and provide guidance for future research of stair ambulation biomechanics. A thorough understanding of the effects of step of interest on these differences is even more critical in clinical applications as often differences in biomechanical variables during stair ambulation may be small between patients and healthy controls. To date no study has been carried out to understand how biomechanical variables change on different steps of interest. Furthermore, no data in the literature exist on how biomechanical variables of lower extremity joints in stair ascent are different from those in level walking, although it is often suggested that stair ascent is a more demanding task. Therefore the purpose of this study was to compare lower extremity joint biomechanics during stair ascent on the first three steps of an instrumented staircase, and level walking. It was hypothesized that lower extremity biomechanical variables on the first step would be different than those on the second and third step and that all steps would be different from level walking.

Methods

Participants

Twelve healthy adults [age: 57.3 years (45 – 68 years), height: 1.77 m (1.63 – 1.95 m) and body mass: 85.9 kg (58.5 – 127.3 kg)] participated in the study. Exclusion criteria included BMI greater than 35, systemic inflammatory arthritis, neurologic diseases, and inability to ascend/descend stairs without the use of a handrail. An *a priori* power analysis using existing stair ascent data showed that a minimum of 10 participants were needed to obtain an alpha of 0.05 and beta of 0.80 for the peak knee extension moment (109). All patients signed an informed consent document approved by the Institutional Review Board.

Instrumentation

A nine-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain three-dimensional (3D) kinematics during testing. Participants wore a standardized laboratory running shoe (Noveto, Adidas, USA) during the experiment. Anatomical and tracking markers were attached to the trunk, pelvis, thighs, shanks and feet (100, 132). An instrumented 3-step staircase (FP-stairs, American Mechanical Technology Inc., Watertown, MA, USA) with a height of 17.8 cm, a depth of 29.9 cm, and a width of 60.0 cm was used in the study (99, 100). The FP-Stairs bolted independently to two force platforms (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA) were used to measure the GRF and the moments of forces during stair walking (Figure 8). Two additional customized wooden steps (4^{th} and 5^{th} steps) of similar dimensions were used in conjunction with the instrumented staircase in order to ensure a continuous motion after the three instrumented steps.

Experimental Protocol

After completion of a 3-minute warm up of walking on a treadmill at a self-selected speed, subjects were asked to perform practice stair ascent trials at a self-selected speed monitored by two sets of photo cells (63501 IR, Lafayette Instrument Inc., IN, USA) mounted on 1^{st} and 4^{th} step and electronic timers (54035A, Lafayette Instrument Inc., IN, USA). Three to five trials at self-selected speed (mean ± 5%) were performed for each of the four test conditions: the right foot on the first and third step, the right foot on the second step during stair ascent, and the right foot on the force platform in walking. Subjects completed at least three steps prior to stair ascent. Stair ascent condition was randomized, while level walking was collected after stair ascent. The participants were required to ascend the stairs in a step over manner without utilizing the handrail.

Data and Statistical Analyses

Visual3D biomechanical analysis software suite (C-Motion, Inc., Germantown, MD, USA) was used to compute the 3D biomechanics variables. A Cardan rotational sequence (X-y-z) was used for the 3D angular computations and a right hand rule was used to define the conventions of angular kinematic and kinetic variables. Kinematic and ground reaction force (GRF) data were filtered using a fourth-order Butterworth low-pass filter at cut-off frequencies of 8 Hz and 50 Hz, respectively. For joint moment calculations, both kinematic and GRF data were filtered with the same cut-off frequency of 8 Hz (99, 100). Joint moments were calculated using an inverse dynamics approach and reported as internal moments in Visual3D. Customized computer programs were utilized to determine variables of interest and organize data for statistical analyses. GRF variables were normalized to subject's body weight (BW) and joint moments were normalized to subject's mass (Nm/kg).

A one-way repeated measures analysis of variance (ANOVA) was performed to detect differences between conditions (19.0, IBM SPSS, Chicago, IL). When the ANOVA revealed a main effect, post-hoc comparisons with Bonferroni adjustments were utilized to compare means between conditions. The alpha level was set at 0.05 *a priori*.

Results

GRF and Foot Variables

For the GRF related variables, the loading-response peak vertical GRF was greater in walking compared to the first step ($p=0.032$, Table 8). The mediolateral center of pressure (COP) displacement was greater for the second step compared with third step ($p<0.001$). The foot toe-out angle was smaller during weight acceptance on first step compared to second ($p=0.008$) and third ($p<0.001$) steps.

Sagittal Plane Angles and Moments

In general there were differences of sagittal-plane variables between level walking and stair ascent. The ankle had a less dorsiflexed contact angle ($p<0.001$), a reduced plantarflexion ROM ($p<0.001$), and a greater push-off peak plantarflexion moment ($p<0.001$) in walking compared to all three steps (Table 9). The knee had a more extended contact angle in walking than all three steps ($p<0.001$) and a reduced ROM than both second ($p=0.01$) and third ($p=0.003$) steps. The loading-response peak knee extension moment in walking was smaller than all three steps ($p<0.001$, Figure 9). The hip had a less flexed contact angle ($p<0.001$), a reduced ROM ($p<0.001$), but had a greater peak flexion moment ($p<0.001$) in walking compared to all three steps.

Overall sagittal-plane variables on the first step were different than those on the second and third steps during stair ascent. The ankle joint had a less dorsiflexed initial contact angle and a decreased plantarflexion ROM on first step compared to second ($p <0.001$ and $p =0.002$) and third ($p<0.001$ and $p<0.001$) steps (Table 9). The loading-response peak ankle plantarflexion moment was reduced on first step compared to second ($p=0.004$) and third three ($p<0.001$) steps. The knee had a more extended contact angle and a decreased extension ROM on first step compared to second ($p<0.001$ and $p<0.001$) and third ($p<0.001$ and $p<0.001$) steps. The push-off peak knee extension moment was greater in first step compared to third step ($p=0.033$). For the hip, the maximum flexion moment was greater in second step compared to third ($p<0.001$).

Frontal plane angles and moments

A majority of frontal-plane variables were different in level walking compared to stair walking. The knee had reduced adduction angle at contact and abduction ROM in walking compared with all three steps ($p<0.001$, Table 10). In walking, the loading-response peak knee abduction moment was greater than first ($p=0.007$) and second step ($p<0.001$), while the push-off peak knee abduction moment was only greater than second step ($p=0.015$). The hip had greater adduction ROM in walking compared to first step ($p=0.011$), an elevated loading-response peak abduction moment compared to second step ($p<0.001$), and a greater push-off peak abduction moment compared to all three steps ($p<0.001$).

The first step had greater loading-response peak ankle inversion moment in second step compared to first ($p<0.001$) and third ($p=0.001$) steps (Table 10). The loading-response peak knee abduction moments were greater in first ($p=0.002$) and third ($p=0.007$) steps compared to second step. Maximum hip adduction angle was smaller on first step compared to third step ($p=0.017$). The loading-response and push-off peak abduction moments were greater in first ($p<0.001$ and $p=0.001$) and third ($p<0.001$ and $p<0.001$) compared to second step.

Discussion

The purpose of this study was to compare lower extremity joint biomechanics during stair ascent on the first three steps of an instrumented staircase, in addition to level walking. As hypothesized, the sagittal kinematics and kinetics of first step were different than those of second and third step. In addition, the level walking condition was different than all three step conditions for all sagittal and some frontal plane kinematic and kinetic variables. Contrary to what we expected, most frontal plane kinematic variables were similar among all step conditions.

The main goal of the stair ascent task is to raise the center of mass of the body while translating forward, a task accomplished primarily by actions of lower extremity joints in the sagittal plane. Not surprisingly, sagittal plane variables during level walking were different from most of the step conditions in this study, as upward movement of the body center of mass (COM) is minimal during level walking. At times these differences exhibited a gradual increase from level to step one and then further differences compared to steps two and three. Ankle contact angle and plantarflexion ROM were the smallest in walking, while these variables on the first step were smaller than those on the second and third steps. A similar pattern was also seen for knee contact angle. Reductions were also noted for loading-response peak knee extension moment but the push-off peak plantarflexion moment and peak hip flexion moment were elevated in level walking compared to all three steps in stair ascent. Our study reported that loading-response peak GRF was slightly elevated in level walking compared with the first step. One previous study reported loading-response peak vertical GRF for both level walking and stair ascent and found, similar to this study, a slight increase in level walking compared to the first step (118).

Among the steps in stair ascent, the first step had reductions in a majority of the ankle and knee variables compared to the second and third steps. Steps two and three were nearly identical for all of the sagittal plane variables. These findings suggest that the first step of stair ascent has different movement pattern and places different demands on the lower extremities, suggesting a transitional nature of the first step from level walking to stair ascent. Yu et al., (130) reported that variability is increased on the first step during stair ascent, and suggested that the first step should be considered as a transition step from level walking to stair ascent. The gradual increase of some sagittal plane variables from level walking to the first three steps shows that the subjects utilized the first step to transition from level walking to stair ascent on the second and third steps. In addition, the differences between the first step and the second and third steps provided clear support that the first step is different from the subsequent steps. The transition from walking to stair on the first step seems to be accomplished more by knee extensors because their moment was greater on the first step than the second and third steps while plantarflexion and hip flexion moments were not different between the steps.

Previous stair ascent studies have analyzed data from either the first or second step, mostly for knee variables. Knee contact angle on the first step in this study (57°, was slightly higher than the 50° reported by a previous study (72). The knee contact angle on the second step (69°) was similar to previous findings on the same variable (23, 36). Other studies have also reported contact knee flexion angles to be slightly smaller (16, 103), though the step of interest was not specified. The differences in the contact knee angle could be influenced by differences in the step height and depth used. The step height (17.8 cm) and depth (29.9 cm) used in this study are similar to the step dimensions used in other studies: 18 cm (height) and 25 cm (depth) (72), 16 cm (height) and 28 cm (depth) (16, 23, 36) and 15 cm (height) and 26 cm (depth) (103).The early peak stance knee extension moment in the current study (1.35 Nm/kg) was greater than those reported in studies on healthy older adults (98, 114), though neither of these studies reported ascent velocity. The ankle and hip contact angles on the second step of this study were smaller than those reported for healthy older adults (48). Variability in subject populations, stair dimensions, and walking velocity make direct comparisons between studies somewhat difficult.

While the frontal plane biomechanics do not drive the stair ascent task, they often have important implications for pathological conditions, e.g. knee osteoarthritis and total joint replacement. Level walking exhibited smaller knee adduction angle at contact and knee frontal plane ROM compared with all step conditions, and a slight increase in hip adduction ROM compared with the first step. Walking seemed to place greater mechanical demands on the knee and hip joints in frontal plane, with elevated peak knee and hip abduction moments compared to stair ascent. However, stair ascent requires greater muscle efforts due to greater elevation of

COM compared to walking. The net muscle moments computed through inverse dynamics cannot truly reflect the greater muscle efforts of agonists in stair ascent because greater antagonist efforts were also accompanied. In comparisons among the steps, the majority of kinematic variables of the frontal plane were similar. This suggests that frontal plane kinematics were the same regardless of the step. Somewhat surprising to us, the kinetic variables in the frontal plane were mostly similar between the first and third step as none of the variables showed any significant difference. However, the second step had reductions in loading-response peak knee abduction moment in addition to reduced loading-response and push-off peak hip abduction moments compared to steps one and three. Foot progression angle and center of pressure may provide additional information when considering these key differences in frontal plane variables. Foot progression angle has been shown to influence frontal plane knee moments during stair ascent (42) and descent (99). Thus the differences in frontal plane moments between step one and two can be partially explained by the increased toe out angle on step two compared to step one, leading to reductions in frontal plane knee moments. Additionally, the elevated moments at the knee and hip on the first step compared to the second may be partially explained by the transitional nature of the first step from level walking to stair ascent. Displacement of the COP in the mediolateral direction can influence the location of the ground reaction force application in the frontal plane. Maly et al. (71) suggested that a more laterally shifted COP during level walking would reduce the moment arm from the GRF to the knee joint center in the frontal plane, thus decreasing the knee external adduction moment. This was further supported by Hiam et al. (43) who found that during level walking a more laterally shifted COP reduced distance between the GRF and center of the knee joint, resulting in a reduced knee adduction moment. The current study did find an increased lateral shift of the COP in the second step compared to the third, thus reductions of knee abduction moments in the second step could be attributed to differences in COP displacement.

It is time consuming to set-up the instrumented staircase, and so the stair ascent conditions were always collected prior to the walking trials. The age range of our subjects was relative large (45 to 68) spanning across two different age groups. Novak et al. (95) found no differences in peak knee or hip extension moment, or any frontal plane moments of ankle, knee, and hip between older (mean 67, range 55 to 83) and younger adults (mean 23.7, range 20 to 30) during stair ascent. Furthermore, the ages of the subjects in our study were at least 45 and similar to the age ranges of other stair ascent studies with healthy older adults (91, 95). Finally, the setup of the instrumented staircase required the first step to cover half of the 1st force platform and so it was not possible to collect complete GRF information for the step just prior to stair ascent.

Conclusion

In summary, the findings of this study suggest that sagittal plane kinematics and kinetics of the lower extremity are different on step one compared to the next two steps and that step two and three are similar. Additionally level walking biomechanics were different than all three steps. The first step of stair ascent should be considered a transition step and should not be treated as a representation of steady state stair ascent ambulation. The understanding of the effect of step of interest on lower extremity biomechanics can aid future studies with clinical applications, as often differences in biomechanical variables during stair ambulation may be small between patients and healthy controls. Future research in stair ambulation biomechanics should explicitly state which step is the step of interest. Direct comparisons of results between these different tasks (steps) should be avoided.

Chapter V Appendix: Tables and Figure

Table 8. Ground reaction force, center of pressure and toe angle variables: mean ± STD.

Variables	Walking	Step One	Step Two	Step Three
Loading-response Peak Vertical GRF (BW)	1.13±0.09*	1.04±0.08	1.04±0.09	1.04±0.09
Push-off Peak Vertical GRF (BW)	1.08±0.45	1.08±0.12	1.10±0.13	1.10±0.12
ML COP Displacement (m)	–	0.011±0.009	0.015±0.008&	0.009±0.009
Peak Toe-Out Angle (deg)	-7.7±3.0	-6.5±4.2+@	-8.4±4.8	-9.2±4.8

Note: * - Significant difference between walking and step one, + - Significant difference between step one and two, @ - Significant differece between step one and three, & Significant difference between step two and three, ML – mediolateral, COP – center of pressure, – - denotes non-comparable value for walking, and Toe-in angle is positive.

Table 9. Sagittal plane joint kinematic and kinetic variables: mean ± STD.

Joint	Variable	Walking	Step One	Step Two	Step Three
Ankle	Contact Angle (deg)	$2.8 \pm 4.9^{*\#\wedge}$	$10.7 \pm 7.2^{+@}$	18.1±7.1	18.7±6.8
	Plantarflex ROM (deg)	$-19.5 \pm 5.6^{*\#\wedge}$	$-26.0 \pm 8.5^{+@}$	-35.5±8.4	-35.9±8.8
	Loading-response Peak Plantarflex Moment (Nm/kg)	–	$-0.56 \pm 0.3^{+@}$	-0.70±0.3	-0.77±0.3
	Push-off Peak Plantarflex Moment (Nm/kg)	$-1.43 \pm 0.16^{*\#\wedge}$	-1.10±0.20	-1.14±0.17	-1.16±0.15
Knee	Contact Angle (deg)	$0.15 \pm 4.2^{*\#\wedge}$	$-57.3 \pm 5.6^{+@}$	-69.1±4.6	-70.7±5.9
	Extension ROM (deg)	$50.1 \pm 4.9^{\#\wedge}$	$44.5 \pm 7.1^{+@}$	57.3±4.0	59.3±3.6
	Push-off Peak Extension Moment (Nm/kg)	–	$0.46 \pm 0.30^{@}$	0.40±0.29	0.37±0.31
Hip	Contact Angle (deg)	$26.6 \pm 9.5^{*\#\wedge}$	54.2±4.5	54.7±6.3	55.0±7.8
	Extension ROM (deg)	$-39.5 \pm 7.0^{*\#\wedge}$	-48.5±4.4	-49.9±4.7	-49.9±4.8
	Peak Flexion Moment (Nm/kg)	$0.83 \pm 0.20^{*\#\wedge}$	0.46±0.16	$0.49 \pm 0.20^{\&}$	0.39±0.20

Note: * - Significant difference between walking and step one, # - Significant difference between walking and step two, ^ - Significant difference between walking and step three, + - Significant difference between step one and two, @ - Significant difference between step one and three, & Significant difference between step two and three, – - denotes non-comparable value for walking. Ankle dorsiflexion and ROM, knee extension angle and ROM, hip flexion angle and ROM, ankle dorsiflexion moment, knee extension moment, and hip flexion moment are positive based on the right hand rule.

Table 10. Frontal plane joint kinematic and kinetic variables: mean ± STD.

Joint	Variable	Walking	Step One	Step Two	Step Three
Ankle	Peak Eversion Angle (deg)	-13.4±4.5	-13.0±4.6	-13.0±4.6	-13.2±4.5
	Loading-response Peak Inversion Moment (Nm/kg)	–	0.26±0.10^{+}	0.33±0.12$^{\&}$	0.25±0.13
	Push-off Peak Inversion Moment (Nm/kg)	0.24±0.10	0.29±0.9	0.35±0.12$^{\&}$	0.24±0.14
Knee	Contact Angle (deg)	-0.75±3.7$^{*\#\wedge}$	10.2±8.5	10.1±8.5	11.0±9.0
	Abduction ROM (deg)	-1.2±1.7$^{*\#\wedge}$	-10.0±5.1	-10.8±5.5	-11.1±6.5
	Loading-response Peak Abduction Moment (Nm/kg)	-0.55±0.14$^{*\#}$	-0.37±0.11^{+}	-0.28±0.14$^{\&}$	-0.39±0.13
	Push-off Peak Abduction Moment (Nm/kg)	-0.35±0.18$^{\#}$	-0.21±0.08	-0.12±0.08	-0.23±0.08
Hip	Peak Adduction Angle (deg)	8.5±1.9	9.1±4.0$^{@}$	10.1±3.6	10.5±3.8
	Adduction ROM (deg)	7.0±2.9*	4.5±1.9	5.0±1.8	5.0±1.2
	Loading-response Peak Abduction Moment (Nm/kg)	-1.05±0.20$^{\#}$	-0.86±0.20^{+}	-0.68±0.17$^{\&}$	-0.89±0.19
	Push-off Peak Abduction Moment (Nm/kg)	-0.97±0.08$^{*\#\wedge}$	-0.58±0.17^{+}	-0.45±0.13$^{\&}$	-0.59±0.15

Note: * - Significant difference between walking and step one, $^{\#}$ - Significant difference between walking and step two, $^{\wedge}$ - Significant difference between walking and step three, $^{+}$ - Significant difference between step one and two, $^{@}$ - Significant difference between step one and three, $^{\&}$ Significant difference between step two and three, – - denotes non-comparable value for walking. Ankle inversion angle, knee adduction angle and ROM, and hip adduction angle and ROM. ankle inversion moment, knee adduction moments and hip adduction moment are positive based on the right hand rule

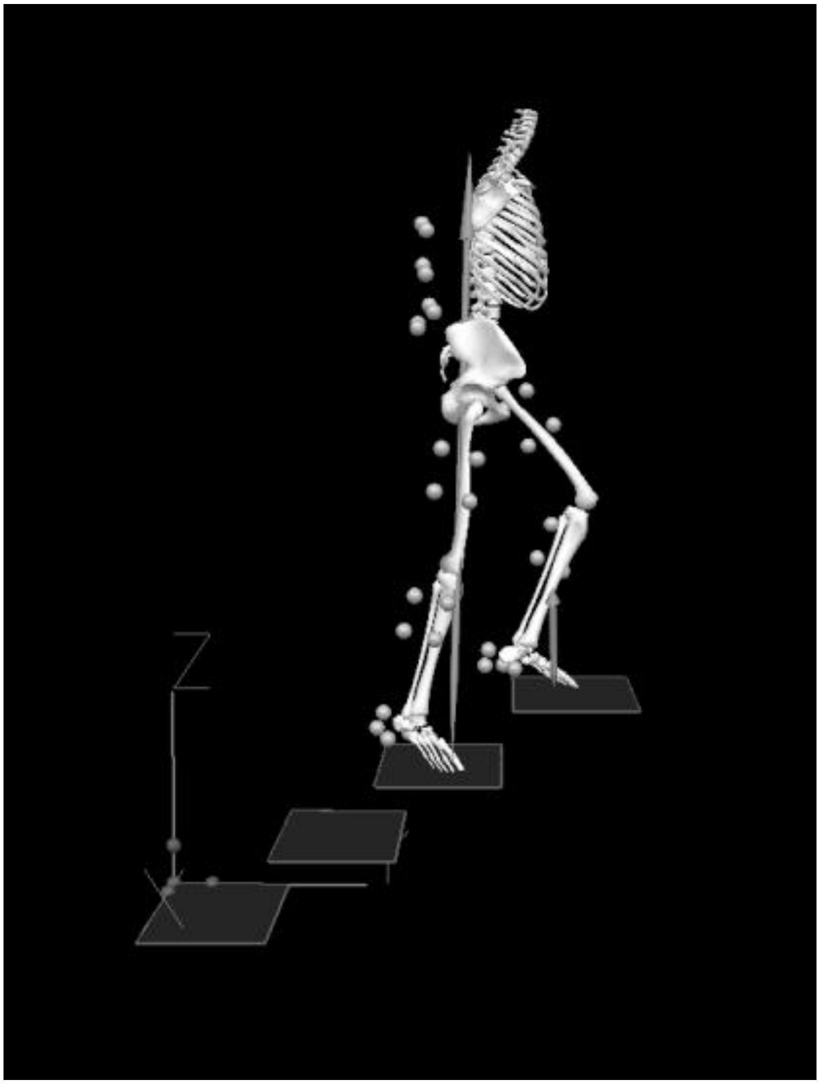


Figure 8. Ground reaction force measured on the instrumented 3-step staircase.

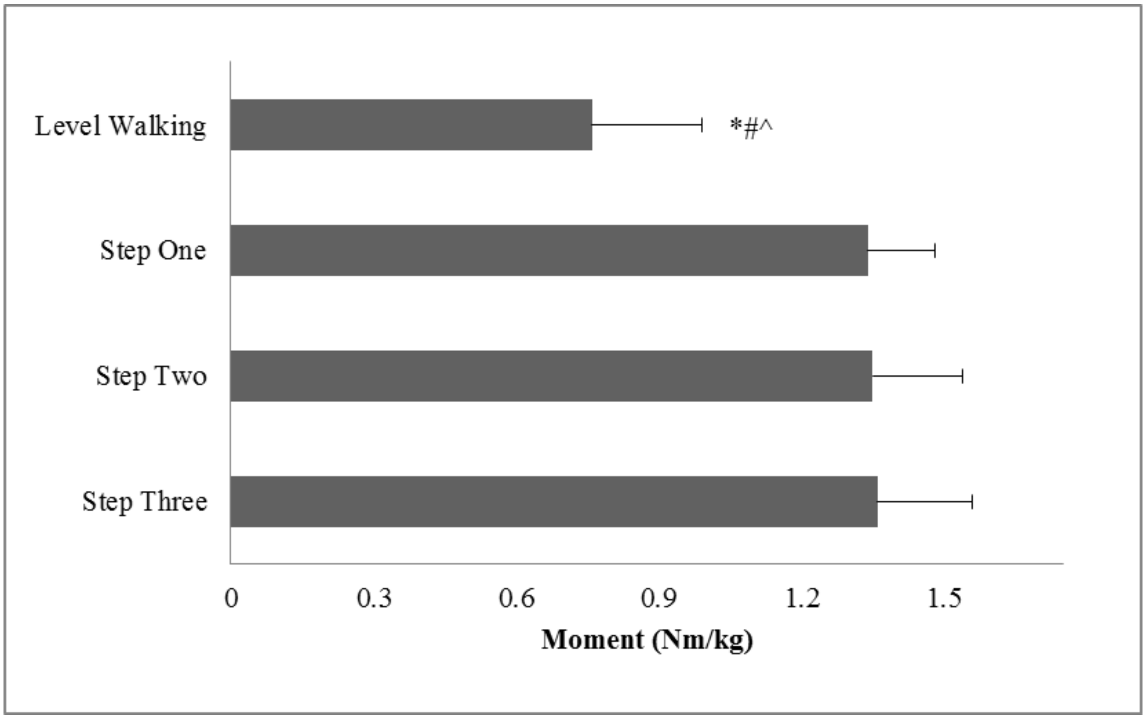


Figure 9. Loading-response peak knee extension moment. Note: * - Significant difference between walking and step one, # - Significant difference between walking and step two, ^ - Significant differencebetween walking and step three

CHAPTER VI

INFLUENCE OF TOTAL KNEE ARTHROPLASTY ON GAIT MECHANICS OF THE REPLACED AND NON-REPLACED LIMB DURING STAIR NEGOTIATION

Abstract

This study compared biomechanics during stair ascent in replaced and non-replaced limbs of total knee arthroplasty (TKA) patients with control limbs of healthy participants. Thirteen TKA patients and fifteen controls performed stair ascent. Replaced and non-replaced knees of TKA patients were less flexed at contact compared to controls. The loading response peak knee extension moment was greater in control and non-replaced knees compared with replaced. The push-off peak knee abduction moment was elevated in replaced limbs compared to controls. Loading and push-off peak hip abduction moments were greater in replaced limbs compared to controls. The push-off peak hip abduction moment was greater in non-replaced limbs compared to controls. Future rehabilitation protocols should consider the replaced knee and also the non-replaced knee and surrounding joints.

Keywords: total knee replacement, TKR, stair biomechanics, contralateral

Introduction

Total knee arthroplasty (TKA) is the most common surgical treatment option for end-stage knee osteoarthritis (OA) and large increases in TKA procedures are predicted as the patient population's average age continues to decrease. TKA surgeries are on the rise in the USA and are expected to increase to 3.5 million a year by 2030, an increase of nearly 700% (65). As a matter of fact, patients younger than 50 saw the largest increase of TKA from 1990 to 2000, and the average age at time of surgery declined from 79.6 to 68.5 years during the same period (82).

The main goal of a TKA is to eliminate pain and has shown to be successful for a majority of patients (21, 46, 62). However, some patients still reported long-term pain following TKA (17). In addition to reduction of pain, TKA should lead to improvements in quality of life and abilities to perform basic activities of daily living. Noble et al. (93) reported a majority of patients are satisfied with their knee arthroplasties though some patients have reported a decreased ability to perform simple activities of daily living (94). Moreover, TKA patients have decreased ability to perform basic functional tests compared to healthy age-matched controls (19, 98).

Despite their previous surgical outcomes, many TKA patients will need a subsequent knee joint arthroplasty in the non-replaced limb (116). Thus, recovery may not be fully complete following the original arthroplasty surgery, especially when considering the compensatory loading of the non-replaced limb. Most TKA surgeries are carried out on patients as a result of end-stage knee OA, and the most common location of knee OA is the medial knee joint compartment. Peak knee internal abduction moment is commonly considered as a surrogate measure of medial knee joint loading (134), and plays a role in the progression and severity of medial compartment knee OA (12, 51, 88). Thus, it is important to examine the knee abduction moment and related frontal-plane variables at the hip of both the replaced and non-replaced limbs following TKA during common activities of daily living.

Stair ascent is more demanding than level walking on lower extremity muscles and joints of both limbs (91, 100) and is a frequent activity of daily living for both younger and older adults (122). Patient deficiencies may become more apparent in the more demanding activities of daily living (91, 100). The ability to climb stairs is also included in the most common knee scoring tools (30, 52, 115) used to assess physical functions following a TKA. In addition, the frontal plane mechanics play a key role in both propulsion and mediolateral stability during stair ascent, especially at the knee and hip joints (7, 91).

A better understanding of how TKA influences gait mechanics of replaced and non-replace limbs during stair ascent is necessary to advance rehabilitation protocols. Only two studies have analyzed non-replaced knee biomechanics during stair ascent following TKA (54, 60). One reported similar sagittal hip, knee, and ankle angles between the replaced and non-replaced limbs during the first or second steps of stair ascent (60). Joglekar et al. (54) found no differences between maximum knee flexion angles for the non-replaced limbs of two different arthroplasty designs on the first step of stair ascent. Only one study examined knee joint kinetics between the replaced and non-replaced knee and found that the maximum internal knee extension moment and maximum knee power were similar in the non-operated knee of two different arthroplasty designs (54). However, no comparisons were made between the operated and healthy control knees. The results from Kelman et al. (60) seem to suggest that the non-replaced knee is comparable to the replaced for sagittal plane knee kinematics during the first step of stair ascent, but they did not include a comparison with a control limb. Currently, there is a lack of comprehensive information on differences of sagittal plane knee kinematics and kinetics between replaced and non-replaced knees during stair ascent, no data of TKA knees compared to control knees, and other surrounding joints (i.e., ankle and hip). Furthermore, there is currently no information regarding frontal plane knee joint (internal) abduction moment and related variables of non-replaced knees during stair ascent, which have been shown to be linked to the severity and progression of knee OA (12, 51, 88). Many TKA patients will have to undergo a subsequent joint arthroplasty at the non-replaced knee (116). Thus, a comprehensive understanding of how the non-replaced limb compares to both the replaced limb and a control limb is necessary, especially for frontal plane variables at the knee and its two surrounding joints during the more demanding daily living task of stair ascent.

The purpose of this study was to compare lower-limb biomechanics of the replaced joint to non-replaced limb of TKA patients and a healthy control limb during stair ascent. We hypothesized that the sagittal plane knee variables would be similar in the replaced limb when compared to the non-replaced limb, but that both would be different compared to a control limb. We further hypothesized that frontal plane knee variables would be different in the replaced limb compared to non-replaced limb, but similar between the replaced limb and a control limb. For the ankle and hip, we anticipated that sagittal plane variables would be similar for all limbs, but that frontal plane variables would be different between the non-replaced limb and the control limb.

Material and methods

Participants

Participants in this study included patients with TKA as well as controls with healthy limbs. Thirteen TKA patients (Table 1) were referred to the primary investigators via phone interviews carried out by an orthopaedic clinic. TKA procedures were all performed by the same surgeon with posterior stabilized designs. TKA patients were between 6 and 72 months post surgery with no additional lower extremity joint arthroplasties. Standard rehabilitation protocols were prescribed following surgery. Additionally, fifteen controls (Table 11) were recruited through flyers, email recruitment and word of mouth. Groups were matched for age, gender, and BMI. Exclusion criteria for both TKA and healthy control participants consisted of the following: BMI greater than 35, systemic inflammatory arthritis, and neurologic diseases. All participants had to be able to negotiate (i.e., ascend and descend) stairs without the use of a handrail.

An *a priori* power analysis using existing stair ascent data showed that a minimum of 9 participants were needed for each group to obtain an alpha of 0.05 and beta of 0.80. The peak knee extension moment, an important variable in TKA patient populations, was utilized to calculate power (109). All participants signed an informed consent document approved by the Institutional Review Board.

Instrumentation

During data collections, a nine-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain three-dimensional (3D) kinematics during testing. Participants wore a standardized laboratory running shoe (Noveto, Adidas, USA) during the experiment. Reflective anatomical markers were placed on toes (i.e., most anterior aspect of the shoes), 1^{st} and 5^{th} metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and acromion processes. A cluster of four reflective markers on a semi rigid thermoplastic shell was used as tracking markers and placed on lateral shank, lateral thigh, lateral pelvis and posterior-inferior trunk. Four individual tracking markers were placed on medial, posterior, lateral and dorsal-lateral heel counter of the shoe. An instrumented 3-step staircase (FP-stairs, American Mechanical Technology Inc., Watertown, MA, USA; 1^{st}, 2^{nd} and 3^{rd} steps) with two additional customized wooden steps (4^{th} and 5^{th} steps) was used in the study. The instrumented staircase bolted independently to two force platforms (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA) was used to measure the ground reaction force (GRF) and the moments of forces during stair gait.

Experimental Procedures

The TKA patients were asked to complete the Knee Society Survey (115), a questionnaire aimed to assess recovery following arthroplasty surgery. TKA patients also completed a brief questionnaire detailing their knee arthroplasty type, surgeon, and rehabilitation protocols. All participants completed a physical activity readiness survey. Following completion of the surveys and questionnaires, participants performed a 3-minute warm up on the treadmill at a self-selected speed and completed a timed up-and-go test (TUG) and a stair ascent/descent test. After one practice trial, participants performed two testing trials of each test. Average times for the two trials were utilized for analysis. Additionally passive knee range of motion (ROM) was measured on both knees with participants lying supine on a treatment table. After completion of these functional tests, participants were fitted with the reflective markers and asked to perform stair ascent trials at a self-selected speed. Three practice trials were used for familiarization and to determine a speed range (average ± 5%) that was used to control each participant's walking speed during the experimental trials using two pairs of photo cells (63501 IR, Lafayette Instrument Inc., IN, USA) in line with the 1^{st} and 4^{th} steps and two electronic timers (54035A, Lafayette Instrument Inc., IN, USA). TKA patients performed 3-5 stair ascent trials at the self-selected speed in each of two test conditions with replaced and non-replaced limbs on the second step. Healthy controls performed 3-5 trials in one test condition with the right limb on the second step. All participants were required to take a least three steps prior to contact with the first step of the staircase. If the ascent speed of a test trial did not fall into the preferred range, or if the handrail was utilized, it was repeated.

Data Analyses

Visual3D biomechanical analysis software suite (5.0, C-Motion, Inc., Germantown, MD, USA) was used to compute the 3D kinematic and kinetic variables. A right-hand rule with a Cardan rotational sequence (X-y-z) was used for the 3D angular computations and a right hand rule was used to define the conventions of angular kinematic and kinetic variables. Kinematics and GRF data were filtered using a fourth-order Butterworth low-pass filter at cut off frequencies of 8 Hz and 50 Hz respectively. For joint moment calculations, both kinematic and GRF data were both filtered with the same cut-off frequency of 8 Hz (99, 100).

A mixed model analysis of variance (ANOVA) was performed to detect differences between the replaced limb, non-replaced limb of TKA patients and the right limb of controls on the second step of stair ascent (69) (SAS 9.3, SAS Institute Inc. Car, NC). Because two of the conditions were measured on the same participant, it was necessary to consider the effect of correlations on the residuals between the replaced and non-replaced limb of TKA patients. Statistical models were run on the data, with and without correlation, and correlation was included between the replaced and the non-replaced limb when the log likelihood test was significant (a reduction of at least 5 points between the two statistical models) (69). When the ANOVA revealed a significant main effect, post-hoc comparisons with Bonferroni adjustments were utilized to compare means between conditions ($p<0.05$). In addition, differences of demographics between the two participant groups were determined using the independent sample t-test.

Results

There were no differences of age, height, mass, and BMI between TKA and control participants (Table 11). For the functional tests, controls had greater passive knee ROM than both the replaced ($p=0.0003$) and non-replaced knees ($p=0.028$) of TKA patients. The non-replaced knee had greater passive ROM than the replaced knee ($p=0.0099$). There were no differences for the TUG between groups, though TKA patients took longer to ascend ($p=0.0358$) and descend ($p=0.0293$) stairs compared with controls. However, there were no differences in ascent velocity or GRF variables between groups during the stair ascent biomechanics test.

At the knee, the control limb was more flexed at contact compared with both the replaced ($p= 0.033$) and non-replaced ($p=0.0078$) limbs of TKA patients (Table 12). The loading response peak knee extension moment of the control limb and the non-replaced limb of TKA patients was greater than the replaced limb of TKA patients ($p=0.0006$ and 0.045 respectively, Figure 10a). The push-off peak abduction moment was smaller in the control limb compared with the replaced limb of TKA patients ($p=0.0177$, Figure 10b).

The hip was more flexed at contact in the replaced limb of TKA patients when compared with the non-replaced ($p=0.0046$) and control limbs ($p=0.0169$, Table 13). The ankle had a greater peak eversion angle in the control limb ($p=0.006$) and the non-replaced limb ($p<0.0001$) of TKA patients compared with the replaced limb.

Differences of frontal plane joint moments were apparent for the ankle and the hip among the three limbs (Table 13). The loading response peak inversion moment was greater in the control limb compared to both the replaced ($p<0.0001$) and the non-replaced ($p=0.0241$) limb of TKA patients. It was also greater for the non-replaced limb compared with the replaced limb of TKA patients ($p=0.0374$). The push-off peak inversion moment was greater in the control limb (p=0.0004) and the non-replaced limb (p=0.0159) compared with the replaced limb. The loading response peak hip abduction moment was smaller in the control limb compared with the replaced limb (p=0.0203) while the push-off peak hip abduction moment of the control limb was smaller than both the replaced (p=0.0017) and the non-replaced limbs (p=0.0426).

Discussion

The purpose of this study was to compare lower-limb biomechanics of the replaced limb to the non-replaced limb of TKA patients and the control limb of healthy participants during stair ascent. We hypothesized there would be no differences in the sagittal plane variables between the replaced and the non-replaced limbs, but that both would be different compared to the control limb. For the ankle and hip, we expected to see similarities in sagittal plane variables among all limbs.

The replaced limb of TKA patients had reductions in the loading response peak knee extension moment compared to the control limb, and the push-off peak knee extension moment was also smaller but not significantly different. These findings suggest that the deficits of the replaced limb in TKA patients is greater during the first half of the stance phase and is apparent compared to both control and non-replaced knees. Peak plantarflexion moments at the ankle are also important for raising the center of gravity (COG) during stair ascent. There were no differences in either of the peak plantarflexion moments between replaced and control limbs. In addition, the hip push-off peak flexion moment was not different for replaced and control limbs. These results suggest that the TKA patients did not compensate for knee deficits by increasing ankle or hip moments. These findings support our hypothesis and show that in the sagittal plane, deficits are apparent in the replaced limb of TKA patients compared to a control limb.

Similar differences in the extension moment between replaced and control knees have been reported in previous studies (16, 23, 36, 72). Most often these differences are attributed to a quad avoidance gait as a result of weaker quadriceps contraction that is seen in many unstable and injured knees (8, 72). It is well understood that TKA patients experience a reduction in quadriceps muscle strength following surgery, leading to reduction in knee extension moments. Greater emphasis on restoring quadriceps strength via rehabilitation may aid in restoring knee extensor strength and knee extension moments.

The loading response peak knee extension moment was also reduced in the replaced knee compared to the non-replaced knee. No other differences were observed for sagittal plane ankle or hip moments. Only one previous study has compared knee extension moments between the replaced and non-replaced limb of TKA patients, and they reported no difference between the two limbs (54). The findings in this study suggest that there were differences between the replaced and non-replaced knees in TKA patients. Both peak knee extension moments were comparable in the non-replaced limb and a control limb. In addition, no differences were observed in any of the ankle or hip sagittal plane moments. The non-replaced limb of TKA patients in this study is more similar to the control limb than the replaced limb. To our knowledge, this study was the first to compare the non-replace knee to a control knee during stair ascent.

When investigating knee extension moments, it is also important to consider effects of walking velocity on GRF, which is closely related to knee extension moments. The TKA patients in this study ascended the stairs at similar velocities compared to controls and also had similar values of GRF variables. This finding is in contrast to other studies, which have reported reductions in stair ascent velocities in TKA patients compared to controls (16, 23, 36, 72). The similar ascent velocities of the TKA patients and controls in this study suggest a very high level of recovery of TKA patients following surgery. TKA patients ascended the stairs at 0.67 m/s, while the fastest mean ascent velocity reported in previous literature was 0.52 m/s (72). Thus, the differences in loading response peak knee extension moment for TKA patients in this study cannot be explained by differences in ascent velocities or GRF's alone between the groups. These results further demonstrate the deficits of replaced knees shown in those TKA patients even when they were able to ascend stairs at similar velocities compared to controls. Similar ascent velocities may also help to explain our finding of comparable knee extension moments in the non-replaced limb and control limb, both of which were elevated compared to the replaced limb. TKA patients in this study may have compensated for deficits in the replaced knee by elevating knee extension moments in the non-replaced limb to levels similar to a control limb in order to achieve similar ascent velocities. Thus, instead of compensating at the ankle and hip of the replaced limb, they might have compensated by elevating knee extension moments of the non-replaced limb.

During stair ascent, the lower limb must rise to achieve placement on the subsequent step. During the stance phase, the contact angles of the knee and hip provide useful information regarding how this placement is achieved in TKA limbs compared to control limbs. The knee contact angle is often reported in TKA populations and has been shown to be reduced compared with control limbs (16, 23, 36, 72). Similar results were observed in this study, TKA patients had reduced knee flexion at contact in the replaced limb compared to controls. Hip flexion contact angle provides useful information regarding compensatory strategies for TKA patients. In order to compensate for the deficits due to the reduced flexion of the replaced knee, TKA patients flexed the hip more at initial contact in order to be able to elevate their COG during ascent, compared to the control limb. The deficits associated with the stiffer knee contact angle may cause a reduced moment arm for the knee extensors in generating knee extension moment and therefore provides further support for the deficit associated with reduced knee extension moment of the replaced knee during loading response. To our knowledge, this study may be the first that reported greater hip flexion contact angles of TKA patients compared to controls during stair ascent.

No differences were observed for knee contact angle between the replaced and non-replaced limbs. The hip contact flexion angle was, however, increased in the replaced limb compared to the non-replaced. Only Kelman et al. (60) compared sagittal plane angles of replaced and non-replaced limbs during stair ascent and reported no differences between the two groups. More studies are needed to depict a more comprehensive picture of these variables between replaced and non-replaced knees. Additionally, the non-replaced knee had a reduced contact angle compared to a control limb, while the hip contact angle was similar between the two groups. This finding suggests that the non-replaced knee is stiffer at contact compared to control knees, and compares better to the replaced limb.

We also anticipated observing differences in frontal plane knee variables between the non-replaced and the control limb, and similarities between the replaced and the control limb. The current study showed no differences for the loading response peak knee abduction moment among the groups. However, TKA participants in this study showed an elevated push-off peak knee abduction moment in only the replaced limb compared with controls. Additionally, there were no differences between groups for peak frontal plane knee angles. Therefore, our hypothesis about frontal variables was only partially supported. Knee abduction moments have been shown to be a good surrogate measure for knee joint loading and play a role in progression and severity of medial compartment knee OA (12, 51, 88). These findings suggest that TKA patients have elevated knee loading following joint arthroplasty. In addition, frontal plane knee variables play an important role in stability and propulsion in stair ascent (7, 91), thus TKA patients may be placing increased load on the replaced limb as a means to increase stability in the frontal plane during push-off. Other studies have reported similar results for loading response peak knee abduction moments when comparing TKA patients and controls during stair ascent (23, 36). The elevated push-off peak knee abduction moment in the replaced limb compared to control limbs was in contrast to previous literature which showed that the replaced limb of TKA patients had similar or reduced internal knee abduction moments compared to control limbs (23, 36, 73). However, TKA patients in this study were able to ascend the stairs at similar velocities as controls. Thus, reductions in the internal abduction knee moment values may have been a result of a reduced stair ascent velocity in previous studies. This study is the first that has shown similar stair walking velocities between TKA patients and controls, and also found an elevated push-off peak knee abduction moment of the non-replaced knee of TKA patients, suggesting that the TKA patients in this study showed some compensation in the replaced knee compared to control knees.

Few studies have analyzed frontal plane hip joint mechanics in patients following TKA. In support of our hypothesis, both peak hip abduction moments in this study were higher in the replaced limb of TKA patients compared to the non-replaced and control limbs. The push-off peak hip abduction moment was also higher in the non-replaced limb compared to the control limb. Frontal plane variables at the hip play a key role in stability and propulsion during stair ascent (7, 91). TKA patients may need to rely on the hip joint even more than control patients during stair ascent as a means to compensate for deficits at the knee joint. The reduction in the loading response peak knee extension moment and frontal plane ankle moments further suggest the importance of greater hip abduction moments to aid in stair ascent. Nadeau et al. (91) suggested that during stair ascent lateral elevation of the hip is necessary to avoid the intermediate step in stair walking and that future studies should investigate frontal plane hip variables in both healthy and pathological populations. Only one other study has reported these variables in TKA patients, and they found no differences in frontal plane hip moments (114). Results from this study suggest that TKA patients used the hip joint more for stability and propulsion than their healthy control counterparts. This result may also be a compensatory mechanism for instability and weakness in the distal knee joint. This potential compensation is of concern from a clinical standpoint as it may lead to further problems at the hip joint, including overload and fatigue which may lead to increased risks for future joint degeneration.

Clinical functional tests can be very beneficial in understanding recovery following orthopedic procedures. When paired with detailed biomechanical assessments, these tests can provide clinicians with the ability to relate them to more detailed and specific biomechanical deficits. In the current study, controls had the greatest passive knee ROM, followed by the non-replaced limb of TKA patients, with the replaced limb of TKA patients having the least ROM. There were no differences in TUG test times between TKA patients and controls. However, during the stair ascent and descent tests, the TKA patients took more time to ascend and descend the 11-step staircase compared to controls during the functional stair test. This finding shows the benefit of more demanding clinical tests in order to bring to light differences that may otherwise be masked between groups. Previous research is lacking when it comes to pairing clinical tests with biomechanical gait assessments, and it has been suggested that studies employing both types of testing could expand the current understanding of recovery following TKA (120). One previous study included clinical tests with biomechanical assessments, but did not include any clinical tests on stairs (98). More demanding clinical tests can provide general deficits, though detailed biomechanical gait analysis can further pinpoint specific deficits.

The sample size of TKA patients in this study is relatively low, but was similar and even greater than several previous studies (16, 23, 36, 54). However all TKA patients in this study had posterior stabilized designed arthroplasty surgeries that were performed by the same surgeon, which may be considered as a strength of this study.

Conclusion

In conclusion, it is apparent that even in TKA patients who have good recovery, there are biomechanical deficits during stair ascent. These deficits include reduced knee extension moment in the replaced limb compared to non-replaced and control limbs, and reduced knee flexion at contact in both the replaced and non-replaced limb compared to a control limb. Additionally, the replaced limb had increased frontal plane knee and hip moments compared to a control limb and the non-replaced limb saw similar differences compared to the control limb. These differences were observed at similar ascent velocities between groups, suggesting there are still apparent biomechanical deficits in the replaced limb and compensation in the non-replaced limb. More studies analyzing these movements are needed in order to better understand the causes of these deficits and how rehabilitation strategies can be targeted to restore more normal stair ascent patterns following joint arthroplasty surgery.

Chapter VI Appendix: Tables and Figure

Table 11. Demographic data for participants: Mean ± STD.

	Total Knee Replacement	Controls
Subjects	13	15
Age (Years)	65.6±6.7	62.3±7.5
Height (Meters)	1.79±0.1	1.79±0.1
Mass (Kg)	90.2±9.9	87.2±14
BMI (Kg/m^2)	28.3±3.4	27.1±3.2
Time From Surgery (Months)	24.5±14	N/A
TUG (Sec)	7.1±1.2	6.8±1.2
Functional Ascent Time (Sec)	6.44±0.94	5.65±0.95^{+}
Functional Descent Time (Sec)	6.06±0.93	5.18±1.1^{+}
Testing Ascent Velocity (m/s)	0.67±0.12	0.77±0.18
Passive Knee ROM	Rep: 111.1± 13.9$^{*\wedge}$ NR: 119.5±16.7$^{\wedge}$	131.9±10

$^{+}$Denotes significant difference between groups, *Denotes significant difference from the non-replaced limb (NR), ^Denotes significant difference from control limb.

Table 12. GRF and Knee variables during stair ascent: Mean ± STD.

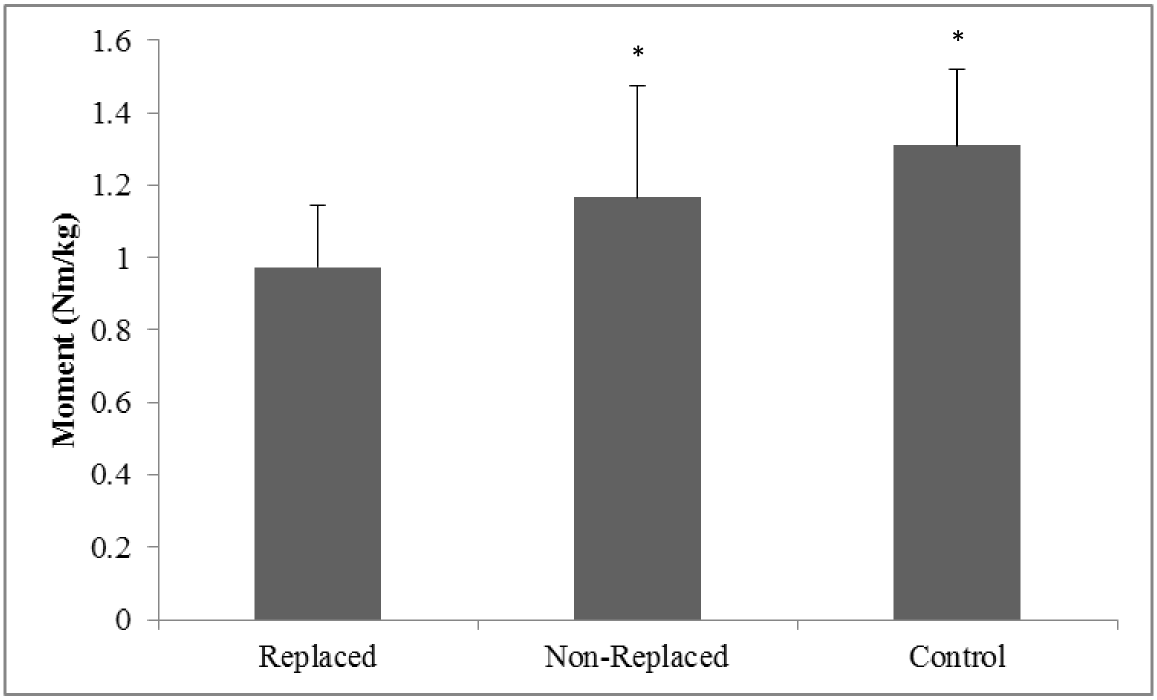
Variables	Replaced	Non-Replaced	Control
Loading Response Peak Vertical Ground Reaction Force (BW)	0.99±0.02	1.01±0.02	1.03±0.03
Push-Off Peak Vertical Ground Reaction Force (BW)	1.14± 0.02	1.19±0.02	1.12±0.03
Knee Contact Flexion Angle (Deg)	65.9±3.5$^{\wedge}$	65.1±2.7$^{\wedge}$	68.9±4.0
Knee Extension ROM (Deg)	55.1±5.4	56.2±5.4	55.8±5.6
Push-Off Peak Knee Extension Moment (Nm/kg)	0.37±0.27	0.35±0.30	0.49±0.33
Minimum Knee Ab/Adduction Angle (Deg)	-1.22±3.5	-1.8±5.7	-0.54±4.9
Loading Response Peak Knee Abduction Moment (Nm/kg)	-0.36±0.16	-0.31±0.14	-0.26±0.16

*Denotes significant difference from the non-replaced limb, ^denotes significant difference from control limb.

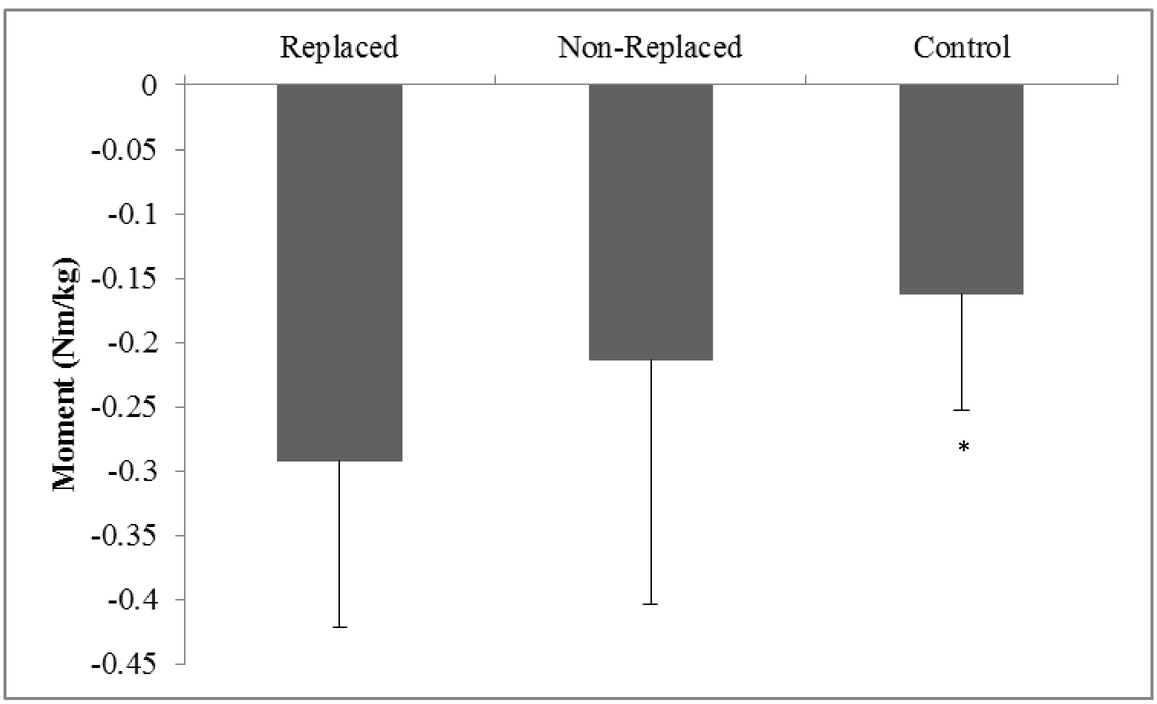
Table 13. Ankle and Hip variables during stair ascent: Mean ± STD.

	Variables	Replaced	Non-Replaced	Control
Ankle	Ankle Contact Angle (Deg)	12.5±5.4	12.9±5.5	17.3±6.9
	Ankle Plantar Flexion ROM (Deg)	31.8±8.6	33.2±8.4	33.7±8.6
	Loading Response Peak Plantar Flexion Moment (Nm/kg)	-0.52±0.12	-0.56±0.18	-0.65±0.25
	Push-Off Peak Plantar Flexion Moment (Nm/kg)	-1.08±0.08	-1.14±0.17	-1.12±0.14
	Peak Eversion Angle (Deg)	-8.17±4.4*^	-12.1±4.4	-12.9±4.4
	Loading Response Peak Inversion Moment (Nm/kg)	0.12±0.11*^	0.22±0.13^	0.33±0.11
	Push-Off Peak Inversion Moment (Nm/kg)	0.11±0.13*^	0.24±0.15	0.32±0.12
Hip	Hip Contact Angle (Deg)	61.1±4.3*^	59.0±5.2	55.9±6.2
	Hip Extension ROM (Deg)	49.7±3.7	49.1±3.6	49.3±3.9
	Peak Hip Flexion Moment (Nm/kg)	0.42±0.22	0.38±0.17	0.44±0.16
	Peak Hip Adduction Angle (Deg)	7.22±4.2	8.33±6.2	9.45±4.7
	Loading Response Peak Hip Abduction Moment (Nm/kg)	-0.87±0.22^	-0.78±0.24	-0.68±0.19
	Push-Off Peak Hip Abduction Moment (Nm/kg)	-0.72±0.22^	-0.62±0.29^	-0.46±0.12

*Denotes significant difference from non-replaced limb, ^denotes significant difference from control limb.



a)



b)

Figure 10. a) Loading response peak knee extension moment and b) Push-off peak knee abduction moment. *Denotes significant difference from replaced limb.

CHAPTER VII

PRINCIPAL COMPONENT ANALYSIS OF KNEE BIOMECHANICS IN TOTAL KNEE REPLACEMENT AND HEALTHY CONTROLS DURING STAIR ASCENT

Abstract

Total knee replacement (TKR) is a common surgery performed. Stair ascent presents a challenge to recovery of functional capacity after TKR. Principal component analysis (PCA) is a statistical technique that is useful for detecting detailed characteristics of waveforms during gait. Comprehensive understanding of sagittal, frontal, and transverse plane kinematics and kinetics throughout the stance phase of stair ascent is necessary for clinicians and researchers. The purpose of this study was to use PCA to compare waveforms of knee biomechanics in the sagittal, frontal, and transverse planes between TKR patients and healthy controls. Thirteen TKR patients and fifteen controls completed trials of stair ascent on a 3-step instrumented staircase. Retained principal components (PC) waveforms were analyzed. PC scores were compared between groups using independent sample t-test ($p<0.05$). PC scores were significantly different between groups and showed that TKR patients had less flexed knees throughout stance, especially at midstance, increased frontal plane knee ROM and less external rotation. In addition, TKR patients had reductions in knee extension moment during loading response, midstance and early push-off, but had elevated moments in frontal and transverse planes during the similar time frames. Findings suggest that TKR patients are compensating for deficits in the sagittal plane by increasing demands placed upon the knee joint in the frontal and transverse planes. These findings may suggest increased risks of compartment wear and tear and also the need for rehabilitation targeting muscles surrounding the knee that contribute to frontal and transverse plane motions.

Key words: TKA, stair ambulation, PCA, transverse plane

Introduction

Total knee replacement (TKR) patients represent a significant clinical population. In 2010, the CDC reported the number of TKR surgeries to be over 700,000 at an estimated cost of 11.3 billion dollars (92) though the total number of TKR surgeries is increasing and expected to reach 3.5 million a year in the United States by 2030 (65). TKR patients have reported having at least some limitations in performing functional activities following a TKR surgery (94) in addition to decreased performance on clinical tests for TKR groups compared to healthy controls (19, 98). Thus recovery appears to be incomplete and more research aimed at detecting differences in TKR patients and healthy controls is important. Following TKR, the ability to climb stairs is an important activity that is assessed in all of the most common knee scoring tools post-surgery (30, 52, 115). Deficits may become more apparent in more demanding gait-related activities such as stair climbing (91, 100).

Biomechanics of stair ascent following TKR has been studied previously using discrete analysis from waveforms of knee flexion angle (16, 23, 36, 54, 72), knee extension moment(16, 23, 36, 54, 72, 119), knee ab/adduction angle (16, 23, 36, 73) and knee ab/adduction moment (16, 23, 36, 73). These studies found a reduced knee flexion at contact (16, 24, 72) and reduced peak knee extension moment(16, 24, 72) in TKR patients compared to controls. Additionally, it was shown that peak internal knee abduction moments were similar between TKR patients and controls (16, 24). These studies provide comparisons between TKR and healthy populations, using only a few key discrete data points on these waveforms, additionally comparing clinical populations during a stair walking task using discrete analysis may at times be difficult due to variability in waveforms. If discrete peaks are not present in curves, or occurring at various times, this analysis may not be adequate to reflect differences between these groups.

Principal component analysis (PCA) is a multivariate statistical technique that is utilized to analyze large data sets. The main purpose of PCA is to extract the information that is the most important to the data (2, 31, 108). Instead of analyzing only discrete data points, PCA can compare entire waveforms for overall patterns and magnitudes. Instead of only being able to compare biomechanics of stair ascent at contact and peak values, PCA can compare waveforms throughout the gait cycle and provide more information regarding biomechanical differences in clinical populations. Though less often utilized in biomechanical research, PCA has been used to study gait and running (27, 38) and at times in patient groups with knee OA (10, 31) and in total knee replacement (TKR) patients (45, 74), and has been shown to be an effective tool in the reduction and interpretation of gait waveform data (31). This type of analysis is especially effective for clinical populations that may have more variable waveform data (29).Chau et al. (26) provided an example of the difficulty comparing able bodied gait to gait of clinical subjects and suggested that at times these can lead to the unclear choice of discrete points which is a common pitfall of comparing clinical gait on the basis of specific landmarks in waveforms.

To our knowledge only one study has utilized PCA to compare stair gait in patients following TKR (74). Mandeville et al. (74) utilized PCA on level walking and stair gait in patients pre- and post TKR in order to rank patient dysfunction both prior to and following surgery. PCA was used to extract principal components (PCs) that were then entered into a discriminant function analysis as a means to predict level of recovery. They measured the moment of support, ankle moment and knee flexion angle during stair ascent and found that together they represented a stair dysfunction sufficient to detect differences between end stage knee osteoarthritis and healthy controls. However, they did not utilize PCA to compare waveforms between TKR patients and healthy controls. In addition the study only examined sagittal plane variables.

There are currently no studies that utilize PCA to compare waveforms of knee variables in the frontal or transverse planes during stair ascent in the literature. Frontal plane variables play a role in the progression of medial compartment knee OA (12, 51, 88) and have been shown to be important for both propulsion and mediolateral stability during stair ascent (7, 91). Kabada et al. (57) suggested that physiological variability in healthy patients during walking was greater in the frontal and transverse planes, with the variability reflected mostly in the transverse plane (37), and that patients with gait disabilities may have even more variability in their gait patterns (37, 57). PCA may be a more appropriate statistical technique when investigating frontal and transverse plane variables in clinical populations.

Therefore, the purpose of this study was to utilize PCA to compare waveforms of common knee biomechanical variables, especially frontal and transverse plane variables, during stair ascent in TKR patients and healthy controls. It was hypothesized that PCA would detect differences between TKR patients and controls for knee flexion angle, knee extension moment and see similarities for peak knee abduction angles and moments. In addition we expected that PCA would be more robust in detecting differences at various time points on the waveform, such as contact, peaks at loading and push-off and midstance, in all planes of motion. Due to the lack of studies, we anticipated no differences of transverse knee angle and moment between the groups.

Methods

Participants

Gait analysis was carried out on thirteen TKR patients following surgery and fifteen controls during stair ascent (Table 1).TKR patients all had received posterior stabilized designs performed by the same surgeon and were between 6 and 72 months post surgery. Standard rehabilitation protocols were prescribed following surgery. Exclusion criteria for both TKR and healthy participants consisted of the following: BMI greater than 35, any additional lower extremity joint replacement, other major lower extremity surgeries, visual conditions affecting gait or balance, women who were pregnant, cardiovascular disease that would preclude participation in aerobic exercise, systemic inflammatory arthritis, and neurologic diseases. All participants had to be able to ascend/descend stairs without the use of a handrail.

Instrumentation

A nine-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain three-dimensional (3D) kinematics during testing. An instrumented 3-step staircase (FP-stairs, American Mechanical Technology Inc., Watertown, MA, USA; 1st, 2nd and 3rd steps) with two additional customized wooden steps (4th and 5th steps) was used in the study. The instrumented staircase, bolted independently to two force platforms (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA), was used to measure the GRF and the moments of forces during stair gait. Each participant was outfitted with reflective markers at various bony landmarks and semi-rigid shells secured to segments (99).

Experimental Procedures

Prior to placement of reflective markers, all participants competed a 3-minute warm-up walking on the treadmill and completed a timed up-and-go test (TUG) and stair ascent and descent test on an 11-step staircase. At the completion of these tests, patients were fitted with markers and completed stair ascent trials at their self-selected velocity. Practice trials were used for familiarization and to determine the preferred ascent velocity and its range (average ± 5%) that was used to control each participant's ascent velocity during the experimental trials using two pairs of photo cells (63501 IR, Lafayette Instrument Inc., IN, USA) and two electronic timers (54035A, Lafayette Instrument Inc., IN, USA). Subjects were required to approach the stairs with at least three steps prior to foot contact on the first step. The second step of stair ascent was used for further analysis with the right limb of healthy patients and the replaced limb of TKR patients. Visual3D (5.0, C-Motion, Inc., Germantown, MD, USA), a biomechanical software, was used to compute the 3D kinematic and kinetic variables. Data were filtered using a fourth-order Butterworth low-pass filter at cut off frequencies of 8 Hz for kinematics and 50 Hz for ground reaction forces (GRF). When calculating joint moments, both 3D kinematic and GRF data filtered at 8 Hz (99, 100). Waveforms of knee joint angles and internal moments in the sagittal, frontal, and transverse plane were utilized for further analysis.

Statistical Analyses

Methodological details of PCA have been explained extensively in the literature (29, 33, 38) and only a summary of the main steps used in this study is provided here. Waveforms of the selected variables were temporally normalized to correspond to 100% of the stance phase on the second step of stair ascent. Following time normalization, each variable was ensemble averaged for each participant, resulting in one waveform for each subject per variable. Six data matrices were constructed, one for each variable of interest, with rows representing time series waveforms for each subject, and columns representing values at each instant on the waveform (61). MATLAB (R2014v, MathWorks, Natick, MA, USA) software was utilized to run six separate PCAs. Output variables from PCA included: normalized eigenvectors as an estimate of the covariance matrix of the data matrix (principal component coefficients), the variation explained by each PC, and the PC scores for each subject calculated as the contribution of each PC loading to each subject's waveform (10). Percent variation explained by each PC was then inspected to decide which PCs should be included for further analysis. In order to determine which PCs to retain, scree plots were analyzed and at least 90% of the variation in the data was explained by the retained PCs (25, 61). The eigenvectors were then plotted across the time normalized gait data and utilized for interpretation of the retained PCs (61). PC scores were returned for all subjects and comparisons of scores between groups were made using an independent sample t-test ($p<0.05$). In addition, differences of participant demographics were determined using the independent sample t-test.

Results

Participant demographics including age, height, weight, and BMI were similar between the two groups (Table 14). Functional test times were similar for the TUG, though the TKR participants took slightly longer to ascend and descend an 11-step staircase. In addition, both TKR patients and healthy controls ascended the stairs with similar velocities during biomechanical stair ascent trials.

Ensemble waveforms of sagittal, frontal, and transverse plane angles and moments for TKR and controls are presented (Figure 11). Two PCs were retained for sagittal, frontal, and transverse plane knee angles accounting for 91.2 %, 90.7% and 95.7% of variation, respectively

(Table 15). For joint moments, two PCs were retained for frontal and transverse plane knee moments accounting for 92.2% and 93% variation, respectively. Finally, three PCs were retained for the sagittal plane knee moment and accounted for 93.5% variation.

Differences in sagittal plane knee angle were observed between TKR and controls for PC1 (Table 16). PC1 had all positive values with a peak occurring just after midstance and represents overall magnitude of knee flexion with focus on magnitude at midstance (Figure 12a) (31). This suggests that TKR patients have less knee flexion during mid-stance compared to controls (Figure 11a). The PC2 had positive values in early stance and negative values at late stance (Figure 12a) and represents the range of motion (ROM) of knee flexion (31). There are no differences of PC2 for TKR patients and controls (Table 16). Furthermore, the scatter plot of sagittal plane knee angle PC scores (Figure 13a) show that there is a separation of TKR and controls on the horizontal axis (PC1) but not the vertical axis (PC2) confirming the group difference in PC1.

The PC1 of frontal plane knee angle was not different between groups (Table 16) and contained all positive values indicating overall magnitude of the frontal plane knee angle (Figure 12b). The lack of difference between groups shows that the frontal plane knee angle was similar between TKR and controls during stance (Figure 11b). The PC2 of frontal plane knee angle was different between groups (Table 16) and contained both positive and negative values at early and late stance (Figure 12b). This PC is an indication of frontal plane knee ROM during stance and shows that TKR patients had more ROM compared to controls (Figure 11b). The scatter plot of the two PC scores for frontal plane knee angle (Figure 13b) show a separation of groups along the vertical axis (PC2) but not the horizontal axis (PC1) further confirming the group difference for PC2.

Both PC1 and PC2 of transverse plane knee angle were significantly different between groups (Table 16). The PC1 had all positive values and represents the magnitude of transverse plane knee angles while PC2 has both negative and positive values and is an indication of the ROM of the knee joint in the transverse plane (Figure 12c). The differences between groups show that TKR patients had less external rotation and overall ROM during stance compared to controls. The scatter plot of PC scores (Figure 13c) shows separations between groups along both the horizontal axis (PC1) and the vertical axis (PC2) as a graphical representation of group differences for both PCs.

For the sagittal plane knee moment, both PC1 and PC2 were significantly different between groups, while PC3 was not different (Table 16). PC1 had all positive values with a peak around midstance and represented the magnitude of the knee extension moment during midstance (Figure 12d), which suggests that the knee extension moment was greater at midstance in controls compared to TKR (Figure 11d). PC2 of sagittal plane knee moment had a very high positive peak coinciding with the loading response peak (Figure 12d) and showed that the controls had greater knee extension moment compared to TKR patients (Figure 11d). The PC3 of sagittal plane knee moment characterized the difference between the average of loading response and push-off peak magnitude (positive values) and midstance magnitude (negative values), which suggested no between group differences prior to the peak loading response and during push-off (Figure 12d). The scatter plot of PC scores for sagittal knee moment (Figure 13d) shows separation between groups along both the horizontal (PC1) and vertical axis (PC2) which again confirms between group differences.

For the frontal plane knee moment, a significant difference was seen between TKR patients and controls for PC1 (Table 16). The PC1 had all positive values with the two peaks

(Figure 12e) corresponding to the knee abduction moment curves (Figure 11e). This suggests that TKR patients had greater knee abduction moment at both loading response and push-off compared to controls. The PC2 had both negative and positive values and represents the amplitude of the knee abduction moment curve (Figure 12e). The scatter plot of PC scores shows apparent separations along the horizontal axis (PC1) suggesting group differences for PC1 (Figure 13e).

The PC1 of transverse plane knee moment has all positive values with peaks at both loading response and push-off suggesting the overall magnitude of the internal rotation moment at these peaks (Figure 12f). Significant differences of PC1 were seen between groups (Table 16) suggesting that TKR patients had a greater internal rotation moment at both loading and push-off. The PC2 has both positive and negative values and represents the amplitude of the internal rotation moment (Figure 12f). The scatter plot for transverse plane knee moment (Figure 13f) shows group separation by the horizontal axis (PC1) but not the vertical (PC2), showing the group differences between TKR and controls.

Discussion

The purpose of this study was to utilize PCA to compare stair ascent in TKR patients and controls. It was hypothesized that PCA would detect differences between TKR patients and controls for knee flexion angle, knee extension moment and see similarities for peak knee abduction angles and moments. In addition we expected that PCA would be more robust in detecting differences at various points on the waveform, such as contact, peaks at loading and push-off in addition to midstance, in all planes of motion. Due to the lack of studies, we anticipated no differences of transverse knee angle and moment between the groups.

In the sagittal plane, TKR patients walked with a less flexed knee during stair ascent, especially around midstance and had reductions in knee extension moment with apparent differences between loading response, midstance and early push-off. These findings supported our hypothesis for these variables using discrete analyses previously reported. Our PCA results also provided additional insight into apparent differences during stance including knee joint angle around midstance, and knee extension moment from loading response to push-off. Previous literature has shown that TKR patients walk with less knee flexion at contact compared to controls (16, 23, 36, 72) and that maximum knee extension moment is also reduced (16, 23, 36, 72). These previous studies have analyzed knee angle at contact and loading response peak knee extension moment. Our PCA showed that knee flexion angle was reduced not only at foot contact, but throughout stance, with large differences exhibited centered around midstance. The lack of differences in knee extension ROM reflected in PC2 of sagittal knee angle, shows that TKR patients' knees are stiffer throughout the gait cycle, but do not differ in extension ROM compared to controls. This similar ROM is not surprising as all subjects have to achieve the same height for the subsequent step which would require similar knee extension ROM during stance. This stiffer knee gait has previously been shown to be a consequence of a quadriceps avoidance gait due to reduced contraction of the quadriceps muscle leading to a reduction in the knee extension moment (15) . The extension moment was reduced in our TKR patients between loading response and early push-off. Thus the stiffer knee gait of TKR patients throughout stance led to reductions in the knee extension moment throughout stance compared to controls. This can partially be explained when considering a stiffer knee would have a joint center that is closer to the GRF vector, which would lead to a decreased moment arm and thus a decreased knee extension moment during stiffer knee gait. Knee extension angle waveforms do not exhibit a peak at midstance and make comparisons by a discrete analysis difficult. The knee extension moment has a minimum at midstance, though this is not often reported in the literature. A previous study from our group using a discrete analysis showed that TKR patients had less flexed knees at contact, similarities in knee extension ROM and reductions in loading response peak knee extension moment compared to controls (121).The findings of the current study not only support these previous findings but also provide additional insight regarding deficiency at midstance for both knee flexion angle and moment. These findings further suggest the presence of a quadriceps avoidance gait occurring not only during loading response but also through midstance and to push-off as a result of weaker quadriceps muscle force that has been hypothesized as a potential explanation to these differences (8, 72).

An additional hypothesis of this study was that PCA would show similarities between groups for the frontal and transverse planes. The findings of this study showed similar frontal plane knee angles between TKR patients and controls, but that ROM in knee abduction is greater in TKR patients. These results partially supported our hypothesis. Contrary to our hypothesis and previous literature, the knee abduction moment was elevated from loading response all the way to push-off, including midstance in TKR participants compared to controls. In support of our hypothesis, the PCA analysis did provide additional details than a discrete analysis, by showing the differences existed throughout stance. Previous literature reports similar maximum knee abduction moment in TKR patients with posterior stabilized designs and controls (16, 23, 36). Our findings were in contrast to previous literature, but the TKR patients in this study ascended stairs with similar velocities as controls, while previous literature have shown significant reductions in TKR ascent velocity compared to controls(16, 23, 36). PCA showed that although peak knee abduction angles were similar between groups, the TKR patients had larger knee abduction ROM which may show frontal plane joint stability is not restored to normal levels. This can be concerning as too much laxity may lead to instability, subluxation and higher stresses and wear (35). Increased frontal plane ROM may also be associated with the elevated levels of knee abduction moment in TKR patients compared to controls. In addition the elevated knee abduction moments in TKR patients suggest greater medial compartment loading (12). The recent discrete analysis from our group showed no differences in maximum ab/adduction knee angles during stair ascent and showed only an elevated peak push-off knee abduction moment but not at loading response for the TKR group compared to controls (121). Typical knee abduction moment curves contain two peaks, one at loading and one at push-off. The average knee abduction moment waveforms in this study for TKR patients contain the traditional double peak, while the controls contain only a peak at early stance. Thus PCA detected elevated knee abduction moment values in TKR patients compared to controls at loading response, midstance, and push-off, and appear to be more robust at detecting differences than a discrete analysis.

Transverse plane knee angles and moments have not been previously reported in TKR patients during stair ascent. Our results showed that the knee of TKR patients were more externally rotated throughout the stance phase and had a reduced ROM compared to controls. In addition, the knee internal rotation moment of TRK patients was greater throughout stance, which was more pronounced at loading response compared to controls. Previous research has utilized PCA on knee rotation moments during level walking in TKR patients and showed that following joint replacement TKR participants had reductions in early stance rotation moment compared to pre-surgery levels (45). The results from this study suggest that internal rotation moments are elevated in TKR compared to controls during stair ascent. This is concerning as previous research has suggested that secondary motions of the knee, such as internal-external rotation can alter the loading to the knee joint (9). Additionally, McEwan et al. (78) reported that rotational movements in the knee increase the wear rate of TKR components. Thus these elevated loadings may be of concern leading more wear and tear of TKR.

It is important to consider how knee joint moments collectively make up the demands placed upon the knee joint during a given task. Waveforms of the sagittal, frontal, and transverse plane moments typically include peaks during the loading response and push-off during stair ascent. This study showed that although TKR patients have a reduction in magnitude of the knee extension moment, they demonstrated concomitant increases in both knee abduction and internal rotation moments compared to controls, especially during the first part of stance. TKR patients in this study ascended the stairs with similar velocities compared to controls and may provide insight into the contrasting findings of knee abduction moment. It appears that the TKR patients are compensating for deficits in the quadriceps function reflected in reduced knee extension moment, by increasing the demands placed upon the knee joint in both the frontal and transverse plane. A recent study from our lab utilizing musculoskeletal modeling reported a reduction in quadriceps muscle force during stair ascent in TKR patients compared to controls (105). Alternatively they reported increases in muscle force of the sartorius, gracilis, short head of the biceps femoris, and the lateral gastrocnemius in the TKR patients compared to controls, providing support of potential roles of these muscles in both frontal and transverse plane knee moments and thus elevated demands in TKR patients. In addition, a previous study from our group examined sagittal and frontal plane biomechanics of the ipsilateral ankle and hip in addition to the contralateral lower limb in this TKR patient group and reported compensation occurring at the ankle, knee and hip of the contralateral limb, as well as a greater demand on the hip joint of the replaced limb during stair ascent (121). Typical rehabilitation programs focus on the quadriceps and to a lesser extent the hamstrings muscles of the replaced limb (5, 22). Other studies report deficits in strength of quadriceps muscle (41, 129) following TKR and improvements in rehabilitation are necessary in order to restore strength to normal levels. The results of this study and others suggest that foci of rehabilitation should be also placed on posterior knee muscles to provide better support of knee and its motions which may be beneficial in relieving the demands placed upon the knee joint of the frontal and transverse planes.

This study reports that even for those TKR patients with good recovery following TKR, by virtue of the ability to climb stairs without a handrail at similar velocities and similar scores on TUG, there are apparent deficits at the knee joint. This has been manifested in this study with reduced knee extension moments and elevated moments in both the knee frontal and transverse planes. Thus compensation appears to occur in the knee frontal and transverse planes. Rehabilitation practices should target all muscles surrounding the knee joint, in addition to muscles acting at the ankle and hip joint in both the replaced and contralateral limb, in order to seek balance of strength and functional capacity to aid in recovery following TKR.

Chapter VII Appendix: Tables and Figure

Table 14. Demographic information between total knee replacement and healthy controls.

	Total Knee Replacement	Controls	P-value
Subjects	13	15	N/A
Age (Years)	65.6±6.7	62.3±7.5	0.23
Height (Meters)	1.79±0.1	1.79±0.1	0.89
Mass (Kg)	90.2±9.9	87.2±14.3	0.53
BMI (Kg/m^2)	28.3±3.4	27.1±3.2	0.33
Time From Surgery (Months)	24.5±14.6	N/A	N/A
TUG (Sec)	7.1±1.2	6.8±1.2	0.51
Functional Ascent Time (Sec)	6.44±0.94	5.65±0.95	**0.04**
Functional Descent Time (Sec)	6.06±0.93	5.18±1.1	**0.03**
Testing Ascent Velocity (m/s)	0.67±0.12	0.77±0.18	0.20

Table15: Percent variation explained by each PC.

Variable	PC1	PC2	PC3	Sum
Sagittal Plane Knee Angle	81.9	9.25	N/A	91.2
Frontal Plane Knee Angle	77.2	13.5	N/A	90.7
Transverse Plane Knee Angle	87.1	8.6	N/A	95.7
Sagittal Plane Knee Moment	53.4	23.4	16.7	93.5
Frontal Plane Knee Moment	79.4	12.8	N/A	92.2
Transverse Plane Knee Moment	82.9	10.1	N/A	93.0

Table 16: PC scores of total knee replacement (TKR) and healthy controls.

Variable	**Retained PC**	**TKR**	**Controls**	**P-value**
Sagittal Plane Knee Angle	1	34.2 ± 61.4	-29.6 ± 45.4	**0.004**
	2	4.1 ± 20.6	-3.55 ± 21.9	0.34
Frontal Plane Knee Angle	1	-0.69 ± 42.6	0.60 ± 34.9	0.93
	2	9.15 ± 12.5	-7.93 ± 14.4	**0.003**
Transverse Plane Knee Angle	1	-29.3 ± 80.4	25.4 ± 48.9	**0.036**
	2	11.3 ± 17.7	-9.79 ± 21.1	**0.0085**
Sagittal Plane Knee Moment	1	-0.96 ±1.36	0.83 ± 1.83	**0.0075**
	2	-0.58 ± 0.87	0.50 ± 1.28	**0.016**
	3	-0.09 ± 0.89	0.08 ±1.16	0.67
Frontal Plane Knee Moment	1	-0.72 ± 1.06	0.63 ± 1.16	**0.0036**
	2	-0.13 ± 0.51	0.11 ± 0.51	0.21
Transverse Plane Knee Moment	1	0.50 ± 0.77	-0.43 ± 0.64	**0.0018**
	2	0.05 ± 0.29	-0.04 ± 0.3	0.41

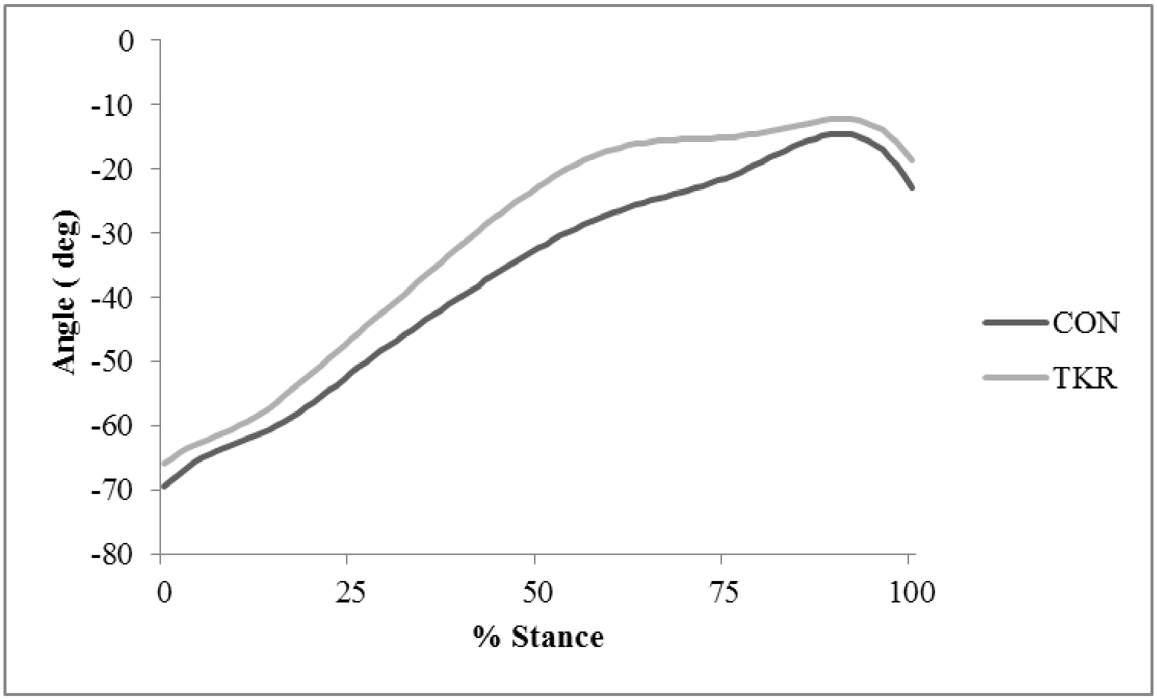


Figure 11a. Comparison of mean sagital knee joint angle for TKR patients (TKR) and healthy controls (CON) during stair ascent.

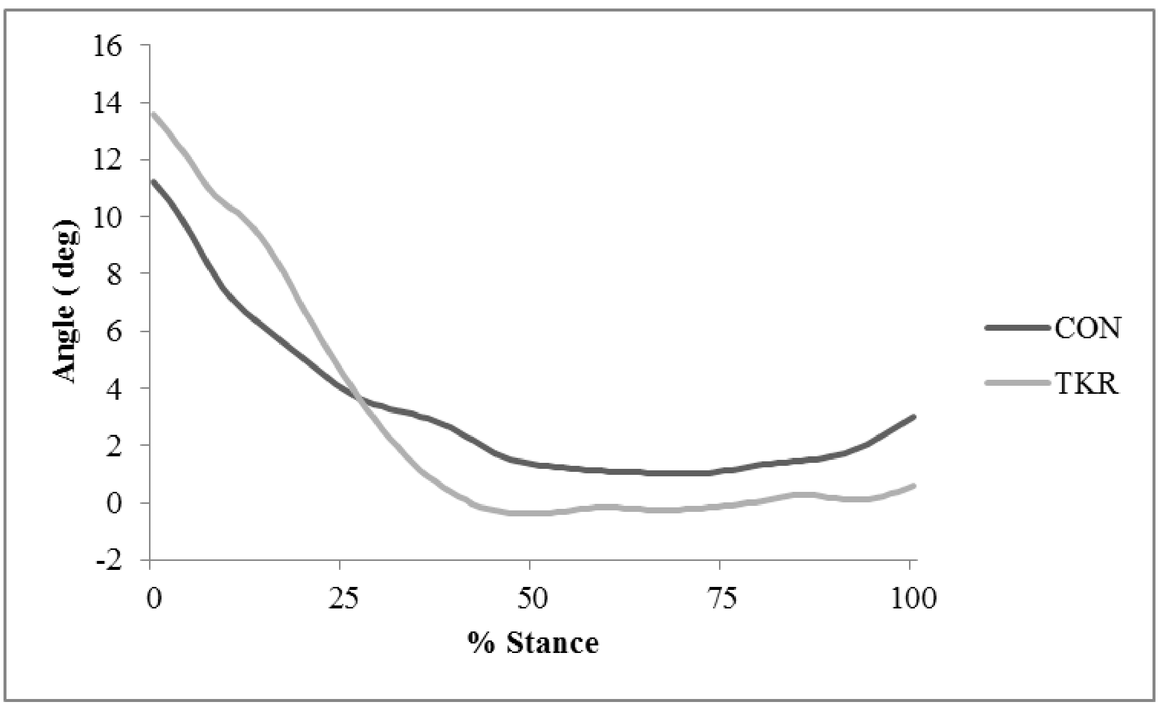


Figure 11b. Comparison of mean frontal knee joint angle for TKR patients (TKR) and healthy controls (CON) during stair ascent.

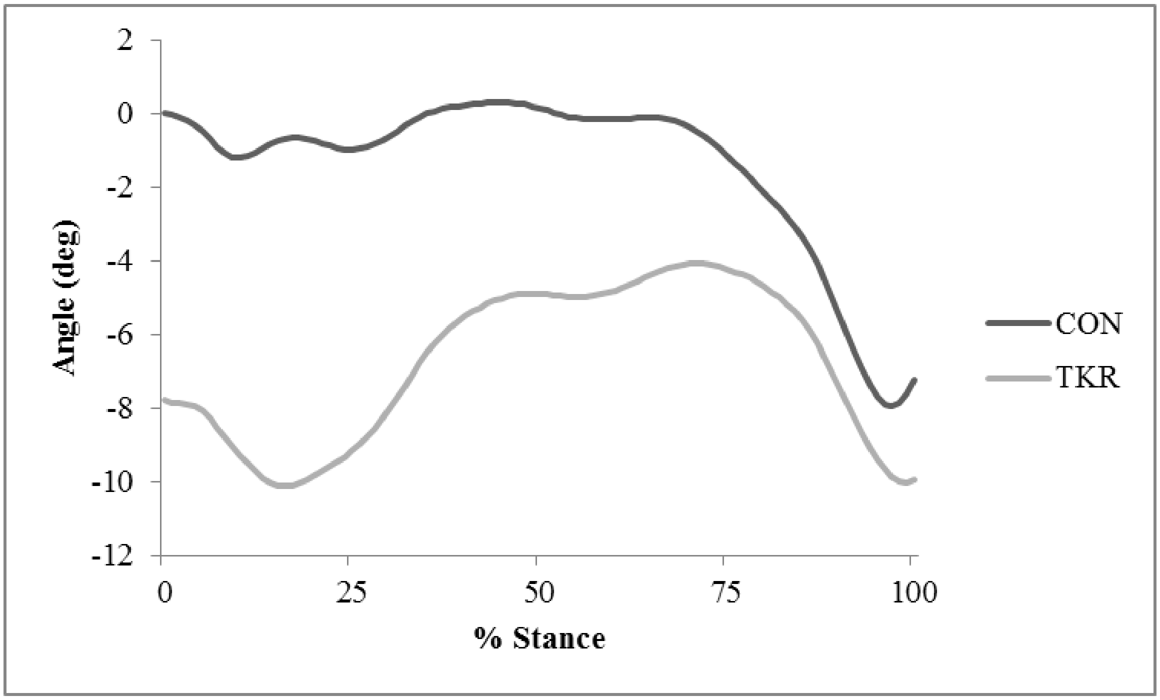


Figure 11c. Comparison of mean transverse knee joint angle for TKR patients (TKR) and healthy controls (CON) during stair ascent.

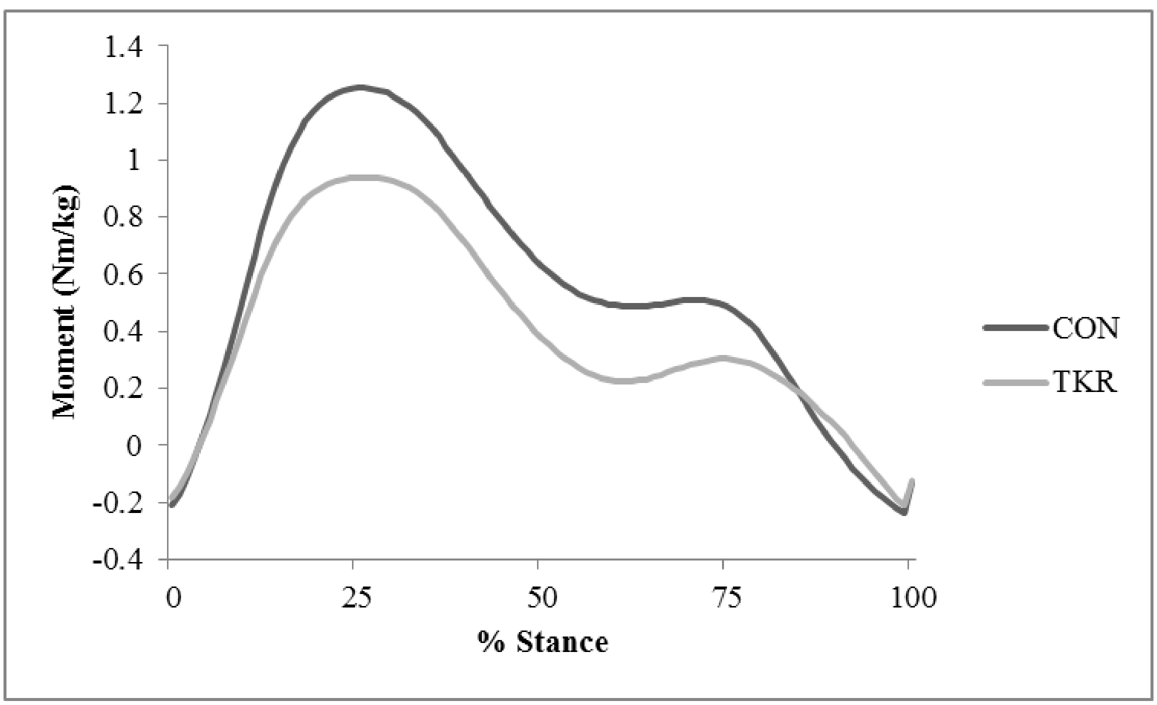


Figure 11d. Comparison of mean sagital knee joint moment for TKR patients (TKR) and healthy controls (CON) during stair ascent.

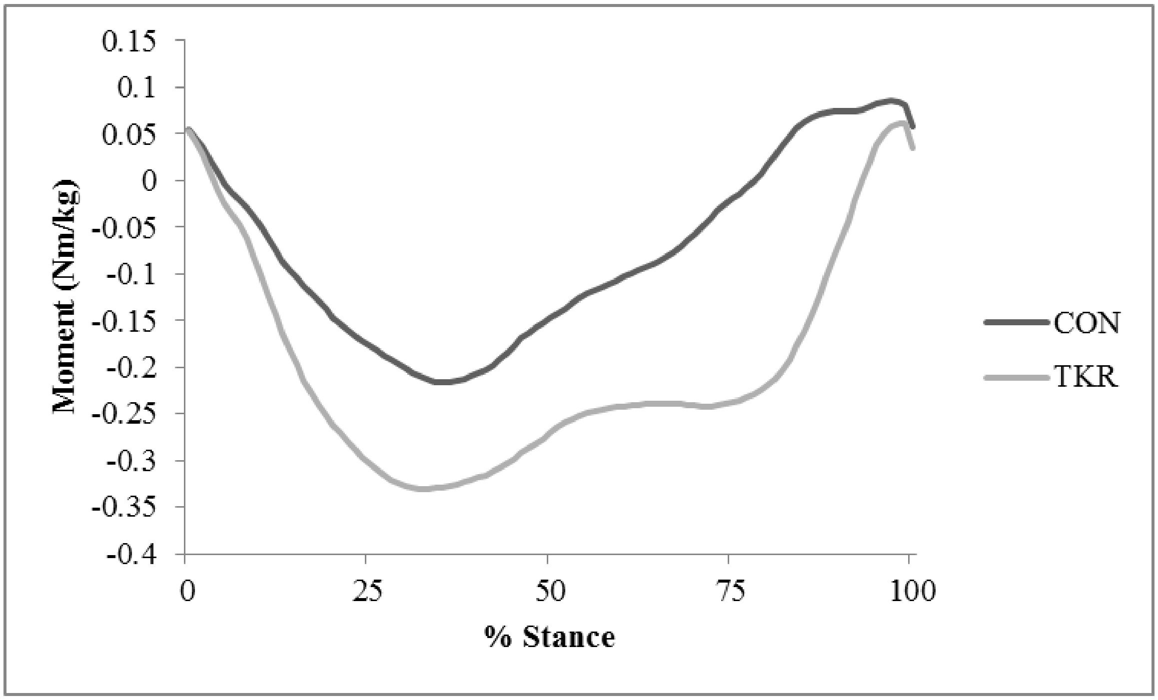


Figure 11e. Comparison of mean frontal knee joint moment for TKR patients (TKR) and healthy controls (CON) during stair ascent.

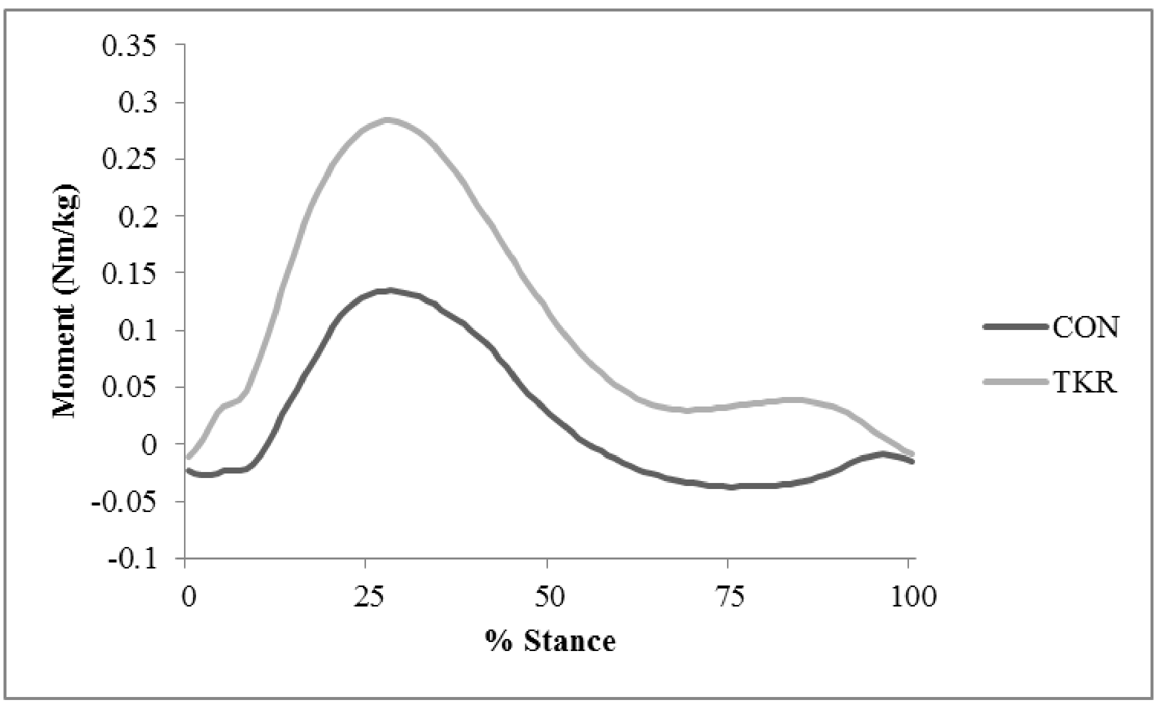


Figure 11f. Comparison of mean transverse knee joint moment for TKR patients (TKR) and healthy controls (CON) during stair ascent.

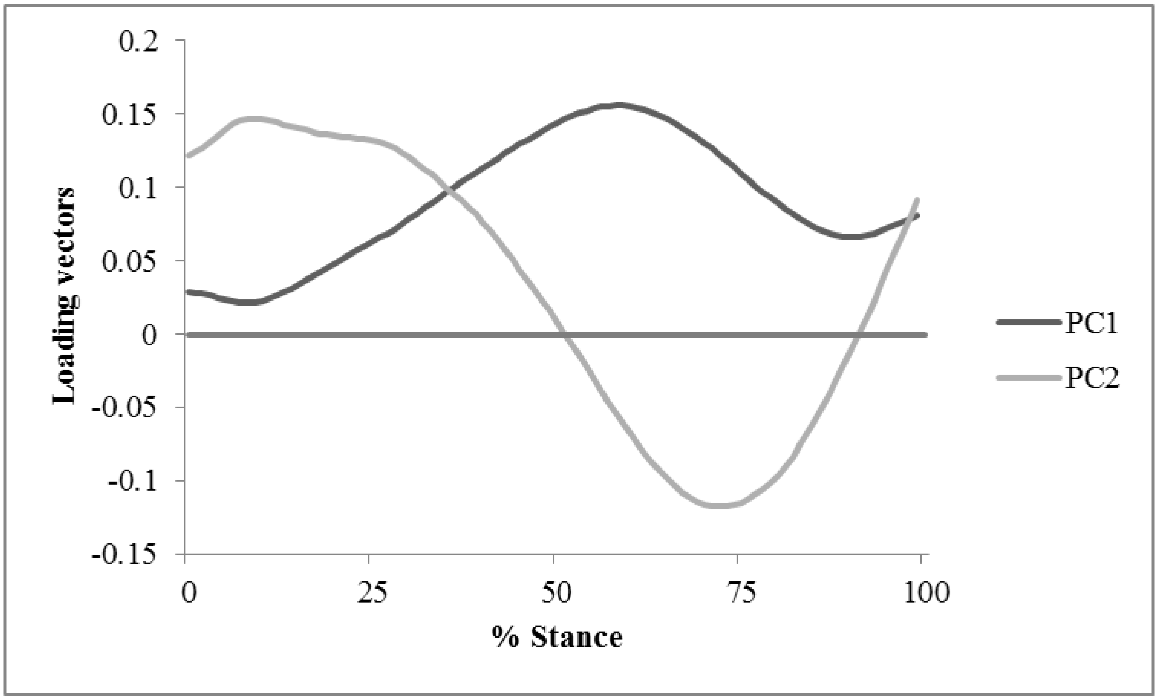


Figure 12a. Loading vectors of the sagittal angle retained principle components (PC) during stance phase.

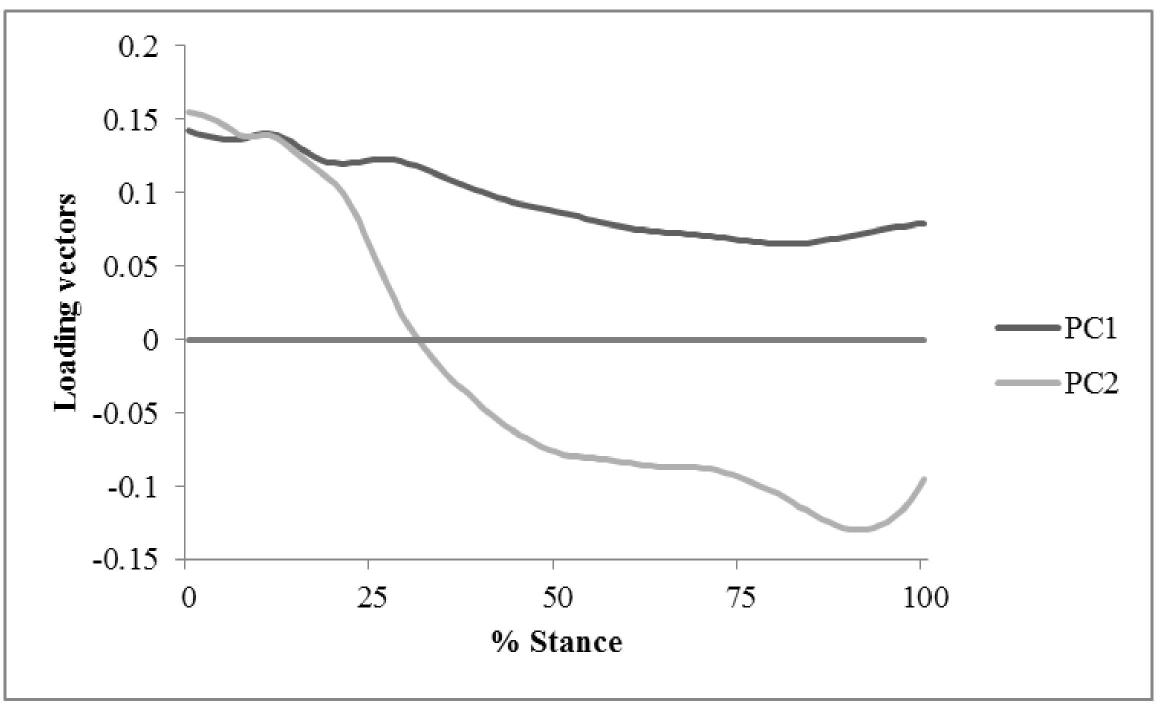


Figure 12b. Loading vectors of the frontal angle retained principle components (PC) during stance phase.

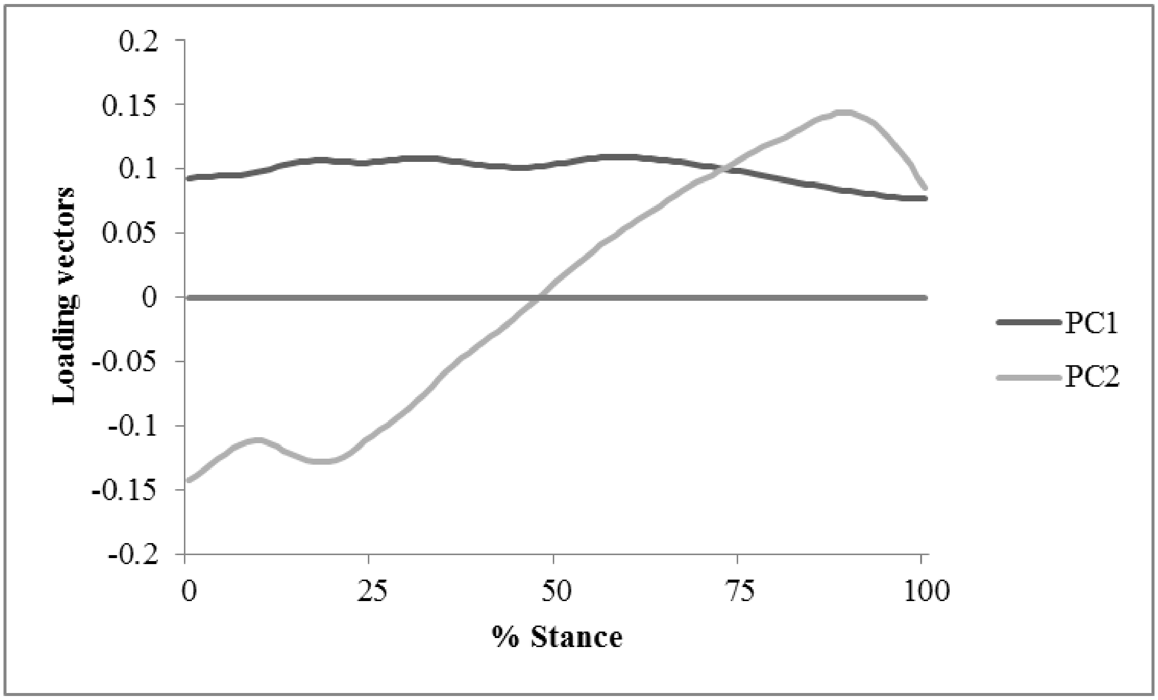


Figure 12c. Loading vectors of the transverse angle retained principle components (PC) during stance phase.

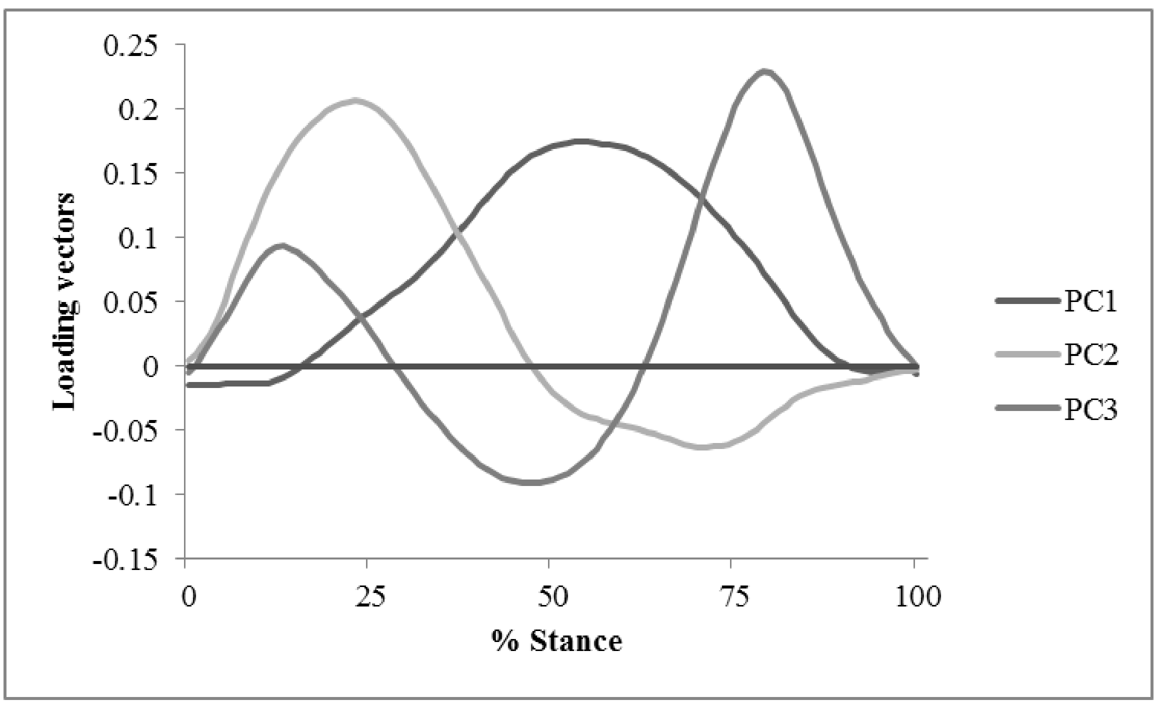


Figure 12d. Loading vectors of the sagittal moment retained principle components (PC) during stance phase.

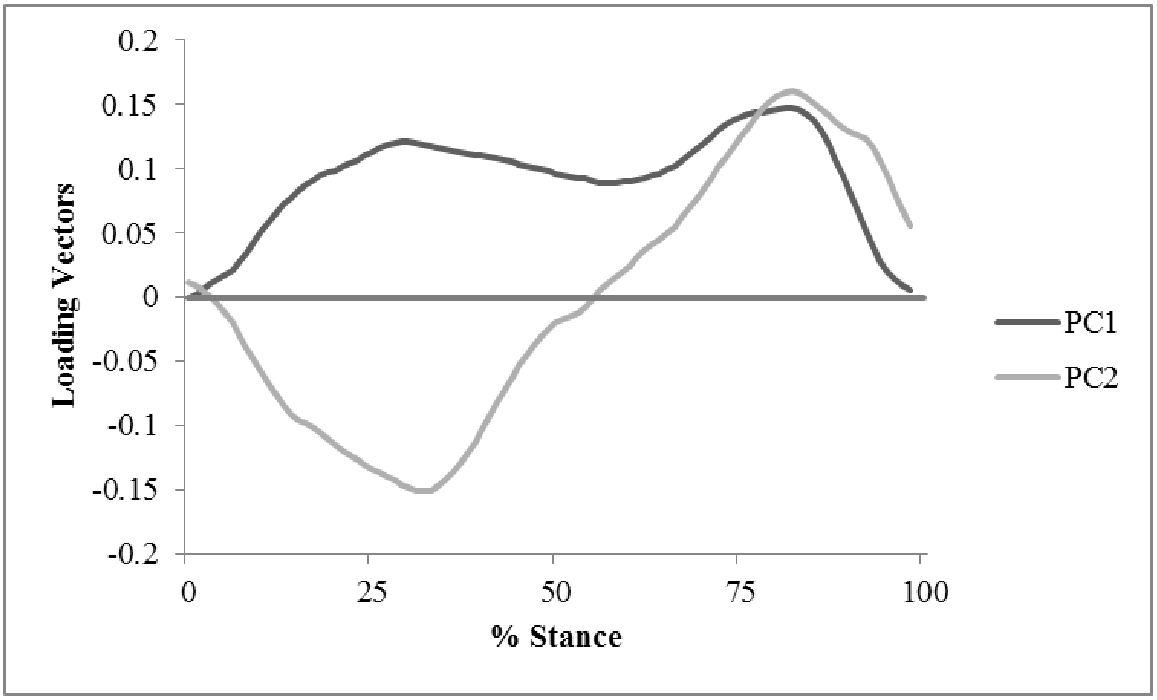


Figure 12e. Loading vectors of the frontal moment retained principle components (PC) during stance phase.

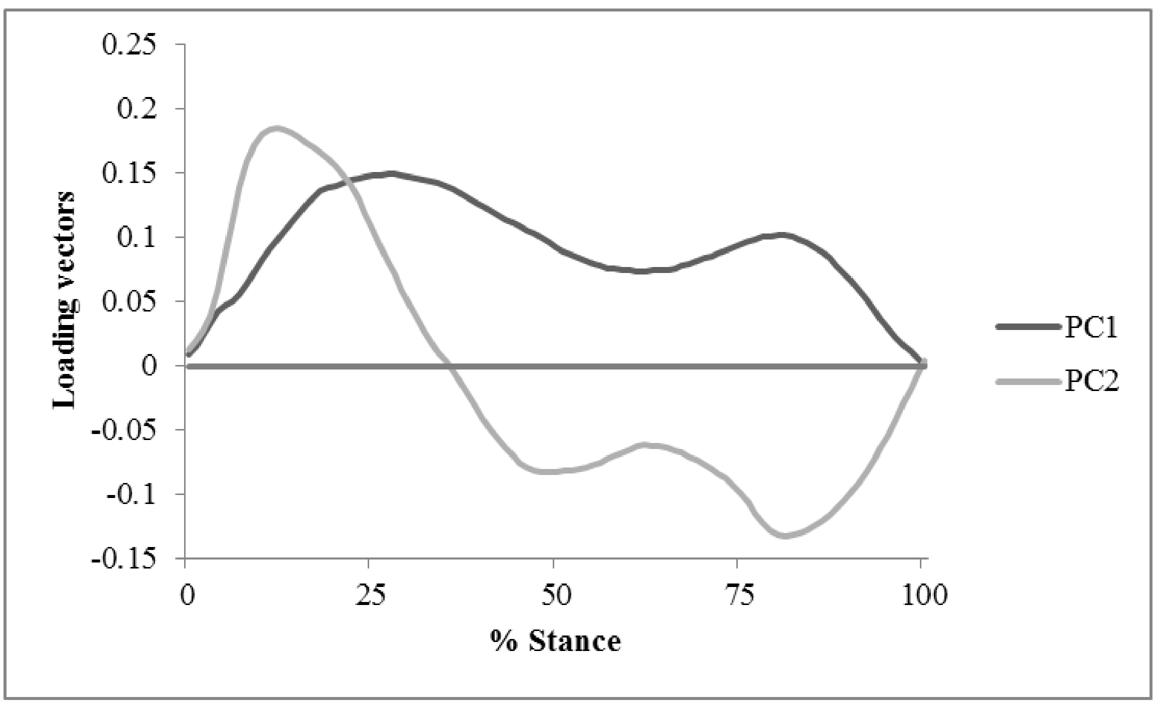


Figure 12f. Loading vectors of the transverse moment retained principle components (PC) during stance phase.

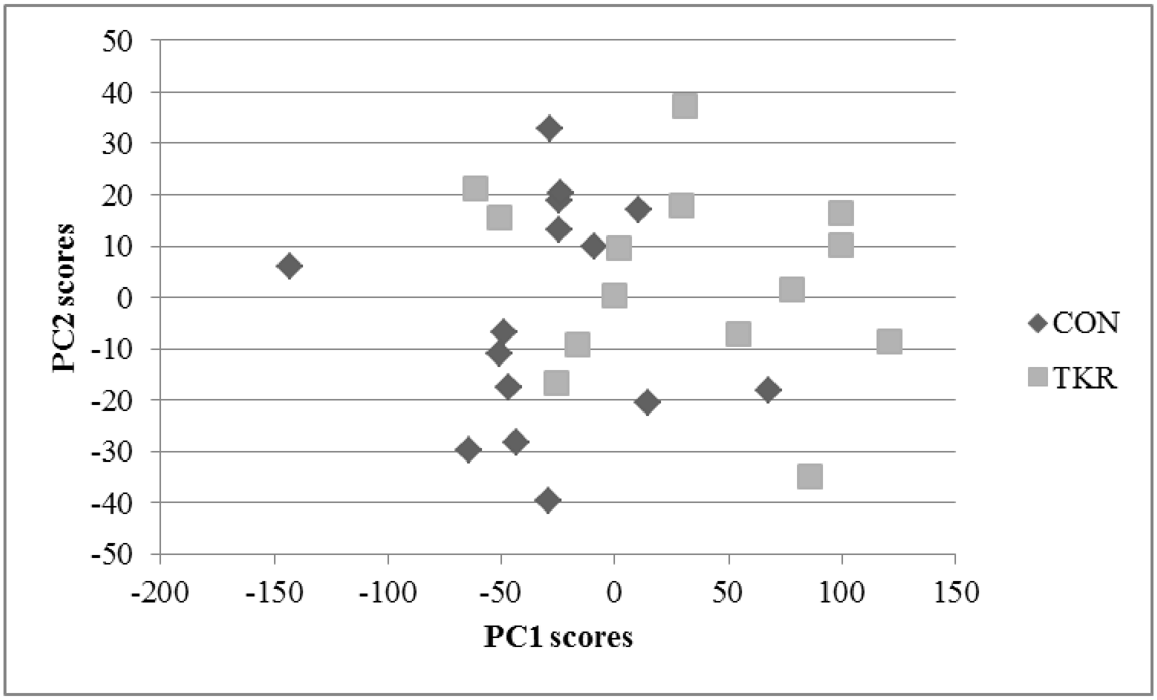


Figure 13a. Principal component scores for sagittal angle PC1 plotted against PC2 by group, total knee replacement (TKR) and control (CON).

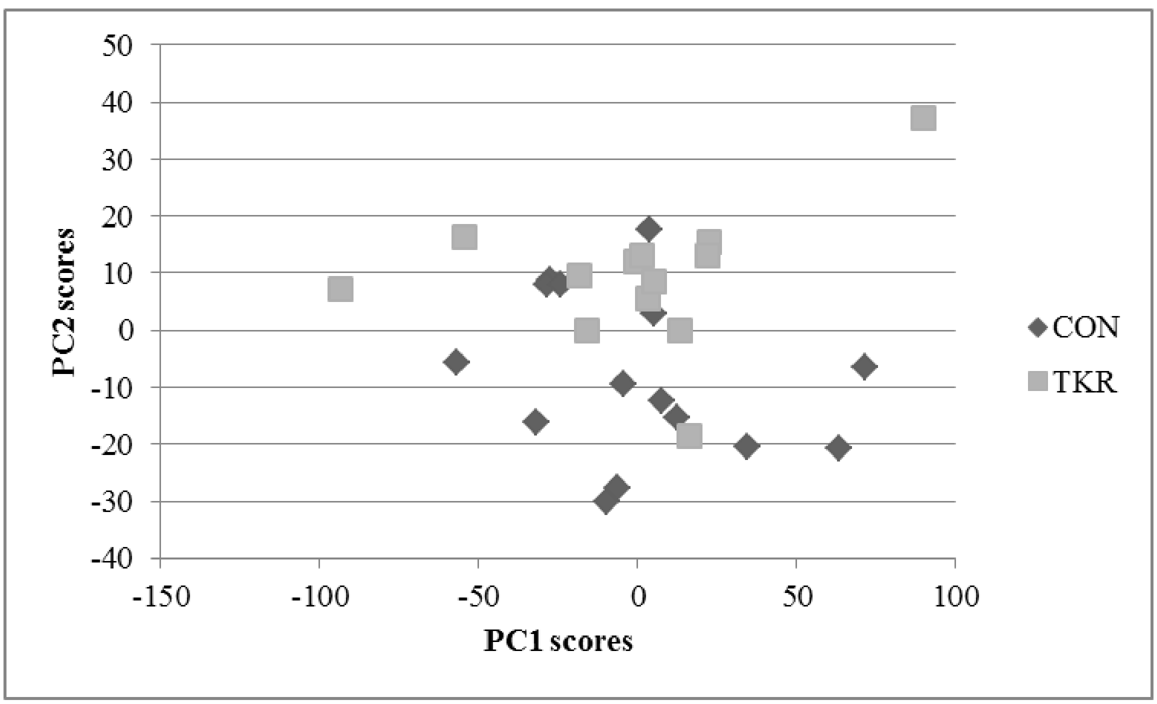


Figure 13b. Principal component scores frontal angle PC1 plotted against PC2 by group, total knee replacement (TKR) and control (CON).

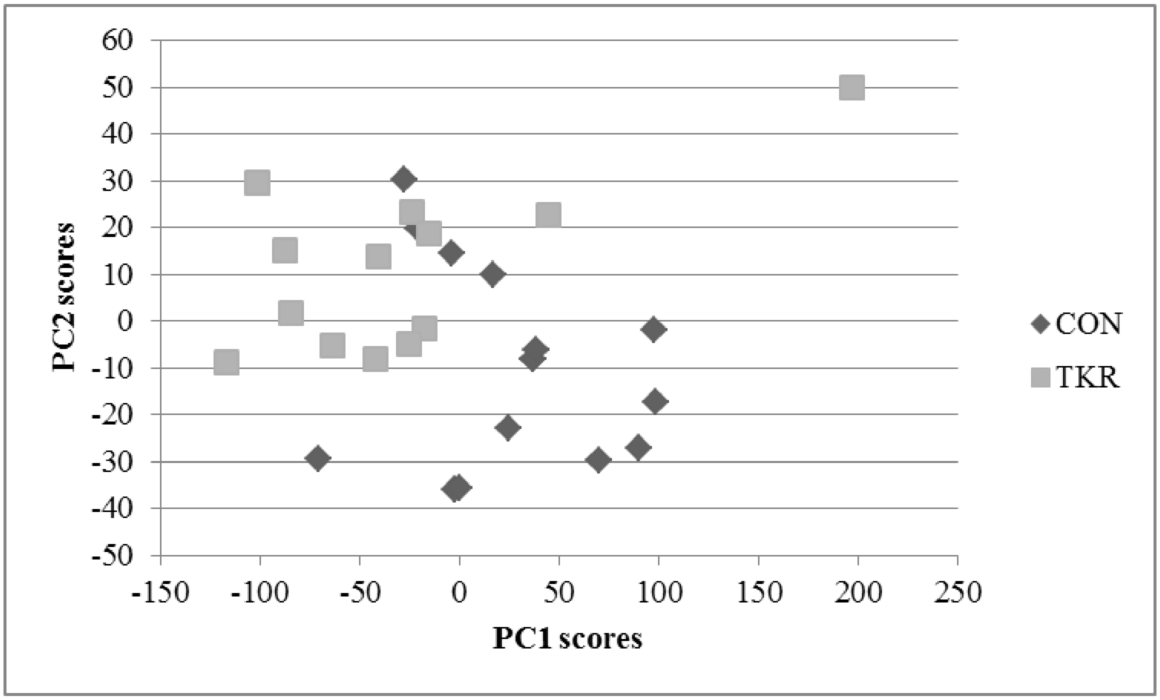


Figure 13c. Principal component scores for transverse angle PC1 plotted against PC2 by group, total knee replacement (TKR) and control (CON).

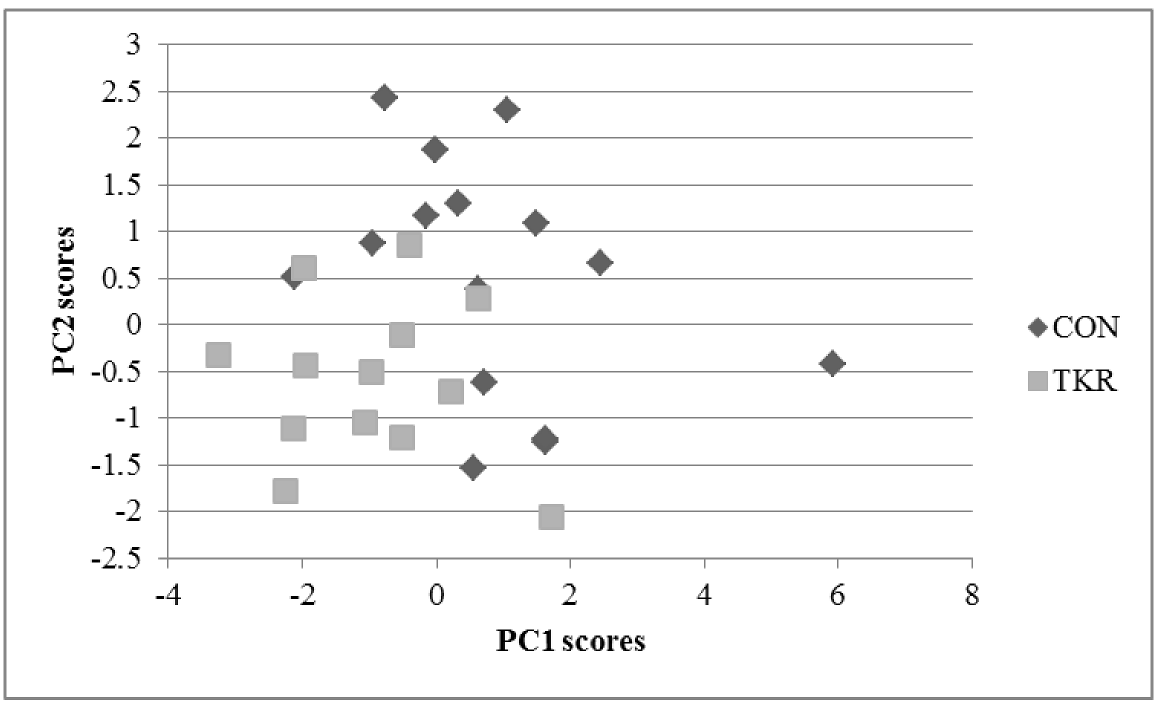


Figure 13d. Principal component scores for sagittal moment PC1 plotted against PC2 by group, total knee replacement (TKR) and control (CON).

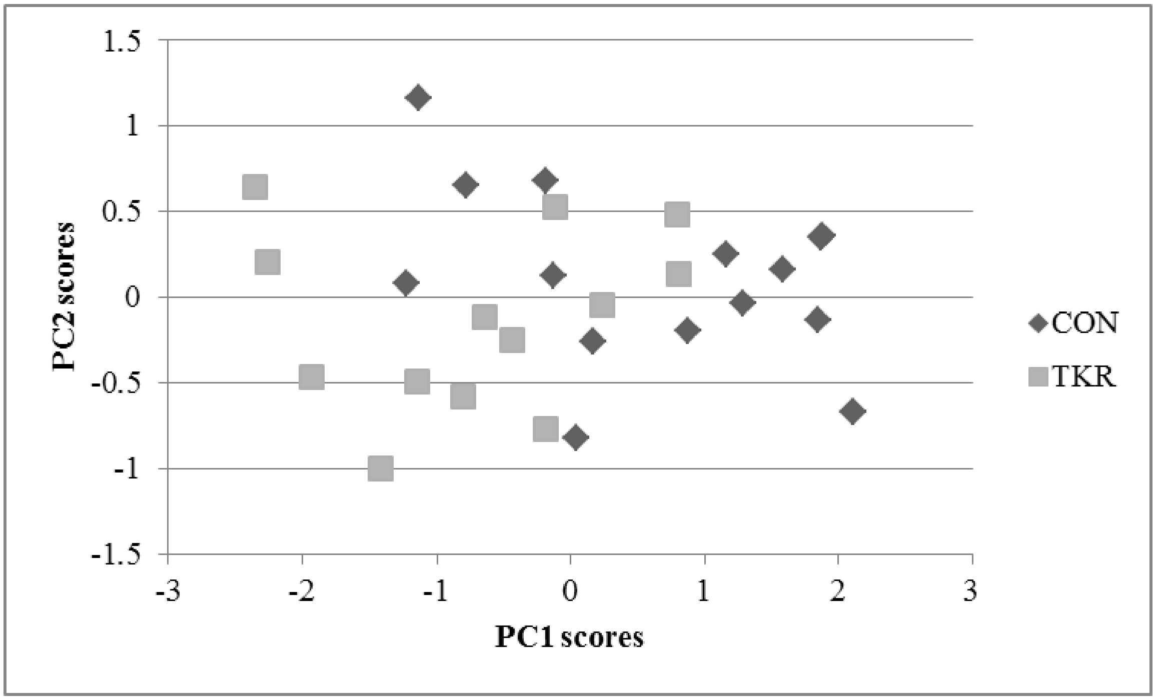


Figure 13e. Principal component scores for frontal moment PC1 plotted against PC2 by group, total knee replacement (TKR) and control (CON).

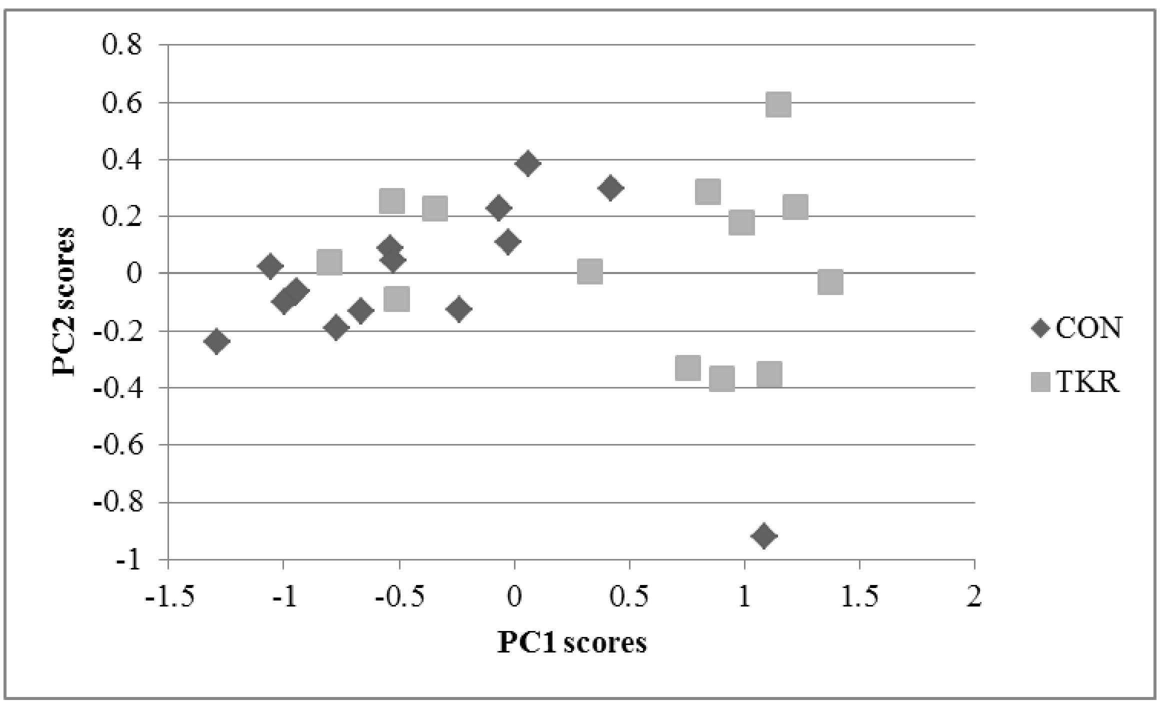


Figure 13f. Principal component scores for transverse moment PC1 plotted against PC2 by group, total knee replacement (TKR) and control (CON).

CHAPTER VII CONCLUSION

The purpose of this dissertation was to better understand lower extremity biomechanics during stair ascent in TKR and healthy controls. In study one, the systematic review of the literature was conducted and showed that during stair ascent, knee flexion angle at heel strike and walking velocity were reduced in TKR subjects compared to controls. Results of other variables were not consistent between studies. Differences in methods can partially explain some of the discrepancies in results between studies and suggest more studies are needed with more consistent and improved methods moving forward. One particular methodological difference is the choice of step for analysis during stair ascent. The findings of study two suggest that there are apparent differences in the first step compared to the second and third steps of stair ascent. Thus, the first step should be thought of as a transition step from walking to stair ascent, and steady state stair walking is only reached on the second or third step. As a result of these findings analysis in future stair ascent studies should utilize at least the second step for analysis.

The findings of study three show that there are differences in biomechanics when comparing the replaced, non-replaced and health control limbs during stair ascent. The loading response peak knee extension moment was greater in control and non-replaced knees compared to replaced. There was an elevated push-off peak knee abduction moment in the replaced limb compared to controls. In addition, there was increased demand in the frontal plane of the replaced and non-replaced limb hip compared to control hip. The findings of study four show decreases in both knee flexion angle and knee extension moment in TKR compared to control at loading, midstance, and push-off during stance. At the same time frames there were increases in knee abduction and knee internal rotation moments in TKR compared to control.

There are differences in lower extremity biomechanics during stair ascent between TKR and healthy controls. These differences can be seen in the replaced and non-replaced limb at the knee and also the hip. The findings of this dissertation support previous findings showing that TKR patients have a decrease in loading response peak knee extension moment during stair walking compared to controls but they have similar ascending velocity. Additional findings suggest that there are greater frontal and transverse plane moments in the replaced knee compared to controls. Additionally TKR patients had greater frontal plane hip moments in both the replaced and non-replaced limb compared to controls. Typically gait studies compare peak (discrete) values of these variables during loading-response and push-off, and provide useful information. Additions of PCA in stair ascent shows differences occurring from loading-response, through midstance and to push-off in many of these variables that are difficult to detect using a discrete analysis.

From a clinical standpoint these TKR patients had a very good recovery. They were able to utilize stairs without a handrail and achieved similar ascent velocities as control participants during biomechanical ascent testing trials. In addition they had comparable functional scores for TUG, and slight deficits during the stair ascent and descent with a longer flight (11 steps). The findings suggest that even with a good recovery there are still apparent deficits in these TKR patients. As a result, future rehabilitation protocols should include work on posterior knee muscles of the replaced limb to provide better support and its motions which may be beneficial in relieving the demands placed upon the replaced knee joint in the frontal and transverse planes. Additionally muscles that act on the hip joint would need to be strengthened due to the greater demands on the hip joint during stair ascent. Finally rehabilitation should also target the non-replaced limb as it has been shown to compensate for deficits of the replaced limb. These types of rehabilitation practices may allow TKR patients to better withstand the increased demands placed upon the surrounding joints of the replaced and non-replaced limb to reduce risks of future degenerative changes.

LIST OF REFERENCES

1 Total Knee Replacement. In: *Book Total Knee Replacement*. Editor (Ed.)^(Eds.) City, 2011, pp.
2 Abdi, H, Williams, LJ. Principal component analysis. *Wiley Interdisciplinary Reviews: Computational Statistics*. 2010; 2(4):433-59.
3 Ahmed, AR, Abd-Elkader, SM, Al-Obathani, KS. Effect of a 6-week rehabilitation program on gait parameters after total knee arthroplasty. *Saudi medical journal*. 2010; 31(9):1032-5.
4 Ainsworth, BE, Haskell, WL, Herrmann, SD, Meckes, N, Bassett, DR, Jr., Tudor-Locke, C, Greer, JL, Vezina, J, Whitt-Glover, MC, Leon, AS. 2011 Compendium of Physical Activities: a second update of codes and MET values. *Med Sci Sport Exer*. 2011; 43(8):1575-81.
5 Akodu, AK, Giwa, SO, Akinbo, SR, Ahmed, UA. Physiotherapy in the management of total knee arthroplasty: a review. *Nigerian quarterly journal of hospital medicine*. 2011; 21(2):99-105.
6 Alnahdi, AH, Zeni, JA, Snyder-Mackler, L. Gait after unilateral total knee arthroplasty: frontal plane analysis. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*. 2011; 29(5):647-52.
7 Andriacchi, TP, Andersson, GB, Fermier, RW, Stern, D, Galante, JO. A study of lower-limb mechanics during stair-climbing. *The Journal of bone and joint surgery. American volume*. 1980; 62(5):749-57.
8 Andriacchi, TP, Galante, JO, Fermier, RW. The influence of total knee-replacement design on walking and stair-climbing. *The Journal of bone and joint surgery. American volume*. 1982; 64(9):1328-35.
9 Andriacchi, TP, Mundermann, A. The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. *Current opinion in rheumatology*. 2006; 18(5):514-8.
10 Astephen, JL, Deluzio, KJ, Caldwell, GE, Dunbar, MJ, Hubley-Kozey, CL. Gait and neuromuscular pattern changes are associated with differences in knee osteoarthritis severity levels. *J Biomech*. 2008; 41(4):868-76.
11 Bade, MJ, Stevens-Lapsley, JE. Early high-intensity rehabilitation following total knee arthroplasty improves outcomes. *The Journal of orthopaedic and sports physical therapy*. 2011; 41(12):932-41.
12 Baliunas, AJ, Hurwitz, DE, Ryals, AB, Karrar, A, Case, JP, Block, JA, Andriacchi, TP. Increased knee joint loads during walking are present in subjects with knee osteoarthritis. *Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society*. 2002; 10(7):573-9.
13 Barbour, KE, Helmick, CG, K.A., T, Murphy, LB, Hootman, JM, Brady, TJ, Cheng, YJ. Prevlanence of doctor-diagnosed arthritis and arthritis-attributable activity limitation - United States, 2010-2012. *Morbidity and Mortality Weekly Report*. 2013; 62(44):869-73.
14 Benedetti, MG, Catani, F, Bilotta, TW, Marcacci, M, Mariani, E, Giannini, S. Muscle activation pattern and gait biomechanics after total knee replacement. *Clin Biomech (Bristol, Avon)*. 2003; 18(9):871-6.
15 Berchuck, M, Andriacchi, TP, Bach, BR, Reider, B. *Gait adaptations by patients who have a deficient anterior cruciate ligament*. 1990.
16 Berti, L, Benedetti, MG, Ensini, A, Catani, F, Giannini, S. Clinical and biomechanical assessment of patella resurfacing in total knee arthroplasty. *Clin Biomech (Bristol, Avon)*. 2006; 21(6):610-6.
17 Beswick, AD, Wylde, V, Gooberman-Hill, R, Blom, A, Dieppe, P. What proportion of patients report long-term pain after total hip or knee replacement for osteoarthritis? A systematic review of prospective studies in unselected patients. *BMJ Open*. 2012; 2(1):e000435.
18 Bolanos, AA, Colizza, WA, McCann, PD, Gotlin, RS, Wootten, ME, Kahn, BA, Insall, JN. A comparison of isokinetic strength testing and gait analysis in patients with posterior cruciate-retaining and substituting knee arthroplasties. *The Journal of arthroplasty*. 1998; 13(8):906-15.
19 Boonstra, MC, De Waal Malefijt, MC, Verdonschot, N. How to quantify knee function after total knee arthroplasty? *The Knee*. 2008; 15(5):390-5.
20 Brown, K, Kachelman, J, Topp, R, Quesada, PM, Nyland, J, Malkani, A, Swank, AM. Predictors of functional task performance among patients scheduled for total knee arthroplasty. *Journal of strength and conditioning research / National Strength & Conditioning Association*. 2009; 23(2):436-43.

21 Bruyere, O, Ethgen, O, Neuprez, A, Zegels, B, Gillet, P, Huskin, JP, Reginster, JY. Health-related quality of life after total knee or hip replacement for osteoarthritis: a 7-year prospective study. *Archives of orthopaedic and traumatic surgery. Archiv fur orthopadische und Unfall-Chirurgie*. 2012; 132(11):1583-7.
22 Cademartiri, C, Soncini, G. Total knee replacement. Postacute phase in rehabilitation: objectives and strategies in postacute treatment. *Acta bio-medica : Atenei Parmensis*. 2004; 75(1):56-62.
23 Catani, F, Benedetti, MG, De Felice, R, Buzzi, R, Giannini, S, Aglietti, P. Mobile and fixed bearing total knee prosthesis functional comparison during stair climbing. *Clin Biomech (Bristol, Avon)*. 2003; 18(5):410-8.
24 Catani, F, Ensini, A, Belvedere, C, Feliciangeli, A, Benedetti, MG, Leardini, A, Giannini, S. In vivo kinematics and kinetics of a bi-cruciate substituting total knee arthroplasty: a combined fluoroscopic and gait analysis study. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*. 2009; 27(12):1569-75.
25 Cattell, RB. The Scree Test For The Number Of Factors. *Multivariate Behavioral Research*. 1966; 1(2):245-76.
26 Chau, T, Young, S, Redekop, S. Managing variability in the summary and comparison of gait data. *J Neuroeng Rehabil*. 2005; 2:22.
27 Chester, VL, Wrigley, AT. The identification of age-related differences in kinetic gait parameters using principal component analysis. *Clin Biomech (Bristol, Avon)*. 2008; 23(2):212-20.
28 Costigan, PA, Deluzio, KJ, Wyss, UP. Knee and hip kinetics during normal stair climbing. *Gait Posture*. 2002; 16(1):31-7.
29 Daffertshofer, A, Lamoth, CJ, Meijer, OG, Beek, PJ. PCA in studying coordination and variability: a tutorial. *Clin Biomech (Bristol, Avon)*. 2004; 19(4):415-28.
30 Dawson, J, Fitzpatrick, R, Murray, D, Carr, A. Questionnaire on the perceptions of patients about total knee replacement. *The Journal of bone and joint surgery. British volume*. 1998; 80(1):63-9.
31 Deluzio, KJ, Astephen, JL. Biomechanical features of gait waveform data associated with knee osteoarthritis: an application of principal component analysis. *Gait Posture*. 2007; 25(1):86-93.
32 Deluzio, KJ, Wyss, UP, Costigan, PA, Sorbie, C, Zee, B. Gait assessment in unicompartmental knee arthroplasty patients: Principal component modelling of gait waveforms and clinical status. *Hum Mov Sci*. 1999; 18(5):701-11.
33 Deluzio, KJ, Wyss, UP, Zee, B, Costigan, PA, Sorbie, C. Principal component models of knee kinematics and kinetics: Normal vs. pathological gait patterns. *Hum Mov Sci*. 1997; 16(2-3):201-17.
34 Ditmyer, MM, Topp, R, Pifer, M. Prehabilitation in preparation for orthopaedic surgery. *Orthopedic nursing*. 2002; 21(5):43-51; quiz 2-4.
35 Draganich, LF, Pottenger, LA. The TRAC PS mobile-bearing prosthesis: design rationale and in vivo 3-dimensional laxity. *The Journal of arthroplasty*. 2000; 15(1):102-12.
36 Fantozzi, S, Benedetti, MG, Leardini, A, Banks, SA, Cappello, A, Assirelli, D, Catani, F. Fluoroscopic and gait analysis of the functional performance in stair ascent of two total knee replacement designs. *Gait Posture*. 2003; 17(3):225-34.
37 Ferber, R, Davis, IM, Williams, DS, Laughton, C. A comparison of within- and between-day reliability of discrete 3D lower extremity variables in runners. *J Orthopaed Res*. 2002; 20(6):1139-45.
38 Foch, E, Milner, CE. The influence of iliotibial band syndrome history on running biomechanics examined via principal components analysis. *J Biomech*. 2014; 47(1):81-6.
39 Freter, SH, Fruchter, N. Relationship between timed 'up and go' and gait time in an elderly orthopaedic rehabilitation population. *Clinical rehabilitation*. 2000; 14(1):96-101.
40 Gao, B, Cordova, ML, Zheng, NN. Three-dimensional joint kinematics of ACL-deficient and ACL-reconstructed knees during stair ascent and descent. *Hum Mov Sci*. 2012; 31(1):222-35.
41 Greene, KA, Schurman, JR, 2nd. Quadriceps muscle function in primary total knee arthroplasty. *The Journal of arthroplasty*. 2008; 23(7 Suppl):15-9.

42 Guo, M, Axe, MJ, Manal, K. The influence of foot progression angle on the knee adduction moment during walking and stair climbing in pain free individuals with knee osteoarthritis. *Gait Posture*. 2007; 26(3):436-41.
43 Haim, A, Rozen, N, Dekel, S, Halperin, N, Wolf, A. Control of knee coronal plane moment via modulation of center of pressure: a prospective gait analysis study. *J Biomech*. 2008; 41(14):3010-6.
44 Hamel, KA, Okita, N, Bus, SA, Cavanagh, PR. A comparison of foot/ground interaction during stair negotiation and level walking in young and older women. *Ergonomics*. 2005; 48(8):1047-56.
45 Hatfield, GL, Hubley-Kozey, CL, Astephen Wilson, JL, Dunbar, MJ. The effect of total knee arthroplasty on knee joint kinematics and kinetics during gait. *The Journal of arthroplasty*. 2011; 26(2):309-18.
46 Hawker, G, Wright, J, Coyte, P, Paul, J, Dittus, R, Croxford, R, Katz, B, Bombardier, C, Heck, D, Freund, D. Health-related quality of life after knee replacement. *The Journal of bone and joint surgery. American volume*. 1998; 80(2):163-73.
47 Heinlein, B, Kutzner, I, Graichen, F, Bender, A, Rohlmann, A, Halder, AM, Beier, A, Bergmann, G. ESB Clinical Biomechanics Award 2008: Complete data of total knee replacement loading for level walking and stair climbing measured in vivo with a follow-up of 6-10 months. *Clin Biomech (Bristol, Avon)*. 2009; 24(4):315-26.
48 Hicks-Little, CA, Peindl, RD, Hubbard, TJ, Scannell, BP, Springer, BD, Odum, SM, Fehring, TK, Cordova, ML. Lower extremity joint kinematics during stair climbing in knee osteoarthritis. *Med Sci Sports Exerc*. 2011; 43(3):516-24.
49 Hootman, JM, Helmick, CG. Projections of US prevalence of arthritis and associated activity limitations. *Arthritis and rheumatism*. 2006; 54(1):226-9.
50 Huang, CH, Cheng, CK, Lee, YT, Lee, KS. Muscle strength after successful total knee replacement: a 6- to 13-year followup. *Clinical orthopaedics and related research*. 1996; (328):147-54.
51 Hurwitz, DE, Ryals, AB, Case, JP, Block, JA, Andriacchi, TP. The knee adduction moment during gait in subjects with knee osteoarthritis is more closely correlated with static alignment than radiographic disease severity, toe out angle and pain. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*. 2002; 20(1):101-7.
52 Insall, JN, Dorr, LD, Scott, RD, Scott, WN. Rationale of the Knee Society clinical rating system. *Clinical orthopaedics and related research*. 1989; (248):13-4.
53 Jevsevar, DS, Riley, PO, Hodge, WA, Krebs, DE. Knee kinematics and kinetics during locomotor activities of daily living in subjects with knee arthroplasty and in healthy control subjects. *Physical therapy*. 1993; 73(4):229-39; discussion 40-2.
54 Joglekar, S, Gioe, TJ, Yoon, P, Schwartz, MH. Gait analysis comparison of cruciate retaining and substituting TKA following PCL sacrifice. *The Knee*. 2012; 19(4):279-85.
55 Jolliffe, I. Principal Component Analysis*Encyclopedia of Statistics in Behavioral Science*: John Wiley & Sons, Ltd; 2005.
56 Judd, DL, Eckhoff, DG, Stevens-Lapsley, JE. Muscle strength loss in the lower limb after total knee arthroplasty. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*. 2012; 91(3):220-6; quiz 7-30.
57 Kadaba, MP, Ramakrishnan, HK, Wootten, ME, Gainey, J, Gorton, G, Cochran, GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*. 1989; 7(6):849-60.
58 Kaiser, HF. The application of electronic computers to factor analysis. *Educational and Psychological Measurement*. 1960; 20:141-51.
59 Kaufman, KR, Hughes, C, Morrey, BF, Morrey, M, An, KN. Gait characteristics of patients with knee osteoarthritis. *J Biomech*. 2001; 34(7):907-15.
60 Kelman, GJ, Biden, EN, Wyatt, MP, Ritter, MA, Colwell, CW, Jr. Gait laboratory analysis of a posterior cruciate-sparing total knee arthroplasty in stair ascent and descent. *Clinical orthopaedics and related research*. 1989; (248):21-5; discussion 5-6.

61 Kevin J. Deluzio, AJH, Norma Coffey, Graham E. Caldwell. Analysis of Biomechanical Waveform Data*Research Methods in Biomechanics*. Champaign, IL: Human Kinetics; 2014. p. 317-36.
62 Ko, Y, Narayanasamy, S, Wee, HL, Lo, NN, Yeo, SJ, Yang, KY, Yeo, W, Chong, HC, Thumboo, J. Health-related quality of life after total knee replacement or unicompartmental knee arthroplasty in an urban asian population. *Value in health : the journal of the International Society for Pharmacoeconomics and Outcomes Research*. 2011; 14(2):322-8.
63 Kramers-de Quervain, IA, Kampfen, S, Munzinger, U, Mannion, AF. Prospective study of gait function before and 2 years after total knee arthroplasty. *The Knee*. 2012; 19(5):622-7.
64 Kristianslund, E, Krosshaug, T, van den Bogert, AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012; 45(4):666-71.
65 Kurtz, S, Ong, K, Lau, E, Mowat, F, Halpern, M. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. *The Journal of bone and joint surgery. American volume*. 2007; 89(4):780-5.
66 Labraca, NS, Castro-Sanchez, AM, Mataran-Penarrocha, GA, Arroyo-Morales, M, Sanchez-Joya, MDM, Moreno-Lorenzo, C. Benefits of starting rehabilitation within 24 hours of primary total knee arthroplasty: randomized clinical trial. *Clinical rehabilitation*. 2011; 25(6):557-66.
67 Levine, M, McElroy, K, Stakich, V, Cicco, J. Comparing conventional physical therapy rehabilitation with neuromuscular electrical stimulation after TKA. *Orthopedics*. 2013; 36(3):e319-24.
68 Levinger, P, Menz, HB, Morrow, AD, Feller, JA, Bartlett, JR, Bergman, NR. Lower limb biomechanics in individuals with knee osteoarthritis before and after total knee arthroplasty surgery. *The Journal of arthroplasty*. 2013; 28(6):994-9.
69 Littell, RC, Stroup, WW, Milliken, GA, Wolfinger, RD, Schabenberger, O. *SAS for Mixed Models, Second Edition*. SAS Institute, 2006.
70 Luepongsak, N, Amin, S, Krebs, DE, McGibbon, CA, Felson, D. The contribution of type of daily activity to loading across the hip and knee joints in the elderly. *Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society*. 2002; 10(5):353-9.
71 Maly, MR, Culham, EG, Costigan, PA. Static and dynamic biomechanics of foot orthoses in people with medial compartment knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2002; 17(8):603-10.
72 Mandeville, D, Osternig, LR, Chou, LS. The effect of total knee replacement on dynamic support of the body during walking and stair ascent. *Clin Biomech (Bristol, Avon)*. 2007; 22(7):787-94.
73 Mandeville, D, Osternig, LR, Lantz, BA, Mohler, CG, Chou, LS. The effect of total knee replacement on the knee varus angle and moment during walking and stair ascent. *Clin Biomech (Bristol, Avon)*. 2008; 23(8):1053-8.
74 Mandeville, DS, Osternig, LR, Lantz, BA, Mohler, CG, Chou, LS. A multivariate statistical ranking of clinical and gait measures before and after total knee replacement. *Gait Posture*. 2009; 30(2):197-200.
75 McClelland, JA, Webster, KE, Feller, JA. Gait analysis of patients following total knee replacement: a systematic review. *The Knee*. 2007; 14(4):253-63.
76 McClelland, JA, Webster, KE, Feller, JA. Variability of walking and other daily activities in patients with total knee replacement. *Gait Posture*. 2009; 30(3):288-95.
77 McClelland, JA, Webster, KE, Feller, JA, Menz, HB. Knee kinematics during walking at different speeds in people who have undergone total knee replacement. *The Knee*. 2011; 18(3):151-5.
78 McEwen, HM, Barnett, PI, Bell, CJ, Farrar, R, Auger, DD, Stone, MH, Fisher, J. The influence of design, materials and kinematics on the in vitro wear of total knee replacements. *J Biomech*. 2005; 38(2):357-65.
79 McFadyen, BJ, Winter, DA. An integrated biomechanical analysis of normal stair ascent and descent. *J Biomech*. 1988; 21(9):733-44.
80 McKay, C, Prapavessis, H, Doherty, T. The effect of a prehabilitation exercise program on quadriceps strength for patients undergoing total knee arthroplasty: a randomized controlled pilot study. *PM & R : the journal of injury, function, and rehabilitation*. 2012; 4(9):647-56.

81 McMahon, M, Block, JA. The risk of contralateral total knee arthroplasty after knee replacement for osteoarthritis. *The Journal of rheumatology*. 2003; 30(8):1822-4.
82 Mehrotra, C, Remington, PL, Naimi, TS, Washington, W, Miller, R. Trends in total knee replacement surgeries and implications for public health, 1990-2000. *Public Health Rep*. 2005; 120(3):278-82.
83 Metcalfe, A, Stewart, C, Postans, N, Barlow, D, Dodds, A, Holt, C, Whatling, G, Roberts, A. Abnormal loading of the major joints in knee osteoarthritis and the response to knee replacement. *Gait Posture*. 2012;
84 Milner, CE. Interlimb asymmetry during walking following unilateral total knee arthroplasty. *Gait Posture*. 2008; 28(1):69-73.
85 Milner, CE. Is gait normal after total knee arthroplasty? Systematic review of the literature. *Journal of orthopaedic science : official journal of the Japanese Orthopaedic Association*. 2009; 14(1):114-20.
86 Milner, CE, O'Bryan, ME. Bilateral frontal plane mechanics after unilateral total knee arthroplasty. *Archives of physical medicine and rehabilitation*. 2008; 89(10):1965-9.
87 Minns Lowe, CJ, Barker, KL, Dewey, M, Sackley, CM. Effectiveness of physiotherapy exercise after knee arthroplasty for osteoarthritis: systematic review and meta-analysis of randomised controlled trials. *Bmj*. 2007; 335(7624):812.
88 Miyazaki, T, Wada, M, Kawahara, H, Sato, M, Baba, H, Shimada, S. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Annals of the rheumatic diseases*. 2002; 61(7):617-22.
89 Mizner, RL, Petterson, SC, Stevens, JE, Vandenborne, K, Snyder-Mackler, L. Early quadriceps strength loss after total knee arthroplasty. The contributions of muscle atrophy and failure of voluntary muscle activation. *The Journal of bone and joint surgery American volume*. 2005; 87(5):1047-53.
90 Morrison, JB. Function of the knee joint in various activities. *Biomed Eng*. 1969; 4(12):573-80.
91 Nadeau, S, McFadyen, BJ, Malouin, F. Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking? *Clin Biomech (Bristol, Avon)*. 2003; 18(10):950-9.
92 NCHS. Cost of hospital discharges with common hospital operating room procedures in nonfederal community hospitals, by age and selected principal procedure: United States, selected years 2000-2011. In: *Book Cost of hospital discharges with common hospital operating room procedures in nonfederal community hospitals, by age and selected principal procedure: United States, selected years 2000-2011*. Editor (Ed.)^(Eds.) City: National Center for Health Statistics, 2013, pp.
93 Noble, PC, Conditt, MA, Cook, KF, Mathis, KB. The John Insall Award: Patient expectations affect satisfaction with total knee arthroplasty. *Clinical orthopaedics and related research*. 2006; 452:35-43.
94 Noble, PC, Gordon, MJ, Weiss, JM, Reddix, RN, Conditt, MA, Mathis, KB. Does total knee replacement restore normal knee function? *Clinical orthopaedics and related research*. 2005; (431):157-65.
95 Novak, AC, Brouwer, B. Sagittal and frontal lower limb joint moments during stair ascent and descent in young and older adults. *Gait Posture*. 2011; 33(1):54-60.
96 O'Connor, KM, Bottum, MC. Differences in cutting knee mechanics based on principal components analysis. *Med Sci Sport Exer*. 2009; 41(4):867-78.
97 Orishimo, KF, Kremenic, IJ, Deshmukh, AJ, Nicholas, SJ, Rodriguez, JA. Does total knee arthroplasty change frontal plane knee biomechanics during gait? *Clinical orthopaedics and related research*. 2012; 470(4):1171-6.
98 Ouellet, D, Moffet, H. Locomotor deficits before and two months after knee arthroplasty. *Arthritis and rheumatism*. 2002; 47(5):484-93.
99 Paquette, MR, Zhang, S, Milner, CE, Fairbrother, JT, Reinbolt, JA. Effects of increased step width on frontal plane knee biomechanics in healthy older adults during stair descent. *The Knee*. 2014; 21(4):821-6.

100 Paquette, MR, Zhang, S, Milner, CE, Klipple, G. Does increasing step width alter knee biomechanics in medial compartment knee osteoarthritis patients during stair descent? *The Knee*. 2014; 21(3):676-82.
101 Parent, E, Moffet, H. Preoperative predictors of locomotor ability two months after total knee arthroplasty for severe osteoarthritis. *Arthritis and rheumatism*. 2003; 49(1):36-50.
102 Piva, SR, Gil, AB, Almeida, GJ, DiGioia, AM, 3rd, Levison, TJ, Fitzgerald, GK. A balance exercise program appears to improve function for patients with total knee arthroplasty: a randomized clinical trial. *Physical therapy*. 2010; 90(6):880-94.
103 Pollo, FE, Jackson, RW, Koeter, S, Ansari, S, Motley, GS, Rathjen, KW. Walking, chair rising, and stair climbing after total knee arthroplasty: patellar resurfacing versus nonresurfacing. *The American journal of knee surgery*. 2000; 13(2):103-8; discussion 8-9.
104 Protopapadaki, A, Drechsler, WI, Cramp, MC, Coutts, FJ, Scott, OM. Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. *Clin Biomech (Bristol, Avon)*. 2007; 22(2):203-10.
105 Rasnick, R, Standifird, TW, Reinbolt, JA, Cates, HE, Zhang, S. Knee joint loads and surrounding muscle forces during stair ascent in patients with total knee replacemenst and healthy individuals. 2015.
106 Ravi, B, Croxford, R, Reichmann, WM, Losina, E, Katz, JN, Hawker, GA. The changing demographics of total joint arthroplasty recipients in the United States and Ontario from 2001 to 2007. *Best Pract Res Clin Rheumatol*. 2012; 26(5):637-47.
107 Reeves, ND, Spanjaard, M, Mohagheghi, AA, Baltzopoulos, V, Maganaris, CN. Influence of light handrail use on the biomechanics of stair negotiation in old age. *Gait Posture*. 2008; 28(2):327-36.
108 Reid, SM, Graham, RB, Costigan, PA. Differentiation of young and older adult stair climbing gait using principal component analysis. *Gait Posture*. 2010; 31(2):197-203.
109 Reid, SM, Lynn, SK, Musselman, RP, Costigan, PA. Knee biomechanics of alternate stair ambulation patterns. *Med Sci Sports Exerc*. 2007; 39(11):2005-11.
110 Riener, R, Rabuffetti, M, Frigo, C. Stair ascent and descent at different inclinations. *Gait Posture*. 2002; 15(1):32-44.
111 Rodgers, JA, Garvin, KL, Walker, CW, Morford, D, Urban, J, Bedard, J. Preoperative physical therapy in primary total knee arthroplasty. *The Journal of arthroplasty*. 1998; 13(4):414-21.
112 Rooks, DS, Huang, J, Bierbaum, BE, Bolus, SA, Rubano, J, Connolly, CE, Alpert, S, Iversen, MD, Katz, JN. Effect of preoperative exercise on measures of functional status in men and women undergoing total hip and knee arthroplasty. *Arthritis and rheumatism*. 2006; 55(5):700-8.
113 Rowe, PJ, Myles, CM, Walker, C, Nutton, R. Knee joint kinematics in gait and other functional activities measured using flexible electrogoniometry: how much knee motion is sufficient for normal daily life? *Gait Posture*. 2000; 12(2):143-55.
114 Saari, T, Tranberg, R, Zugner, R, Uvehammer, J, Karrholm, J. Total knee replacement influences both knee and hip joint kinematics during stair climbing. *International orthopaedics*. 2004; 28(2):82-6.
115 Scuderi, GR, Bourne, RB, Noble, PC, Benjamin, JB, Lonner, JH, Scott, WN. The new Knee Society Knee Scoring System. *Clinical orthopaedics and related research*. 2012; 470(1):3-19.
116 Shakoor, N, Block, JA, Shott, S, Case, JP. Nonrandom evolution of end-stage osteoarthritis of the lower limbs. *Arthritis and rheumatism*. 2002; 46(12):3185-9.
117 Smith, AJ, Lloyd, DG, Wood, DJ. A kinematic and kinetic analysis of walking after total knee arthroplasty with and without patellar resurfacing. *Clin Biomech*. 2006; 21(4):379-86.
118 Stacoff, A, Diezi, C, Luder, G, Stussi, E, Kramers-de Quervain, IA. Ground reaction forces on stairs: effects of stair inclination and age. *Gait Posture*. 2005; 21(1):24-38.
119 Standifird, TW, Cates, HE, Mann, K, Zhang, S. Biomechanical outcomes of stair ascent and functional tests following total knee replacement. In *Proceedings of the 61st Annual Meeting of the American College of Sports Medicine*. Orlando, FL, 2014.
120 Standifird, TW, Cates, HE, Zhang, S. Stair ambulation biomechanics following total knee arthroplasty: a systematic review. *The Journal of arthroplasty*. 2014; 29(9):1857-62.

121 Standifird, TW, Saxton, AM, Coe, DP, Cates, HE, Reinbolt, JA, Zhang, S. Influence of total knee arthroplasty on gait mechanics of the replaced and non-replaced limb during stair negotiation. 2015.
122 Startzell, JK, Owens, DA, Mulfinger, LM, Cavanagh, PR. Stair negotiation in older people: a review. *Journal of the American Geriatrics Society*. 2000; 48(5):567-80.
123 Stevens-Lapsley, JE, Balter, JE, Wolfe, P, Eckhoff, DG, Schwartz, RS, Schenkman, M, Kohrt, WM. Relationship between intensity of quadriceps muscle neuromuscular electrical stimulation and strength recovery after total knee arthroplasty. *Physical therapy*. 2012; 92(9):1187-96.
124 Studenski, S, Perera, S, Patel, K, Rosano, C, Faulkner, K, Inzitari, M, Brach, J, Chandler, J, Cawthon, P, Connor, EB, Nevitt, M, Visser, M, Kritchevsky, S, Badinelli, S, Harris, T, Newman, AB, Cauley, J, Ferrucci, L, Guralnik, J. Gait speed and survival in older adults. *Jama*. 2011; 305(1):50-8.
125 Vergis, A, Gillquist, J. Sagittal plane translation of the knee during stair walking. Comparison of healthy and anterior cruciate ligament--deficient subjects. *The American journal of sports medicine*. 1998; 26(6):841-6.
126 Wilken, JM, Sinitski, EH, Bagg, EA. The role of lower extremity joint powers in successful stair ambulation. *Gait Posture*. 2011; 34(1):142-4.
127 Williamson, JD, Fried, LP. Characterization of older adults who attribute functional decrements to "old age". *Journal of the American Geriatrics Society*. 1996; 44(12):1429-34.
128 Wilson, SA, McCann, PD, Gotlin, RS, Ramakrishnan, HK, Wootten, ME, Insall, JN. Comprehensive gait analysis in posterior-stabilized knee arthroplasty. *The Journal of arthroplasty*. 1996; 11(4):359-67.
129 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. *Clin Biomech (Bristol, Avon)*. 2008; 23(3):320-8.
130 Yu, B, Kienbacher, T, Growney, ES, Johnson, ME, An, KN. Reproducibility of the kinematics and kinetics of the lower extremity during normal stair-climbing. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*. 1997; 15(3):348-52.
131 Zeni, JA, Jr., Snyder-Mackler, L. Preoperative predictors of persistent impairments during stair ascent and descent after total knee arthroplasty. *The Journal of bone and joint surgery. American volume*. 2010; 92(5):1130-6.
132 Zhang, S, Clowers, KG, Powell, D. Ground reaction force and 3D biomechanical characteristics of walking in short-leg walkers. *Gait Posture*. 2006; 24(4):487-92.
133 Zhang, S, Standifird, T, Arwood, M. Knee Biomechanics on First Step of Stair Ascent is different from Second or Third Step. In *Proceedings of the 7th World Congress of Biomechanics*. Boston, MA, 2014
134 Zhao, D, Banks, SA, Mitchell, KH, D'Lima, DD, Colwell, CW, Jr., Fregly, BJ. Correlation between the knee adduction torque and medial contact force for a variety of gait patterns. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*. 2007; 25(6):789-97.

APPENDICES

Appendix A: Subject Characteristics Study Two

Table 17. Individual healthy subject characteristics

Subject	Gender	Age (yrs)	Height (m)	Weight (kg)	BMI (kg/m^2)
1	f	68	1.76	80	25.83
2	m	45	1.8	91.8	28.33
3	m	63	1.95	127.3	33.48
7	f	55	1.76	96.8	31.25
8	f	55	1.69	91.8	32.14
10	f	53	1.69	85	29.76
11	m	64	1.76	78.9	25.47
12	m	53	1.87	86.6	24.76
13	f	51	1.65	58.5	21.49
14	f	63	1.63	64	24.09
15	m	68	1.89	92.2	25.81
16	m	52	1.79	79	24.66
mean	-	57.5	1.77	85.99	27.26

Appendix B: Subject Characteristics Study 3 and 4

Table 18. Individual control subject characteristics

Subject	Gender	Age (yrs)	Height (m)	Weight (kg)	BMI (kg/m^2)
1	f	68	1.76	80	25.83
3	m	63	1.95	127.3	33.48
7	f	55	1.76	96.8	31.25
8	f	55	1.69	91.8	32.14
10	f	53	1.69	85	29.76
11	m	64	1.76	78.9	25.47
12	m	53	1.87	86.6	24.76
14	f	63	1.63	64	24.09
15	m	68	1.89	92.2	25.81
16	m	52	1.79	79	24.66
22	m	64	1.89	97.10	27.33
26	m	68	1.82	93.44	28.36
28	m	65	1.79	82.55	25.91
29	m	79	1.82	75.30	22.86
30	m	65	1.78	78.02	24.76
mean	-	62.33	1.791	87.20	27.10

Table 19. Individual TKR subject characteristics.

Subject	Gender	Age (yrs)	Replacement Side	Time from Surgery (months)	Height (m)	Weight (kg)	BMI (kg/m^2)
4	m	63.00	L	14	1.88	95.91	27.14
5	f	67.00	L	12	1.66	77.95	28.29
6	f	62.00	R	11	1.69	76.82	26.90
9	f	51.00	L	17	1.69	91.40	32.00
17	m	75.00	L	19	1.80	92.98	28.70
18	m	64.00	R	44	1.83	105.20	31.41
19	m	71.00	R	24	1.86	92.10	26.62
20	m	73.00	L	26	1.78	110.50	34.88
21	m	67.00	R	12	1.76	89.40	28.86
23	m	60.00	L	52	1.84	81.60	24.10
24	m	60.00	L	16	1.88	83.46	23.74
25	m	67.00	L	20	1.85	83.46	24.39
27	f	73.00	L	52	1.72	91.63	31.15
mean	-	65.62	-	24.54	1.79	90.19	28.24

Appendix C: Informed Consents

Informed Consent Form for TKR Subjects

INFORMED CONSENT FORM

Principal Investigator:	Tyler Standifird	Faculty Advisor:	Songning Zhang, Ph.D.
Address:	136 HPER 1914 Andy Holt Avenue Knoxville, TN 37996 Phone: (865) 974-2091	Address:	340 HPER 1914 Andy Holt Avenue Knoxville, TN 37996 Phone: (865) 974-4716

Introduction

You are invited to participate in this research study because you are an adult with a total knee replacement (TKR) aged between 35 and 80 years old. The objectives of this proposed research are to investigate the differences during stair climbing in people with total knee replacements (TKR) and healthy controls. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be a participant in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol

If you qualify for the study based on the initial phone screening, you will be asked to attend one biomechanical test session (i.e. testing your joint movements) in the Biomechanics/Sports Medicine Lab on the UT campus that will take approximately 1.5 hours. Parking on campus will be free to you. You will also be asked to fill out a knee survey form to assess your knee pain and function, and associated problems during common daily activities on both of your knees. Additionally, you will be asked to complete the physical activity readiness survey, if you mark "yes" on the survey you will be required to obtain written consent from your doctor indicating you are healthy enough to participate in the study. For the testing session, you will be asked to wear clothing appropriate for exercise which includes spandex shorts and t-shirt. If you do not have spandex type of clothing, paper laboratory shorts will be provided.

Prior to data collection you will be required to change into exercise type clothing. Body weight and height will be measured and BMI will be calculated. If BMI is greater than 35, participation will end immediately. You will be asked to warm up on the treadmill for 3 minutes to allow your joints and muscles to get ready for the testing session. You will also be asked to rate your knee pain at several points during the warm-up and testing session. After the warm up, you will perform a timed-up-and-go test, a stair ascend/descend test and a knee range of motion test. After these tests, reflective markers will be placed on both sides of your feet, ankles, legs, knees, thighs, pelvis and trunk in order to capture your movements during walking.

Upon completion of all marker placement you will perform 3-5 successful trials for each of overground walking and both stair ascent and stair descent. Trials need to be completed at self-selected speed for both right and left legs without the use of the handrail. If the speed is not achieved or the handrail is used during a trial, you will be asked to repeat the trial. It is anticipated that you will not be required to perform more than ten to twelve trials of each condition. You will be given a minimum 30-second rest between each trial performed. You can end any condition early and are under no obligation to complete the test.

During the testing, biomechanics instruments such as reflective markers and motion capture cameras will be used to obtain measurements. The reflective markers will be placed on your body using double stick medical tape and hook and loop wraps. None of the instruments will impede your ability to engage in normal and effective motions during the test. The cameras will not record images of you. If you have any further questions, interests or concerns about any equipment, please feel free to ask the investigator

Potential Risks

Risks associated with this study are minimal. You will be asked to walk up and down stairs without the use of a handrail. Practice trials will be performed to allow you to familiarize yourself with the staircase negotiation. In order to prevent potential falls and trips, the staircase includes a handrail on the right side (left side during descent) of the steps for support if needed. The top platform of the staircase is surrounded by a guard rail. In addition, a researcher will be available close to the stairs if needed to provide additional protection. Should any injury occur during the course of testing, standard first aid procedures will be administered as necessary. At least one researcher with a basic knowledge of first aid procedures will be present at each test session. All tests will be conducted and the equipment will be handled by qualified research personnel in the Biomechanics/Sports Medicine Laboratory. In the unlikely event a physical injury is suffered as a result of participation in this study (during the warm up and testing session), the University of Tennessee does not automatically provide reimbursement for medical care or other compensation and you will be responsible for any medical expenses. If physical injury is suffered in the course of the study, or for more information, please notify Tyler Standifird (974-2091).

Benefits of Participation

Results from the proposed study will help better understand the gait deficits that are present after total knee replacement surgery. Identifying the gait abnormalities following TKR may provide useful information for improvement of future TKR designs, surgical methods and rehabilitation.

Confidentiality

Information in the study records will be kept confidential. Data will be stored securely and will be made available only to persons conducting the study unless you specifically give permission in writing to do otherwiseYour identity will be held in strict confidence through the use of a coded subject number during data collection, data analysis, and in all references made to the data, both during and after the study, and in the reporting of the results. The results will be disseminated in the form of presentations at conferences, and publications in journals. The consent form containing your identity information will be destroyed three years after the completion of the study. If you decide to withdraw from the study, your information sheet and consent form with your identity and injury history will be destroyed.

Contact Information

If you have any questions about the study at any time or if you experience adverse effects as a result of participating in this study you can contact Tyler Standifird at 1914 Andy Holt Ave. 136 HPER Bldg, The University of Tennessee (974-2091). Questions about your rights as a participant can be addressed to Compliance Officer in the Office of Research at the University of Tennessee at (865) 974-3466.

Voluntary Participation and Withdrawal

Your participation is entirely voluntary and your refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You may withdraw from the study at any time without penalty. Your participation in this study may be stopped if you fail to follow the study procedures or if the investigators feels that it is in your best interest to stop participation.

Consent Statement

I have read the above information. I agree to participate in this study. I have received a copy of this form.

Subject's Name: ____________________ Subject's Signature: __________________________ Date: __________

Investigator's Signature: ______________________________ Date: ___________ Subject # ______

Informed Consent Form for Healthy Subjects

INFORMED CONSENT FORM

Principal Investigator: Tyler Standifird
Address: 136 HPER
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: (865) 974-2091

Faculty Advisor: Songning Zhang, Ph.D.
Address: 340 HPER
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: (865) 974-4716

Introduction

You are invited to participate in this research study because you are a healthy adult aged between 35 and 80 years old. The objectives of this proposed research are to investigate the differences during stair climbing in people with total knee replacements (TKR) and healthy controls. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be a participant in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol

If you qualify for the study based on the initial phone screening, you will be asked to attend one biomechanical test session (i.e. testing your joint movements) in the Biomechanics/Sports Medicine Lab on the UT campus that will take approximately 1.5 hours. Parking on campus will be free to you. For the testing session, you will be asked to wear clothing appropriate for exercise which includes spandex shorts and t-shirt. If you do not have spandex type of clothing, paper laboratory shorts will be provided.

Prior to data collection, you will be asked to complete the physical activity readiness survey. If you mark "yes" on the survey you will be required to obtain written consent from your doctor indicating you are healthy enough to participate in the study. You will be required to change into exercise type clothing. Body weight and height will be measured and BMI will be calculated. If BMI is greater than 35 participation will end immediately. You will be asked to warm up on the treadmill for 3 minutes to allow your joints and muscles to get ready for the testing session. You will also be asked to rate your knee pain at several points during the warm-up and testing session. After the warm up, you will perform a timed-up-and-go test, a stair ascend/descend test and a knee range of motion test. After these tests, reflective markers will be placed on both sides of your feet, ankles, legs, knees, thighs, pelvis and trunk in order to capture your movements during walking.

Upon completion of all marker placement you will perform 3-5 successful trials for each of overground walking and both stair ascent and stair descent. Trials need to be completed at self-selected speed for both right and left legs without the use of the handrail. If the speed is not achieved or the handrail is used during a trial, you will be asked to repeat the trial. It is anticipated that you will not be required to perform more than ten to twelve trials of each condition. You will be given a minimum 30-second rest between each trial performed. You can end any condition early and are under no obligation to complete the test.

During the testing, biomechanics instruments such as reflective markers and motion capture cameras will be used to obtain measurements. The reflective markers will be placed on your body using double stick medical tape and hook and loop wraps. None of the instruments will impede your ability to engage in normal and effective motions during the test. The cameras will not record images of you. If you have any further questions, interests or concerns about any equipment, please feel free to ask the investigator

Potential Risks

Risks associated with this study are minimal. You will be asked to walk up and down stairs without the use of a handrail. Practice trials will be performed to allow you to familiarize yourself with the staircase negotiation. In order to prevent potential falls and trips, the staircase includes a handrail on the right side (left side during descent) of the steps for support if needed. The top platform of the staircase is surrounded by a guard rail. In addition, a researcher will be available close to the stairs if needed to provide additional protection. Should any injury occur during the course of testing, standard first aid procedures will be administered as necessary. At least one researcher with a basic knowledge of first aid procedures will be present at each test session. All tests will be conducted and the equipment will be handled by qualified research personnel in the Biomechanics/Sports Medicine Laboratory. In the unlikely event a physical injury is suffered as a result of participation in this study (during the warm up and testing session), the University of Tennessee does not automatically provide reimbursement for medical care or other compensation and you will be responsible for any medical expenses. If physical injury is suffered in the course of the study, or for more information, please notify Tyler Standifird (974-2091).

Benefits of Participation

Results from the proposed study will help better understand the gait deficits that are present after total knee replacement surgery. Identifying the gait abnormalities following TKR may provide useful information for improvement of future TKR designs, surgical methods and rehabilitation.

Confidentiality

Information in the study records will be kept confidential. Data will be stored securely and will be made available only to persons conducting the study unless you specifically give permission in writing to do otherwiseYour identity will be held in strict confidence through the use of a coded subject number during data collection, data analysis, and in all references made to the data, both during and after the study, and in the reporting of the results. The results will be disseminated in the form of presentations at conferences, and publications in journals. The consent form containing your identity information will be destroyed three years after the completion of the study. If you decide to withdraw from the study, your information sheet and consent form with your identity and injury history will be destroyed.

Contact Information

If you have any questions about the study at any time or if you experience adverse effects as a result of participating in this study you can contact Tyler Standifird at 1914 Andy Holt Ave. 136 HPER Bldg, The University of Tennessee (974-2091). Questions about your rights as a participant can be addressed to Compliance Officer in the Office of Research at the University of Tennessee at (865) 974-3466.

Voluntary Participation and Withdrawal

Your participation is entirely voluntary and your refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You may withdraw from the study at any time without penalty. Your participation in this study may be stopped if you fail to follow the study procedures or if the investigators feels that it is in your best interest to stop participation.

Consent Statement

I have read the above information. I agree to participate in this study. I have received a copy of this form.

Subject's Name: ___________________ Subject's Signature: ________________________ Date: _________

Investigator's Signature: ____________________________ Date: __________ Subject # ______

Appendix D: Recruitment Flyer

HAVE A TOTAL KNEE REPLACEMENT (TKR)? WANT TO ADVANCE THE UNDERSTANDING OF THE EFFECTS OF TKR?

A team of researchers from the department of Kinesiology Recreation and Sports Studies at UT are conducting a research study to understand the affects of TKR on various activities of daily living. Test and control participants will be required to attend one 1-1.5 hour testing session in the biomechanics/sports medicine lab.

Qualifications to participate in the study include:

- Between the ages of 35 and 70
- A TKR in one knee (Test)
- No TKR in one knee (Control)
- No other joint replacements
- Able to ascend/descend stairs

If you would like to participate or for more information contact Tyler Standifird at the UT Biomechanics/Sports Medicine Lab.
Office: 865-974-2091
Cel: 801-318-7326
Email: tstandif@utk.edu

Contact: Tyler S.
P: 974-2091
E: tstandif@utk.edu

Contact: Tyler S.
P: 974-2091
E: tstandif@utk.edu

Contact: Tyler S.
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E: tstandif@utk.edu

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E: tstandif@utk.edu

Contact: Tyler S.
P: 974-2091
E: tstandif@utk.edu

Contact: Tyler S.
P: 974-2091
E: tstandif@utk.edu

Appendix E: Physical Activity Readiness Survey

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

Name:________________________________ Date(MM/DD/YY): : _____/_____/_____

Please answer the following questions to the best of your knowledge (circle YES or NO).

1. **Yes** **No** Has your doctor ever said you had heart trouble or a heart murmur?

2. **Yes** **No** Do you ever suffer pains in your chest?

3. **Yes** **No** Do you ever feel faint or have spells of severe dizziness, passed out, palpitations or rapid heart beat?

4. **Yes** **No** Has the doctor ever told you that your blood pressure was too high? (systolic $\geq$ 160 mm Hg or diastolic $\geq$ 90 mm Hg on at least 2 separate occasions)

5. **Yes** **No** Do you smoke cigarettes?

6. **Yes** **No** Do you have any neuropathy as a result of diabetes?

7. **Yes** **No** Do you have a family history of coronary or other atherosclerotic disease in parents or siblings prior to age 55?

8. **Yes** **No** Has your serum cholesterol ever been elevated?

9. **Yes** **No** Is there any physical reason not mentioned here why you should not follow an activity program even if you wanted to?

Below please provide an explanation for any of the questions to which you answered YES.

____

____

____

____

____

____

Appendix F: Demographic Questionnaire

DEMOGRAPHIC QUESTIONNAIRE

Subject #:_________ Date (MM/DD/YY): _____/_____/_______

Date of Birth: _____/_____/_______ Shoe Size (US) _______________

Height: ___ Feet ___ Inches or ______ cm Weight: _________lbs or _________ kg

Gender (circle one): Female Male

For knee replacement subjects

Knee replacement side (circle one): Right Left

Date of replacement (MM/YY): _____/_______

Knee replacement type (circle one):

Posterior Stabilized Mobile Bearing Fixed Bearing Other Unknown

If select "Other", please provide more details below.

____

Office ________________and doctor who performed surgery ____________________

Rehabilitation clinic and duration: ___________________________

For all subjects

Osteoarthritis at any joints of the leg (circle one): Yes No

Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis): Yes No

Any other joint surgeries of the lower extremity (circle one): Yes No

If yes please explain further:

Joint: ____________ Type of surgery: ___________________________

Date of surgery (MM/YY): _____/_______

Appendix G: Knee Society Survey

DEMOGRAPHIC INFORMATION **(To be completed by patient)**

1- Today's date

☐☐ / ☐☐ / ☐☐☐☐

Enter dates as:
mm/dd/yyyy

2- Date of birth

☐☐ / ☐☐ / ☐☐☐☐

3- Height (ft' in")

☐ ☐☐

4- Weight (lbs.)

☐☐☐

5- Sex

○ Male ○ Female

6- Side of this (surgically treated) knee

○ Left ○ Right

If both knees have been operated on,
please use a different form for each knee

7- Ethnicity

○ Native Hawaiian or other Pacific Islander ○ American Indian or Alaska Native ○ Hispanic or Latino

○ Arab or Middle Eastern ○ African American or Black ○ Asian ○ White

8- Please indicate date and surgeon for your knee replacement operation

Date

☐☐ / ☐☐ / ☐☐☐☐

Enter dates as:
mm/dd/yyyy

Name of Surgeon

☐

9- Was this a primary or revision knee replacement?

○ Primary ○ Revision

To be completed by surgeon

10- Charnley Functional Classification **(Use Code Below)** ☐

A	Unilateral Knee Arthritis	C1	TKR, but remote arthritis affecting ambulation
B1	Unilateral TKA, opposite knee arthritic	C2	TKR, but medical condition affecting ambulation
B2	Bilateral TKA	C3	Unilateral or Bilateral TKA with Unilateral or Bilateral THR

SYMPTOMS

(To be completed by patient)

1- Pain with level walking (10 - Score)

0	1	2	3	4	5	6	7	8	9	10

none severe

2- Pain with stairs or inclines (10 - Score)

0	1	2	3	4	5	6	7	8	9	10

none severe

3- Does this knee feel "normal" to you? (5 points)

○ Always (5 pts) ○ Sometimes (3 pts) ○ Never (0 pts)

Maximum total points (25 points)

PATIENT SATISFACTION

1- Currently, how satisfied are you with the pain level of your knee while sitting? (8 points)

○ Very Satisfied (8 pts) ○ Satisfied (6 pts) ○ Neutral (4 pts) ○ Dissatisfied (2 pts) ○ Very Dissatisfied (0 pts)

2- Currently, how satisfied are you with the pain level of your knee while lying in bed? (8 points)

○ Very Satisfied (8 pts) ○ Satisfied (6 pts) ○ Neutral (4 pts) ○ Dissatisfied (2 pts) ○ Very Dissatisfied (0 pts)

3- Currently, how satisfied are you with your knee function while getting out of bed? (8 points)

○ Very Satisfied (8 pts) ○ Satisfied (6 pts) ○ Neutral (4 pts) ○ Dissatisfied (2 pts) ○ Very Dissatisfied (0 pts)

4- Currently, how satisfied are you with your knee function while performing light household duties? (8 points)

○ Very Satisfied (8 pts) ○ Satisfied (6 pts) ○ Neutral (4 pts) ○ Dissatisfied (2 pts) ○ Very Dissatisfied (0 pts)

5- Currently, how satisfied are you with your knee function while performing leisure recreational activities? (8 points)

○ Very Satisfied (8 pts) ○ Satisfied (6 pts) ○ Neutral (4 pts) ○ Dissatisfied (2 pts) ○ Very Dissatisfied (0 pts)

Maximum total points (40 points)

PATIENT EXPECTATION (To be completed by patient)

Compared to what you expected before your knee replacement:

1- My expectations for pain relief were... **(5 points)**

- ○ Too High- "I'm a lot worse than I thought" (1 pt)
- ○ Too High- "I'm somewhat worse than I thought" (2 pts)
- ○ Just Right- "My expectations were met" (3 pts)
- ○ Too Low- "I'm somewhat better than I thought" (4 pts)
- ○ Too Low- "I'm a lot better than I thought" (5 pts)

2- My expectations for being able to do my normal activities of daily living were... **(5 points)**

- ○ Too High- "I'm a lot worse than I thought" (1 pt)
- ○ Too High- "I'm somewhat worse than I thought" (2 pts)
- ○ Just Right- "My expectations were met" (3 pts)
- ○ Too Low- "I'm somewhat better than I thought" (4 pts)
- ○ Too Low- "I'm a lot better than I thought" (5 pts)

3- My expectations for being able to do my leisure, recreational or sports activities were... **(5 points)**

- ○ Too High- "I'm a lot worse than I thought" (1 pt)
- ○ Too High- "I'm somewhat worse than I thought" (2 pts)
- ○ Just Right- "My expectations were met" (3 pts)
- ○ Too Low- "I'm somewhat better than I thought" (4 pts)
- ○ Too Low- "I'm a lot better than I thought" (5 pts)

Maximum total points (15 points)

FUNCTIONAL ACTIVITIES (To be completed by patient)

WALKING AND STANDING (30 points)

1 - Can you walk without any aids (such as a cane, crutches or wheelchair)? **(0 points)**

○ Yes ○ No

2 - If no, which of the following aid(s) do you use? **(-10 points)**

○ wheelchair (-10 pts) ○ walker (-8 pts) ○ crutches (-8 pts) ○ two canes (-6 pts)

○ one crutch (-4 pts) ○ one cane (-4 pts) ○ knee sleeve / brace (-2 pts)

○ other

3 - Do you use these aid(s) because of your knees? **(0 points)**

○ Yes ○ No

4 - For how long can you stand (with or without aid) before sitting due to knee discomfort? **(15 points)**

○ cannot stand (0 pts) ○ 0-5 minutes (3 pts) ○ 6-15 minutes (6 pts)

○ 16-30 minutes (9 pts) ○ 31-60 minutes (12 pts) ○ more than an hour (15 pts)

5 - For how long can you walk (with or without aid) before stopping due to knee discomfort? **(15 points)**

○ cannot walk (0 pts) ○ 0-5 minutes (3 pts) ○ 6-15 minutes (6 pts)

○ 16-30 minutes (9 pts) ○ 31-60 minutes (12 pts) ○ more than an hour (15 pts)

Maximum points (30 points)

STANDARD ACTIVITIES (30 points)

How much does your knee bother you during each of the following activities?	no bother 5	slight 4	moderate 3	severe 2	very severe 1	cannot do (because of knee) 0	I never do this	
1 - Walking on an uneven surface	○	○	○	○	○	○	○	
2 - Turning or pivoting on your leg	○	○	○	○	○	○	○	
3 - Climbing up or down a flight of stairs	○	○	○	○	○	○	○	
4 - Getting up from a low couch or a chair without arms	○	○	○	○	○	○	○	
5 - Getting into or out of a car	○	○	○	○	○	○	○	
6 - Moving laterally (stepping to the side)	○	○	○	○	○	○	○	

Maximum points (30 points)

ADVANCED ACTIVITIES (25 points)

1 - Climbing a ladder or step stool	○	○	○	○	○	○	○	
2 - Carrying a shopping bag for a block	○	○	○	○	○	○	○	
3 - Squatting	○	○	○	○	○	○	○	
4 - Kneeling	○	○	○	○	○	○	○	
5 - Running	○	○	○	○	○	○	○	

Maximum points (25 points)

DISCRETIONARY KNEE ACTIVITIES (15 points)

Please check 3 of the activities below that you consider *most important* to you.
(Please do not write in additional activities)

Recreational Activities

- ☐ Swimming
- ☐ Golfing (18 holes)
- ☐ Road Cycling (>30mins)
- ☐ Gardening
- ☐ Bowling
- ☐ Racquet Sports (Tennis, Racquetball, etc.)
- ☐ Distance Walking
- ☐ Dancing / Ballet
- ☐ Stretching Exercises (stretching out your muscles)

Workout and Gym Activities

- ☐ Weight-lifting
- ☐ Leg Extensions
- ☐ Stair-Climber
- ☐ Stationary Biking / Spinning
- ☐ Leg Press
- ☐ Jogging
- ☐ Elliptical Trainer
- ☐ Aerobic Exercises

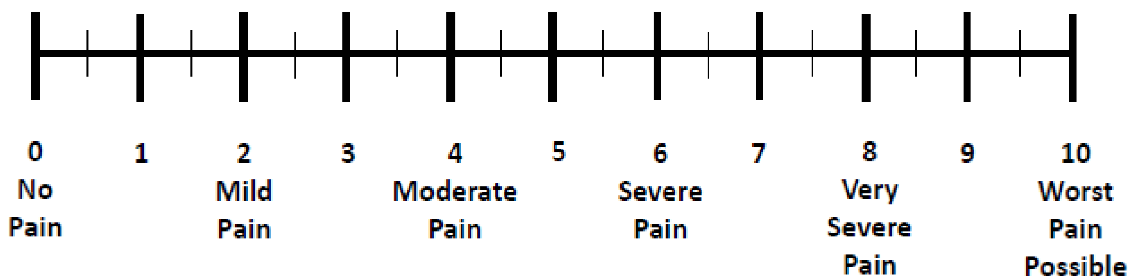
Please copy all 3 checked activities into the empty boxes below.

How much does your knee bother you during each of these activities?

Activity (Please write the 3 activites from list above)	no bother 5	slight 4	moderate 3	severe 2	very severe 1	cannot do (because of knee) 0	
1.	○	○	○	○	○	○	
2.	○	○	○	○	○	○	
3.	○	○	○	○	○	○	
						Maximum points (15 points)	

Appendix H: Visual Analogue Pain Scale

Pain Intensity Scale



Appendix I: Individual Results for Select Variables

Table 20. Loading-response and push-off Peak Vertical GRF.

Subject	Loading-response Peak Vertical GRF (BW)				Push-off Peak Vertical GRF (BW)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	1.069±0.008	0.985±0.031	0.994±0.043	0.969±0.024	1.070±0.003	1.168±0.121	1.196±0.028	1.159±0.019
2	1.095±0.034	1.058±0.021	0.998±0.077	1.109±0.070	1.130±0.032	1.098±0.110	1.068±0.080	1.081±0.046
3	1.025±0.043	0.943±0.028	0.919±0.019	0.971±0.025	1.044±0.019	1.125±0.024	1.073±0.069	1.055±0.017
7	1.007±0.025	1.065±0.027	1.070±0.006	1.051±0.032	1.043±0.023	1.011±0.048	1.020±0.018	1.065±0.046
8	1.160±0.056	0.930±0.036	0.881±0.026	0.886±0.043	1.080±0.013	1.261±0.035	1.258±0.040	1.282±0.095
10	1.090±0.035	0.986±0.023	1.027±0.032	0.998±0.026	1.058±0.013	1.076±0.067	1.053±0.035	1.164±0.095
11	1.171±0.033	1.056±0.029	1.093±0.033	1.138±0.054	1.113±0.026	1.141±0.033	1.112±0.092	1.015±0.078
12	1.306±0.021	1.129±0.031	1.181±0.039	1.167±0.055	1.169±0.044	1.034±0.042	0.993±0.047	0.974±0.067
13	1.170±0.045	0.944±0.016	0.991±0.016	0.954±0.026	1.118±0.026	1.251±0.070	1.344±0.024	1.267±0.027
14	1.274±0.032	1.136±0.018	1.115±0.024	1.094±0.018	1.054±0.041	0.914±0.040	1.037±0.038	1.032±0.035
15	1.139±0.019	1.109±0.039	1.138±0.053	1.099±0.059	0.999±0.010	0.847±0.030	0.849±0.037	0.910±0.076
16	1.081±0.035	1.121±0.041	1.106±0.056	1.105±0.048	1.118±0.048	1.068±0.069	1.140±0.066	1.193±0.045
mean	1.132±0.091	1.038±0.078	1.043±0.090	1.045±0.087	1.083±0.047	1.083±0.122	1.095±0.129	1.100±0.115

Table 21. Mediolateral COP displacement and peak toe out angle.

Subject	ML COP Displacement (m)				Peak Toe-Out Angle (Deg)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	-	0.002±0.006	0.009±0.008	0.003±0.009	-6.941±0.692	-3.114±1.616	-2.864±1.700	-5.408±2.311
2	-	-0.002±0.007	0.022±0.002	0.017±0.004	-2.668±0.672	-0.922±1.570	-2.591±0.583	-4.397±1.529
3	-	0.016±0.006	-	0.018±0.006	-5.482±1.088	-6.661±1.819	-9.132±0.927	-9.526±1.550
7	-	0.002±0.006	0.009±0.005	0.000±0.006	-7.665±1.781	-4.108±1.189	-7.950±2.259	-8.035±1.640
8	-	0.011±0.005	0.004±0.006	0.003±0.003	-3.589±1.429	0.933±1.914	0.295±2.190	0.205±1.278
10	-	0.018±0.004	0.017±0.002	0.005±0.007	-5.227±1.451	-6.719±1.129	-6.515±1.445	-6.475±0.338
11	-	0.015±0.003	0.010±0.009	-0.003±0.008	-11.385±1.202	-13.453±1.006	-15.483±1.257	-14.520±1.684
12	-	0.020±0.003	0.025±0.008	0.018±0.006	-12.128±0.780	-10.782±0.580	-13.771±1.863	-16.022±2.495
13	-	0.019±0.005	0.017±0.006	0.012±0.005	-10.681±0.264	-10.475±1.016	-9.966±0.750	-14.057±1.302
14	-	0.004±0.002	0.012±0.005	0.005±0.002	-9.242±1.477	-7.484±2.439	-12.352±3.405	-11.639±1.639
15	-	0.026±0.003	0.031±0.002	0.023±0.003	-10.370±0.979	-9.112±0.970	-12.332±1.691	-13.002±1.511
16	-	0.005±0.001	0.011±0.002	-0.001±0.005	-7.389±0.504	-5.526±0.735	-7.980±0.826	-7.264±0.992
mean	-	0.011±0.009	0.015±0.008	0.009±0.009	-7.731±3.097	-6.452±4.208	-8.387±4.834	-9.178±4.837

Table 22. Sagittal ankle contact angle and plantarflexion ROM.

Subject	**Ankle Contact Angle (deg)**				**Plantarflexion ROM (deg)**			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	2.726±1.482	4.472±1.310	20.388±3.403	24.730±2.382	-20.055±2.616	-19.612±3.937	-34.741±4.083	-42.851±5.593
2	4.452±0.440	12.164±1.152	19.744±1.084	21.305±1.201	-16.990±1.460	-28.985±3.666	-38.319±3.298	-36.809±1.492
3	-0.938±2.158	14.258±5.468	21.288±1.215	19.268±0.735	-15.682±3.141	-17.272±5.652	-39.068±1.665	-31.185±1.908
7	-3.705±1.278	3.588±2.091	16.289±1.257	16.684±0.427	-28.277±1.628	-25.287±2.784	-41.026±1.195	-38.091±0.992
8	3.684±1.834	14.127±3.783	24.971±1.885	27.085±0.980	-17.689±3.026	-19.938±1.392	-37.218±1.628	-36.291±4.308
10	2.395±0.508	9.074±1.601	20.241±1.275	19.495±1.007	-21.259±2.392	-38.716±2.998	-49.679±1.711	-50.459±4.240
11	5.891±0.503	16.875±2.003	18.290±2.914	19.633±0.940	-24.601±2.026	-37.317±1.287	-39.499±4.971	-44.057±1.809
12	0.393±0.637	6.899±1.073	8.296±1.289	9.933±1.079	-8.979±1.353	-19.726±1.088	-22.345±1.814	-25.533±2.930
13	3.130±0.582	3.991±3.243	11.005±0.890	12.141±0.906	-21.012±1.492	-20.085±3.557	-31.173±1.772	-30.885±1.340
14	15.762±1.643	28.772±1.788	33.170±2.823	30.967±0.560	-28.111±1.861	-41.307±1.770	-44.125±3.699	-46.126±1.192
15	-0.803±0.263	6.401±1.020	8.617±1.219	8.936±0.569	-16.569±2.224	-23.477±2.105	-25.035±1.582	-25.673±1.702
16	0.556±0.577	8.179±0.559	14.796±1.048	13.994±2.133	-14.774±1.276	-20.357±2.170	-23.896±0.730	-23.322±2.623
mean	2.795±4.875	10.733±7.183	18.091±7.056	18.681±6.790	-19.500±5.630	-26.007±8.527	-35.510±8.432	-35.940±8.815

Table 23. Loading-response and push-off peak plantarflexion moments.

Subject	Loading-response Peak Plantarflexion Moment (Nm/kg)				Push-off Peak Plantarflexion Moment (Nm/kg)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	-	-0.461±0.204	-0.730±0.129	-0.660±0.027	-1.418±0.010	-1.244±0.095	-1.378±0.063	-1.293±0.041
2	-	-0.922±0.060	-0.944±0.115	-1.036±0.097	-1.701±0.046	-1.317±0.133	-1.325±0.093	-1.365±0.057
3	-	-0.396±0.004	-0.342±0.000	-0.623±0.374	-1.488±0.042	-1.390±0.091	-1.020±0.095	-1.102±0.080
7	-	-0.135±0.049	-0.383±0.083	-0.297±0.055	-1.352±0.027	-0.966±0.060	-1.002±0.033	-1.033±0.031
8	-	-0.188±0.057	-0.536±0.037	-0.608±0.147	-1.474±0.018	-1.249±0.047	-1.232±0.015	-1.253±0.064
10	-	-0.347±0.140	-0.465±0.207	-0.435±0.159	-1.173±0.042	-0.843±0.041	-0.869±0.036	-0.974±0.071
11	-	-0.355±0.082	-0.448±0.094	-0.768±0.322	-1.451±0.047	-1.061±0.039	-1.111±0.108	-1.016±0.158
12	-	-0.885±0.069	-1.079±0.071	-1.163±0.059	-1.635±0.021	-1.096±0.057	-1.172±0.047	-1.151±0.038
13	-	-0.528±0.106	-0.590±0.094	-0.646±0.053	-1.394±0.035	-1.094±0.045	-1.260±0.026	-1.285±0.017
14	-	-0.598±0.169	-0.793±0.062	-0.842±0.041	-1.174±0.066	-0.780±0.062	-0.975±0.023	-0.973±0.023
15	-	-0.919±0.076	-1.102±0.111	-1.150±0.101	-1.412±0.018	-0.916±0.043	-0.988±0.061	-1.104±0.079
16	-	-0.929±0.078	-0.979±0.054	-1.055±0.048	-1.537±0.052	-1.209±0.068	-1.312±0.056	-1.368±0.051
mean	-	-0.555±0.294	-0.699±0.276	-0.774±0.281	-1.434±0.157	-1.097±0.192	-1.137±0.166	-1.160±0.148

Table 24. Sagittal knee contact angle and extension ROM.

Subject	Knee Contact Angle (deg)				Knee Extension ROM (deg)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	-2.931±0.677	-59.047±1.828	-74.627±3.201	-79.224±1.559	52.827±1.289	42.463±2.406	59.466±4.423	63.859±2.243
2	8.985±0.745	-51.453±4.897	-63.358±1.400	-64.812±0.938	60.899±1.209	44.062±3.800	55.635±1.763	57.382±2.389
3	-1.423±0.976	-64.150±3.252	-71.476±0.649	-68.566±0.924	54.549±0.804	50.209±2.910	57.801±1.035	55.393±2.525
7	4.164±0.702	-52.378±1.592	-62.155±0.662	-63.050±0.993	51.446±1.910	51.236±1.448	60.392±2.496	63.609±0.781
8	-3.905±1.333	-55.024±3.740	-69.761±1.101	-78.325±0.678	41.864±2.176	31.911±3.485	56.476±3.553	59.413±0.899
10	-1.283±2.411	-50.540±1.487	-68.178±4.279	-63.869±0.526	45.982±1.854	44.582±1.091	59.397±2.957	61.455±1.322
11	4.862±1.055	-63.452±2.678	-67.577±1.574	-65.387±1.815	51.467±0.899	57.619±1.339	61.930±2.091	59.940±4.371
12	-1.881±0.135	-62.251±1.798	-75.026±2.363	-76.074±2.752	50.734±1.710	42.842±2.481	58.754±2.367	58.414±2.888
13	-1.499±0.740	-62.176±3.585	-72.001±2.834	-73.331±0.669	47.857±1.118	48.980±3.773	60.742±3.513	63.051±2.912
14	1.824±0.965	-48.287±5.049	-62.071±0.999	-66.696±2.481	49.574±1.732	34.201±3.790	47.514±1.564	51.701±2.480
15	-5.651±1.030	-57.273±3.752	-69.248±1.127	-73.544±0.906	44.686±1.948	40.383±3.391	52.457±1.222	57.098±0.977
16	0.517±1.219	-61.452±1.797	-73.495±0.936	-75.516±2.578	49.300±1.068	45.235±1.447	57.232±2.127	61.360±1.799
mean	0.148±4.159	-57.290±5.591	-69.081±4.605	-70.699±5.928	50.099±4.936	44.477±7.130	57.316±4.011	59.390±3.630

Table 25. Sagittal hip contact angle and extension ROM.

Subject	Hip Contact Angle (deg)				Hip Extension ROM (deg)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	14.193±0.663	48.775±1.555	43.135±1.460	42.932±2.445	-35.627±0.287	-55.397±3.278	-49.817±2.077	-50.123±2.800
2	16.620±0.963	55.247±1.057	53.997±0.822	54.814±1.558	-38.282±0.942	-52.160±1.041	-56.423±3.197	-52.298±2.624
3	26.942±1.011	55.682±1.406	58.718±1.875	57.306±1.417	-33.553±1.110	-48.825±0.332	-50.570±2.243	-47.759±1.607
7	22.710±1.543	47.817±1.690	46.190±1.617	46.668±0.375	-38.622±1.336	-50.582±1.839	-49.290±1.158	-48.432±0.945
8	51.983±0.859	63.843±0.713	63.426±1.561	71.281±1.530	-57.907±0.840	-46.866±1.571	-52.989±2.918	-58.075±1.373
10	23.866±1.607	54.903±1.343	61.703±1.826	60.852±2.749	-40.378±2.881	-47.218±2.020	-53.072±2.380	-51.935±4.235
11	24.940±2.024	50.672±1.204	50.424±1.690	47.995±1.934	-39.998±2.303	-47.657±2.139	-46.509±2.803	-44.318±3.471
12	24.739±0.767	51.752±1.431	52.707±1.640	51.305±0.831	-41.193±0.773	-51.270±2.413	-53.870±1.769	-51.880±1.024
13	29.740±0.766	58.608±1.045	60.310±0.901	61.537±1.218	-45.706±1.912	-52.477±1.868	-54.307±1.822	-57.623±2.165
14	24.814±1.085	52.732±1.657	55.176±1.255	56.019±0.756	-30.204±1.382	-38.204±1.047	-40.490±1.008	-43.177±1.483
15	24.535±0.946	52.850±0.834	50.817±0.607	49.920±0.316	-35.479±0.722	-45.334±1.672	-43.605±0.875	-44.809±0.447
16	34.374±0.720	58.025±0.963	59.980±1.290	59.193±1.252	-37.251±1.306	-46.515±2.001	-48.161±1.266	-48.571±1.167
mean	26.621±9.556	54.242±4.507	54.715±6.360	54.985±7.802	-39.517±7.016	-48.542±4.410	-49.925±4.679	-49.917±4.778

Table 26. Loading-response and push-off peak knee extension moments.

Subject	**Loading-response Peak Knee Extension Moment (Nm/kg)**				**Push-off Peak Knee Extension Moment (Nm/kg)**			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	0.784±0.022	1.426±0.141	1.360±0.131	1.451±0.112	0.364±0.005	0.498±0.265	0.372±0.134	0.364±0.068
2	0.834±0.075	1.232±0.170	1.311±0.148	1.394±0.046	0.306±0.018	0.250±0.057	0.341±0.193	0.025±0.085
3	0.743±0.052	1.355±0.068	1.134±0.050	1.646±0.100	0.743±0.052	0.482±0.103	0.102±0.059	0.274±0.102
7	0.321±0.086	1.297±0.060	1.333±0.039	1.288±0.043	0.331±0.031	0.000±0.037	-0.048±0.024	-0.021±0.020
8	0.575±0.057	1.025±0.076	0.952±0.073	0.961±0.059	0.245±0.006	1.035±0.078	0.972±0.139	1.053±0.183
10	0.907±0.067	1.335±0.039	1.357±0.127	1.291±0.077	0.368±0.023	0.741±0.112	0.765±0.053	0.639±0.112
11	0.431±0.376	1.552±0.032	1.561±0.071	1.436±0.030	0.299±0.075	0.096±0.082	0.135±0.136	0.106±0.053
12	1.089±0.066	1.482±0.036	1.652±0.059	1.501±0.110	0.259±0.014	0.677±0.137	0.434±0.091	0.563±0.221
13	0.868±0.092	1.234±0.058	1.284±0.035	1.134±0.072	0.428±0.029	0.758±0.106	0.662±0.097	0.472±0.065
14	1.084±0.076	1.425±0.119	1.262±0.032	1.183±0.051	0.320±0.024	0.292±0.067	0.269±0.075	0.277±0.036
15	0.751±0.065	1.334±0.098	1.402±0.084	1.371±0.080	0.258±0.022	0.371±0.059	0.354±0.007	-
16	0.807±0.052	1.428±0.126	1.573±0.170	1.606±0.132	0.346±0.019	0.320±0.037	0.407±0.074	0.311±0.066
mean	0.766±0.232	1.344±0.139	1.348±0.192	1.355±0.197	0.356±0.133	0.460±0.300	0.397±0.288	0.370±0.310

Table 27. Peak hip flexion moment and peak ankle eversion angle.

Subject	Peak Hip Flexion Moment (Nm/kg)				Peak Ankle Eversion Angle (deg)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	0.738±0.039	0.365±0.109	0.485±0.031	0.390±0.070	-9.935±0.935	-15.240±2.009	-16.365±3.072	-15.777±2.123
2	1.056±0.062	0.705±0.090	0.818±0.079	0.719±0.096	-8.431±0.386	-6.427±1.668	-7.709±1.878	-7.519±1.757
3	0.501±0.069	0.390±0.035	0.169±0.052	0.028±0.038	-8.638±0.275	-9.042±2.064	-8.301±1.727	-10.600±1.120
7	0.889±0.028	0.401±0.112	0.505±0.065	0.399±0.007	-11.767±1.497	-9.762±2.102	-10.412±1.488	-12.235±1.208
8	0.932±0.038	0.584±0.041	0.701±0.087	0.522±0.050	-22.628±1.358	-21.045±1.552	-22.431±1.262	-22.030±0.570
10	1.115±0.090	0.712±0.062	0.718±0.055	0.616±0.039	-14.383±1.124	-12.904±1.641	-11.185±2.122	-15.807±1.584
11	0.897±0.020	0.375±0.032	0.463±0.077	0.382±0.049	-14.256±1.147	-11.293±1.109	-12.382±1.763	-11.633±2.175
12	0.856±0.014	0.587±0.072	0.607±0.021	0.565±0.072	-9.262±0.718	-9.155±0.542	-8.028±1.247	-6.769±1.122
13	0.807±0.052	0.459±0.034	0.467±0.053	0.320±0.047	-10.995±0.479	-9.398±0.995	-10.331±2.269	-8.762±0.861
14	0.931±0.038	0.355±0.054	0.374±0.051	0.322±0.064	-19.666±1.824	-19.224±4.036	-17.662±1.656	-16.950±1.146
15	0.528±0.037	0.324±0.054	0.324±0.033	0.221±0.024	-13.377±0.290	-15.849±0.718	-14.515±0.539	-13.692±0.491
16	0.665±0.026	0.229±0.028	0.232±0.054	0.171±0.024	-17.274±0.329	-16.569±0.522	-16.912±0.677	-17.003±0.601
mean	0.826±0.190	0.457±0.155	0.489±0.198	0.388±0.196	-13.384±4.533	-12.992±4.566	-13.020±4.591	-13.231±4.509

Table 28. Loading-response and push-off peak ankle inversion moments.

Subject	**Loading-response Peak Ankle Inversion Moment (Nm/kg)**				**Push-off Peak Ankle Inversion Moment (Nm/kg)**			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	-	0.201±0.040	0.342±0.062	0.215±0.021	0.115±0.019	0.271±0.042	0.327±0.045	0.110±0.084
2	-	0.137±0.029	0.192±0.039	0.121±0.017	-	0.008±0.005	-	-
3	-	0.306±0.026	0.450±0.023	0.500±0.054	0.415±0.014	0.473±0.032	0.610±0.048	0.567±0.055
7	-	0.246±0.031	0.349±0.052	0.179±0.007	0.241±0.031	0.318±0.034	0.409±0.018	0.252±0.034
8	-	0.153±0.029	0.195±0.058	0.101±0.024	0.318±0.015	0.244±0.025	0.269±0.046	0.142±0.041
10	-	0.188±0.021	0.228±0.026	0.154±0.060	0.128±0.023	0.198±0.033	0.279±0.027	0.167±0.099
11	-	0.290±0.069	0.308±0.034	0.304±0.105	0.323±0.025	0.288±0.083	0.349±0.066	0.198±0.049
12	-	0.337±0.010	0.390±0.027	0.308±0.026	0.246±0.043	0.279±0.034	0.182±0.024	0.151±0.044
13	-	0.260±0.023	0.336±0.019	0.233±0.022	0.258±0.006	0.325±0.059	0.427±0.044	0.273±0.022
14	-	0.145±0.058	0.228±0.032	0.133±0.009	0.062±0.030	-	0.102±0.012	-0.001±0.002
15	-	0.528±0.012	0.606±0.049	0.493±0.018	0.428±0.027	0.294±0.070	0.322±0.028	-
16	-	0.317±0.018	0.400±0.028	0.306±0.017	0.137±0.034	0.173±0.059	0.306±0.051	0.272±0.039
mean	-	0.259±0.110	0.335±0.120	0.254±0.134	0.24±0.10	0.29±0.9	0.35±0.12	0.24±0.14

Table 29. Frontal plane knee contact angle and knee abduction ROM.

Subject	Knee Contact Angle (deg)				Knee Abduction ROM (deg)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	0.579±0.765	7.542±1.092	6.842±0.564	7.258±1.451	0.059±0.867	-7.266±0.989	-5.800±1.186	-7.005±1.268
2	0.624±0.303	9.684±2.057	11.938±0.850	14.144±1.494	-0.443±0.320	-7.931±2.335	-11.639±0.851	-13.017±1.069
3	-4.345±0.145	15.394±1.184	17.361±1.111	17.517±0.763	1.662±0.465	-16.886±1.088	-17.990±1.175	-18.718±1.035
7	-1.769±0.764	-8.652±1.289	-8.284±1.024	-7.226±1.716	-2.442±2.219	-4.212±0.516	-4.970±1.133	-4.614±0.343
8	-8.404±0.275	17.041±1.649	14.655±3.829	22.639±1.952	-0.353±0.391	-17.153±1.425	-18.347±3.038	-23.811±2.110
10	-5.925±0.252	1.050±1.977	1.027±2.067	0.920±2.914	-2.761±0.281	-4.667±2.163	-5.346±1.991	-4.200±2.360
11	4.307±0.842	14.248±1.928	13.316±2.133	12.541±1.156	-4.838±1.590	-13.798±1.070	-13.086±2.673	-11.461±0.582
12	1.499±0.307	11.353±0.522	11.513±0.814	10.241±1.105	-2.082±1.376	-7.179±1.017	-7.893±1.424	-5.558±0.853
13	1.323±0.227	20.496±1.240	19.488±1.146	20.180±1.320	-0.679±0.193	-16.656±0.952	-16.638±1.717	-17.414±0.982
14	0.279±0.479	4.813±1.900	4.240±2.409	3.961±1.544	-0.881±0.715	-4.973±2.254	-4.760±2.746	-4.904±1.850
15	0.783±0.213	21.527±0.755	21.936±1.391	22.106±0.885	0.104±0.422	-13.514±3.683	-16.694±0.887	-15.344±2.465
16	2.114±0.127	7.654±0.890	7.042±0.219	7.718±0.638	-1.637±0.206	-6.167±1.390	-6.827±0.639	-7.486±1.090
mean	-0.745±3.687	10.179±8.569	10.089±8.485	11.000±9.078	-1.191±1.687	-10.033±5.146	-10.833±5.501	-11.128±6.536

Table 30. Loading-response and push-off peak knee abduction moments.

Subject	**Loading-response Knee Peak Abduction Moment (Nm/kg)**				**Push-off Peak Knee Abduction Moment (Nm/kg)**			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	-0.503±0.017	-0.368±0.043	-0.274±0.038	-0.359±0.020	-0.452±0.021	-0.288±0.037	-0.145±0.008	-0.283±0.036
2	-0.369±0.021	-0.326±0.166	-0.279±0.066	-0.399±0.052	-0.513±0.026	-0.241±0.024	-0.183±0.061	-0.221±0.046
3	-0.368±0.027	-0.209±0.020	-	-0.717±0.057	-0.233±0.027	-0.157±0.040	-0.132±0.097	-
7	-0.322±0.038	-	-	-	-0.283±0.035	-0.208±0.011	-0.034±0.009	-0.257±0.058
8	-0.323±0.008	-0.289±0.065	-0.133±0.102	-0.404±0.053	-0.114±0.039	-0.153±0.061	-0.014±0.061	-0.292±0.076
10	-0.367±0.048	-0.255±0.062	-0.014±0.016	-0.287±0.083	-0.127±0.020	-0.084±0.000	-0.156±0.036	-0.104±0.000
11	-0.575±0.027	-0.282±0.051	-0.222±0.079	-0.288±0.083	-0.315±0.051	-0.087±0.041	-0.080±0.116	-0.101±0.029
12	-0.728±0.036	-0.473±0.013	-0.462±0.028	-0.580±0.048	-0.352±0.047	-0.284±0.087	-0.238±0.000	-0.294±0.102
13	-0.679±0.012	-0.389±0.019	-0.292±0.054	-0.343±0.018	-0.364±0.020	-0.262±0.017	-0.145±0.049	-0.226±0.038
14	-0.555±0.038	-0.285±0.054	-0.169±0.037	-0.273±0.018	-0.317±0.017	-0.138±0.013	-	-0.163±0.023
15	-0.702±0.033	-0.620±0.055	-0.545±0.029	-0.632±0.073	-0.330±0.018	-0.202±0.026	-	-0.174±0.000
16	-0.495±0.010	-0.327±0.034	-0.204±0.022	-0.277±0.038	-0.672±0.021	-0.333±0.019	-0.234±0.019	-0.365±0.037
mean	-0.499±0.150	-0.37±0.11	-0.28±0.14	-0.39±0.13	-0.339±0.156	-0.21±0.08	-0.12±0.08	-0.23±0.08

Table 31. Peak hip adduction angle and adduction ROM.

Subject	Peak Hip Adduction Angle (deg)				Hip Adduction ROM (deg)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	9.338±0.332	7.675±1.139	8.600±1.098	10.864±1.502	6.153±0.873	2.284±0.722	1.754±0.820	2.505±0.588
2	5.316±0.321	1.981±1.529	3.298±1.275	3.795±1.099	6.032±0.796	1.329±0.991	3.389±0.868	4.491±1.584
3	8.783±1.082	14.021±0.863	14.296±0.414	15.051±0.913	2.184±0.660	4.860±0.744	6.341±0.369	5.286±0.374
7	10.761±0.283	16.392±0.311	16.006±0.468	17.129±0.506	9.175±0.874	6.584±0.657	5.318±0.948	5.492±1.089
8	12.382±1.217	13.378±1.070	12.716±0.516	12.678±0.707	10.439±1.017	6.535±0.342	9.194±1.184	6.837±0.701
10	7.019±0.710	8.558±0.818	11.554±1.285	11.557±0.480	2.530±1.161	2.429±1.393	4.636±1.384	4.006±1.278
11	6.498±0.566	7.837±0.572	7.412±0.700	9.212±1.528	8.763±0.414	5.792±0.825	5.719±1.184	6.976±1.219
12	8.986±0.233	7.509±0.634	9.453±1.140	7.747±0.940	10.150±0.188	6.477±0.745	5.635±1.769	5.119±1.255
13	8.559±0.496	7.693±0.564	9.169±0.470	9.872±0.305	10.670±0.658	6.256±0.563	5.215±0.630	4.974±0.490
14	8.292±0.900	11.669±0.701	12.990±1.191	12.046±0.793	5.606±1.529	3.299±0.439	3.351±0.585	4.799±1.640
15	8.742±0.492	4.883±0.862	6.151±0.314	5.309±0.573	6.006±0.557	5.043±0.716	5.529±1.309	5.423±0.671
16	6.797±0.231	8.408±0.395	10.060±0.644	10.179±0.475	5.875±0.454	2.751±0.507	4.083±0.467	4.572±0.671
mean	8.456±1.919	9.167±4.041	10.142±3.598	10.453±3.750	6.965±2.893	4.470±1.938	5.014±1.848	5.040±1.186

Table 32. Loading-response and push-off peak hip abduction moments.

Subject	Loading-response Peak Hip Abduction Moment (Nm/kg)				Push-off Peak Hip Abduction Moment (Nm/kg)			
	Walking	Step One	Step Two	Step Three	Walking	Step One	Step Two	Step Three
1	-1.144±0.008	-0.942±0.048	-0.738±0.044	-0.866±0.063	-1.080±0.013	-0.788±0.094	-0.594±0.042	-0.793±0.083
2	-0.855±0.046	-0.650±0.035	-0.515±0.069	-0.705±0.102	-0.971±0.043	-0.376±0.040	-0.201±0.076	-0.336±0.063
3	-0.955±0.051	-0.800±0.024	-0.607±0.049	-0.870±0.065	-1.038±0.039	-0.792±0.036	-0.535±0.119	-0.594±0.068
7	-1.047±0.030	-1.257±0.036	-0.952±0.032	-1.287±0.072	-1.038±0.047	-0.819±0.041	-0.586±0.013	-0.863±0.103
8	-1.064±0.021	-0.597±0.083	-0.427±0.079	-0.606±0.057	-0.924±0.035	-0.289±0.057	-0.288±0.078	-0.455±0.045
10	-0.708±0.374	-0.785±0.072	-0.572±0.208	-0.869±0.060	-0.841±0.039	-0.577±0.108	-0.600±0.104	-0.681±0.040
11	-0.919±0.015	-0.760±0.065	-0.683±0.085	-0.831±0.098	-0.931±0.065	-0.485±0.026	-0.342±0.068	-0.424±0.027
12	-1.371±0.027	-1.059±0.055	-0.930±0.041	-1.166±0.046	-1.005±0.058	-0.635±0.077	-0.412±0.038	-0.538±0.065
13	-1.037±0.033	-0.658±0.031	-0.557±0.061	-0.709±0.027	-0.878±0.031	-0.645±0.063	-0.521±0.044	-0.639±0.045
14	-1.409±0.061	-1.102±0.048	-0.824±0.028	-1.066±0.024	-0.941±0.077	-0.483±0.047	-0.389±0.064	-0.543±0.033
15	-1.152±0.011	-0.925±0.073	-0.812±0.057	-0.943±0.111	-0.978±0.015	-0.463±0.047	-0.396±0.020	-0.505±0.298
16	-0.893±0.023	-0.761±0.037	-0.595±0.041	-0.808±0.048	-1.074±0.054	-0.596±0.076	-0.479±0.065	-0.689±0.034
mean	-1.046±0.204	-0.858±0.202	-0.684±0.168	-0.894±0.197	-0.975±0.076	-0.579±0.168	-0.445±0.129	-0.588±0.154

Table 33. Functional testing times and testing ascent velocities in control and TKR.

Subject	Group	Timed up and Go (sec)	Functional Ascent Time (sec)	Functional Descent Time (sec)	Testing Ascent Velocity (sec)
1	Control	7.98	6.48	6.14	0.69
3	Control	7.55	6.51	6.20	0.41
7	Control	7.29	6.31	5.98	0.75
8	Control	5.98	6.10	5.74	0.73
10	Control	9.02	6.01	5.84	0.62
11	Control	8.32	6.38	5.90	0.73
12	Control	6.03	3.91	3.37	0.79
14	Control	5.82	5.85	5.54	0.72
15	Control	5.71	6.11	4.89	0.82
16	Control	7.07	4.61	4.30	0.73
22	Control	4.99	4.25	3.84	0.82
26	Control	6.80	5.21	4.71	1.00
28	Control	4.98	4.35	3.32	1.24
29	Control	6.85	5.66	5.29	0.84
30	Control	7.58	6.98	6.73	0.71
4	TKR	6.89	6.85	5.84	0.68
5	TKR	7.08	8.07	8.07	0.39
6	TKR	7.39	6.94	6.40	0.65
9	TKR	8.14	6.60	6.38	0.68
17	TKR	7.72	6.29	6.08	0.66
18	TKR	8.72	6.82	6.25	0.69
19	TKR	7.31	7.01	6.22	0.62
20	TKR	6.37	6.76	5.68	0.67
21	TKR	6.70	5.41	5.43	0.97
23	TKR	6.51	6.35	6.25	0.81
24	TKR	4.26	4.31	3.84	0.60
25	TKR	6.44	5.41	6.64	0.72
27	TKR	8.76	6.94	5.77	0.64
Mean	Control	6.80	5.65	5.18	0.77
Mean	TKR	7.10	6.44	6.06	0.67

Table 34. Control knee passive ROM, loading-response and push-off peak vertical GRF.

Subject	Group	Right Knee Passive ROM (deg)	Left Knee Passive Knee ROM (deg)	Loading Response Peak Vertical Ground Reaction Force (BW)	Push-Off Peak Vertical Ground Reaction Force (BW)
1	Control	114	115	0.994±0.043	1.196±0.028
3	Control	126	123	0.919±0.019	1.073±0.069
7	Control	130	125	1.070±0.006	1.020±0.018
8	Control	133	132	0.881±0.026	1.258±0.040
10	Control	129	133	1.027±0.032	1.053±0.035
11	Control	127	125	1.093±0.033	1.112±0.092
12	Control	137	138	1.191±0.035	0.999±0.048
14	Control	138	138	1.119±0.027	1.039±0.039
15	Control	116	120	1.143±0.058	0.846±0.041
16	Control	138	138	1.108±0.059	1.145±0.069
22	Control	130	130	0.979±0.015	1.392±0.103
26	Control	128	129	1.000±0.032	1.028±0.035
28	Control	132	134	-	-
29	Control	157	147	0.848±0.028	1.190±0.039
30	Control	128	127	1.038±0.009	1.264±0.059
Mean	Control	130.87±9.9	130.27±8.2	1.03±0.03	1.12±0.03

Table 35. Replaced and non-replaced knee passive ROM, loading-response and push-off peak vertical GRF.

Subject	Group	Knee Passive Knee ROM (deg)	Loading Response Peak Vertical Ground Reaction Force (BW)	Push-Off Peak Vertical Ground Reaction Force (BW)
4	Replaced	118	0.926±0.058	1.119±0.050
5	Replaced	103	1.032±0.016	1.010±0.032
6	Replaced	109	0.996±0.018	1.261±0.042
9	Replaced	120	1.025±0.030	1.317±0.045
17	Replaced	118	1.015±0.013	1.073±0.053
18	Replaced	110	1.045±0.021	1.086±0.025
19	Replaced	95	1.023±0.046	1.145±0.064
20	Replaced	81	1.037±0.013	1.115±0.033
21	Replaced	121	0.940±0.072	1.245±0.104
23	Replaced	131	0.951±0.027	1.044±0.013
24	Replaced	124	0.916±0.012	1.129±0.026
25	Replaced	118	1.047±0.008	1.131±0.022
27	Replaced	96	0.955±0.024	1.178±0.031
4	Non-Replaced	126	1.003±0.018	1.339±0.129
5	Non-Replaced	104	1.018±0.015	1.044±0.011
6	Non-Replaced	118	0.948±0.030	1.241±0.032
9	Non-Replaced	127	0.892±0.024	1.145±0.011
17	Non-Replaced	109	0.973±0.019	1.084±0.021
18	Non-Replaced	127	1.074±0.015	1.226±0.079
19	Non-Replaced	123	1.049±0.018	1.187±0.037
20	Non-Replaced	75	0.990±0.045	1.139±0.042
21	Non-Replaced	117	0.967±0.021	1.140±0.022
23	Non-Replaced	137	1.150±0.032	1.296±0.028
24	Non-Replaced	135	1.052±0.040	1.240±0.070
25	Non-Replaced	137	1.054±0.024	1.139±0.043
27	Non-Replaced	118	0.994±0.026	1.220±0.023
Mean	Replaced	111.08±13.9	0.993±0.048	1.142±0.088
Mean	Non-Replaced	119.46±16.7	1.013±0.065	1.188±0.083

Table 36. Control knee sagittal plane kinematic and kinetic variables.

Subject	Group	Knee Contact Flexion Angle (deg)	Knee Extension ROM (deg)	Loading Response Peak Knee Extension Moment (Nm/kg)	Push-Off Peak Knee Extension Moment (Nm/kg)
1	Control	-74.627±3.201	59.466±4.423	1.360±0.131	0.372±0.134
3	Control	-71.476±0.649	57.801±1.035	1.134±0.050	0.102±0.059
7	Control	-62.155±0.662	60.392±2.496	1.333±0.039	-0.048±0.024
8	Control	-69.761±1.101	56.476±3.553	0.952±0.073	0.972±0.139
10	Control	-68.178±4.279	59.397±2.957	1.357±0.127	0.765±0.053
11	Control	-67.577±1.574	61.930±2.091	1.561±0.071	0.135±0.136
12	Control	-75.026±2.363	58.754±2.367	1.652±0.059	0.434±0.091
14	Control	-62.071±0.999	47.514±1.564	1.262±0.032	0.269±0.075
15	Control	-69.248±1.127	52.457±1.222	1.402±0.084	0.354±0.007
16	Control	-73.495±0.936	57.232±2.127	1.573±0.170	0.407±0.074
22	Control	-67.505±1.067	53.825±2.476	1.136±0.046	1.090±0.340
26	Control	-65.397±2.014	56.740±3.646	1.208±0.036	0.408±0.118
28	Control	-65.729±1.813	40.457±1.479	1.381±0.084	0.721±0.045
29	Control	-71.756±2.090	59.739±3.837	0.921±0.037	0.658±0.028
30	Control	-70.030±0.944	55.326±1.814	1.444±0.050	0.818±0.245
Mean	Control	-68.935±4.027	55.834±5.581	1.312±0.214	0.497±0.330

Table 37. Replaced and non-replaced knee sagittal plane kinematic and kinetic variables.

Subject	Group	Knee Contact Flexion Angle (deg)	Knee Extension ROM (deg)	Loading Response Peak Knee Extension Moment (Nm/kg)	Push-Off Peak Knee Extension Moment (Nm/kg)
4	Replaced	-66.930±1.499	63.615±0.899	0.707±0.072	0.089±0.141
5	Replaced	-63.136±3.012	57.231±7.249	0.739±0.031	0.199±0.000
6	Replaced	-63.366±1.464	58.746±2.094	0.976±0.024	0.435±0.123
9	Replaced	-61.663±0.548	50.324±1.632	1.101±0.040	0.718±0.109
17	Replaced	-68.325±1.266	64.509±1.735	0.911±0.050	-0.120±0.014
18	Replaced	-70.182±2.367	55.417±1.765	1.246±0.034	0.245±0.056
19	Replaced	-68.754±1.841	47.308±1.816	1.009±0.076	0.487±0.071
20	Replaced	-59.049±0.639	52.529±1.192	0.889±0.056	0.255±0.065
21	Replaced	-65.889±1.775	49.924±2.679	0.849±0.088	0.887±0.128
23	Replaced	-70.262±1.306	53.210±2.109	0.897±0.056	0.309±0.110
24	Replaced	-69.981±2.974	58.874±2.614	1.144±0.043	0.148±0.061
25	Replaced	-64.276±0.976	49.159±1.343	1.259±0.046	0.554±0.056
27	Replaced	-65.366±2.409	55.443±3.124	0.932±0.022	0.562±0.015
4	Non-Replaced	-66.611±1.513	51.857±4.286	1.537±0.038	0.721±0.250
5	Non-Replaced	-59.567±1.908	53.535±0.535	0.850±0.027	0.109±0.096
6	Non-Replaced	-64.222±1.197	66.129±2.636	0.866±0.088	-0.001±0.135
9	Non-Replaced	-63.571±0.906	66.990±1.047	0.801±0.030	-0.132±0.020
17	Non-Replaced	-65.390±1.297	58.097±0.688	0.968±0.067	-0.005±0.005
18	Non-Replaced	-68.795±0.530	52.945±2.073	1.410±0.114	0.658±0.144
19	Non-Replaced	-67.212±1.768	48.442±0.926	1.364±0.066	0.606±0.084
20	Non-Replaced	-62.573±1.828	53.700±1.381	0.977±0.051	0.381±0.048
21	Non-Replaced	-65.798±1.083	54.216±1.471	0.933±0.140	0.760±0.200
23	Non-Replaced	-66.823±1.260	57.435±1.493	1.754±0.036	0.529±0.122
24	Non-Replaced	-67.225±0.861	52.759±1.522	1.387±0.079	0.128±0.052
25	Non-Replaced	-67.356±3.157	59.925±3.344	1.336±0.054	0.298±0.057
27	Non-Replaced	-61.458±1.355	54.773±1.476	0.983±0.021	0.431±0.052
Mean	Replaced	-65.937±3.547	55.099±5.394	0.974±0.174	0.367±0.275
Mean	Non-Replaced	-65.123±2.691	56.216±5.438	1.167±0.309	0.345±0.302

Table 38. Control knee frontal plane kinematic and kinetic variables.

Subject	Group	Minimum Knee Ab/Adduction Angle (deg)	Loading Response Peak Knee Abduction Moment (Nm/kg)	Push-Off Peak Knee Abduction Moment (Nm/kg)
1	Control	1.042±0.958	-0.274±0.038	-0.145±0.008
3	Control	-0.629±0.343	-	-0.132±0.097
7	Control	-13.254±0.338	-	-0.034±0.009
8	Control	-3.692±1.462	-0.133±0.102	-0.014±0.061
10	Control	-4.319±1.837	-0.014±0.016	-0.156±0.036
11	Control	0.230±0.998	-0.222±0.079	-0.080±0.116
12	Control	3.620±0.762	-0.462±0.028	-0.238±0.000
14	Control	-0.959±0.404	-0.169±0.037	-
15	Control	5.242±0.994	-0.545±0.029	-
16	Control	0.218±0.480	-0.204±0.022	-0.234±0.019
22	Control	2.568±0.432	-0.420±0.021	-0.315±0.037
26	Control	7.365±2.982	-0.378±0.047	-0.253±0.166
28	Control	-1.025±0.546	-0.154±0.049	-0.145±0.055
29	Control	-4.593±0.945	-0.091±0.007	-
30	Control	0.052±0.816	-0.325±0.045	-0.205±0.029
Mean	Control	-0.542±4.852	-0.26±0.16	-0.163±0.09

Table 39. Replaced and non-replaced knee frontal plane kinematic and kinetic variables.

Subject	Group	Minimum Knee Ab/Adduction Angle (deg)	Loading Response Peak Knee Abduction Moment (Nm/kg)	Push-Off Peak Knee Abduction Moment (Nm/kg)
4	Replaced	-6.081±0.927	-0.310±0.024	-0.316±0.034
5	Replaced	-0.487±0.339	-0.614±0.011	-0.445±0.000
6	Replaced	-2.804±0.304	-0.302±0.057	-0.188±0.060
9	Replaced	-9.850±0.206	-0.205±0.019	-0.260±0.025
17	Replaced	2.645±0.379	-0.677±0.032	-0.410±0.030
18	Replaced	-0.206±0.700	-0.367±0.034	-0.124±0.041
19	Replaced	-1.651±1.022	-0.179±0.040	-0.088±0.039
20	Replaced	-0.794±0.999	-0.541±0.034	-0.418±0.025
21	Replaced	2.971±0.333	-0.187±0.057	-0.199±0.048
23	Replaced	0.516±0.356	-0.298±0.030	-0.228±0.032
24	Replaced	0.053±0.445	-0.281±0.017	-0.504±0.038
25	Replaced	0.798±0.909	-0.345±0.014	-0.252±0.023
27	Replaced	-0.986±0.144	-0.374±0.014	-0.370±0.021
4	Non-Replaced	2.424±1.783	-0.233±0.038	-0.164±0.060
5	Non-Replaced	-2.264±1.893	-0.282±0.020	-0.093±0.034
6	Non-Replaced	-2.668±0.247	-0.519±0.072	-0.475±0.046
9	Non-Replaced	-16.856±0.498	-0.088±0.017	0.110±0.045
17	Non-Replaced	7.905±0.813	-0.424±0.036	-0.315±0.016
18	Non-Replaced	-5.243±0.534	-0.191±0.026	-0.233±0.051
19	Non-Replaced	1.343±1.022	-0.563±0.039	-0.622±0.044
20	Non-Replaced	-2.942±0.521	-0.262±0.049	-0.207±0.017
21	Non-Replaced	-3.404±1.064	-0.302±0.041	-0.077±0.045
23	Non-Replaced	-1.396±1.022	-0.291±0.056	-
24	Non-Replaced	3.390±1.778	-0.300±0.041	-0.127±0.077
25	Non-Replaced	-1.163±2.173	-0.161±0.030	-0.099±0.017
27	Non-Replaced	-2.579±1.495	-0.388±0.071	-0.245±0.009
Mean	Replaced	-1.221±3.462	-0.360±0.158	-0.292±0.129
Mean	Non-Replaced	-1.804±5.726	-0.308±0.136	-.214±0.19

Table 40. Control ankle sagittal plane kinematic and kinetic variables.

Subject	Group	Ankle Contact Angle (deg)	Ankle Plantar Flexion ROM (deg)	Loading Response Peak Plantar Flexion Moment (Nm/kg)	Push-Off Peak Plantar Flexion Moment (Nm/kg)
1	Control	20.388±3.403	-34.741±4.083	-0.730±0.129	-1.378±0.063
3	Control	21.288±1.215	-39.068±1.665	-0.342±0.000	-1.020±0.095
7	Control	16.289±1.257	-41.026±1.195	-0.383±0.083	-1.002±0.033
8	Control	24.971±1.885	-37.218±1.628	-0.536±0.037	-1.232±0.015
10	Control	20.241±1.275	-49.679±1.711	-0.465±0.207	-0.869±0.036
11	Control	18.290±2.914	-39.499±4.971	-0.448±0.094	-1.111±0.108
12	Control	8.296±1.289	-22.345±1.814	-1.079±0.071	-1.172±0.047
14	Control	33.170±2.823	-44.125±3.699	-0.793±0.062	-0.975±0.023
15	Control	8.617±1.219	-25.035±1.582	-1.102±0.111	-0.988±0.061
16	Control	14.796±1.048	-23.896±0.730	-0.979±0.054	-1.312±0.056
22	Control	14.539±1.132	-34.856±2.183	-0.404±0.143	-1.260±0.065
26	Control	13.933±1.680	-38.084±2.719	-0.583±0.255	-1.047±0.037
28	Control	7.054±1.998	-26.192±2.507	-0.763±0.144	-1.127±0.123
29	Control	22.183±1.089	-24.967±2.323	-0.671±0.139	-1.239±0.057
30	Control	15.880±0.857	-24.695±2.105	-0.453±0.080	-1.115±0.104
Mean	Control	17.329±6.862	-33.695±8.569	-0.649±0.253	-1.123±0.142

Table 41. Replaced and non-replaced ankle sagittal plane kinematic and kinetic variables.

Subject	Group	Ankle Contact Angle (deg)	Ankle Plantar Flexion ROM (deg)	Loading Response Peak Plantar Flexion Moment (Nm/kg)	Push-Off Peak Plantar Flexion Moment (Nm/kg)
4	Replaced	3.960±2.807	-18.740±4.086	-0.468±0.090	-1.154±0.043
5	Replaced	17.892±0.162	-44.302±0.927	-0.579±0.084	-0.927±0.032
6	Replaced	21.733±1.786	-41.964±2.991	-0.416±0.089	-1.041±0.035
9	Replaced	18.236±0.729	-27.728±1.493	-0.597±0.106	-1.195±0.028
17	Replaced	13.173±0.721	-38.446±1.097	-0.564±0.126	-1.097±0.123
18	Replaced	8.154±1.858	-22.972±2.721	-0.607±0.136	-1.195±0.067
19	Replaced	16.287±1.298	-29.449±1.964	-0.656±0.129	-1.121±0.052
20	Replaced	8.139±0.484	-26.847±1.631	-0.382±0.135	-0.949±0.057
21	Replaced	13.886±2.177	-44.801±1.949	-0.570±0.014	-1.076±0.079
23	Replaced	13.643±0.801	-22.917±1.353	-0.531±0.118	-1.022±0.062
24	Replaced	5.299±1.533	-26.993±2.138	-0.641±0.082	-1.177±0.060
25	Replaced	7.885±1.325	-31.386±1.958	-0.526±0.064	-1.134±0.034
27	Replaced	14.894±1.380	-36.894±1.716	-0.227±0.145	-1.046±0.044
4	Non-Replaced	11.877±1.943	-17.855±4.113	-0.500±0.163	-1.479±0.099
5	Non-Replaced	20.691±1.795	-46.551±1.852	-0.686±0.090	-1.081±0.069
6	Non-Replaced	3.522±1.110	-40.358±0.906	-0.700±0.073	-1.143±0.040
9	Non-Replaced	20.583±0.919	-33.739±1.563	-0.417±0.051	-0.901±0.028
17	Non-Replaced	13.980±0.827	-37.248±0.942	-0.661±0.089	-1.119±0.046
18	Non-Replaced	12.426±0.092	-22.499±1.043	-0.494±0.133	-1.103±0.063
19	Non-Replaced	15.902±0.624	-29.604±0.998	-0.654±0.146	-1.149±0.036
20	Non-Replaced	10.326±0.830	-28.276±0.903	-0.349±0.107	-0.950±0.094
21	Non-Replaced	7.628±2.132	-37.139±2.732	-0.632±0.029	-0.972±0.040
23	Non-Replaced	19.873±0.401	-39.140±1.300	-0.410±0.123	-1.137±0.059
24	Non-Replaced	11.137±0.487	-38.213±0.874	-0.815±0.074	-1.423±0.077
25	Non-Replaced	5.537±1.236	-22.519±1.864	-0.743±0.279	-1.206±0.029
27	Non-Replaced	15.241±1.940	-37.920±2.799	-0.218±0.079	-1.103±0.008
Mean	Replaced	12.552±5.439	-31.803±8.641	-0.520±0.120	-1.087±0.088
Mean	Non-Replaced	12.979±5.514	-33.159±8.395	-0.560±0.176	-1.136±0.165

Table 42. Control ankle frontal plane kinematic and kinetic variables.

Subject	Group	Peak Ankle Eversion Angle (deg)	Loading Response Peak Ankle Inversion Moment (Nm/kg)	Push-Off Peak Ankle Inversion Moment (Nm/kg)
1	Control	-16.365±3.072	0.342±0.062	0.327±0.045
3	Control	-8.301±1.727	0.450±0.023	0.610±0.048
7	Control	-10.412±1.488	0.349±0.052	0.409±0.018
8	Control	-22.431±1.262	0.195±0.058	0.269±0.046
10	Control	-11.185±2.122	0.228±0.026	0.279±0.027
11	Control	-12.382±1.763	0.308±0.034	0.349±0.066
12	Control	-8.028±1.247	0.390±0.027	0.182±0.024
14	Control	-17.662±1.656	0.228±0.032	0.102±0.012
15	Control	-14.515±0.539	0.606±0.049	0.322±0.028
16	Control	-16.912±0.677	0.400±0.028	0.306±0.051
22	Control	-14.371±0.359	0.169±0.037	0.259±0.035
26	Control	-15.778±2.685	0.339±0.101	0.321±0.055
28	Control	-10.629±0.374	0.398±0.000	-
29	Control	-7.500±1.935	0.323±0.065	0.443±0.026
30	Control	-8.007±2.548	0.254±0.019	0.291±0.016
Mean	Control	-12.965±4.368	0.332±0.112	0.32±0.12

Table 43. Replaced and non-replaced ankle frontal plane kinematic and kinetic variables.

Subject	Group	Peak Ankle Eversion Angle (deg)	Loading Response Peak Ankle Inversion Moment (Nm/kg)	Push-Off Peak Ankle Inversion Moment (Nm/kg)
4	Replaced	-4.630±1.197	0.332±0.040	0.228±0.140
5	Replaced	-18.066±1.265	0.051±0.000	0.051±0.000
6	Replaced	-12.163±1.296	0.213±0.076	0.363±0.037
9	Replaced	-13.175±0.604	0.024±0.005	-0.010±0.013
17	Replaced	-5.613±3.347	0.025±0.000	0.006±0.000
18	Replaced	-6.137±1.268	0.215±0.027	0.192±0.013
19	Replaced	-9.177±0.582	0.271±0.023	0.280±0.041
20	Replaced	-6.903±0.344	0.031±0.000	0.031±0.000
21	Replaced	-10.912±3.026	0.165±0.015	0.192±0.020
23	Replaced	-3.041±1.486	0.025±0.020	-0.008±0.027
24	Replaced	-6.812±1.254	0.028±0.011	0.018±0.014
25	Replaced	-6.216±0.631	0.071±0.012	0.037±0.010
27	Replaced	-3.304±0.835	.±.	.±.
4	Non-Replaced	-9.462±2.445	0.332±0.033	0.505±0.169
5	Non-Replaced	-20.116±0.339	0.321±0.033	0.295±0.020
6	Non-Replaced	-13.472±1.237	-0.014±0.040	-0.023±0.037
9	Non-Replaced	-21.377±0.627	0.182±0.015	0.276±0.008
17	Non-Replaced	-11.577±0.922	0.375±0.019	0.337±0.025
18	Non-Replaced	-6.121±1.028	0.110±0.002	0.082±0.000
19	Non-Replaced	-12.637±1.998	.±.	.±.
20	Non-Replaced	-7.803±1.153	0.206±0.033	0.252±0.027
21	Non-Replaced	-12.968±1.403	0.054±0.025	0.041±0.007
23	Non-Replaced	-9.316±1.357	0.208±0.013	0.295±0.036
24	Non-Replaced	-11.417±1.011	0.362±0.034	0.342±0.033
25	Non-Replaced	-9.297±0.357	0.364±0.060	0.308±0.017
27	Non-Replaced	-12.074±0.459	0.196±0.029	0.301±0.037
Mean	Replaced	-8.165±4.358	0.12±0.11	0.11±0.13
Mean	Non-Replaced	-12.126±4.385	0.22±0.13	0.24±0.15

Table 44. Control hip sagittal plane kinematic and kinetic variables.

Subject	Group	Hip Contact Angle (deg)	Hip Extension ROM (deg)	Peak Hip Flexion Moment (Nm/kg)
1	Control	43.135±1.460	-49.817±2.077	0.485±0.031
3	Control	58.718±1.875	-50.570±2.243	0.169±0.052
7	Control	46.190±1.617	-49.290±1.158	0.505±0.065
8	Control	63.426±1.561	-52.989±2.918	0.701±0.087
10	Control	61.703±1.826	-53.072±2.380	0.718±0.055
11	Control	50.424±1.690	-46.509±2.803	0.463±0.077
12	Control	52.707±1.640	-53.870±1.769	0.607±0.021
14	Control	55.176±1.255	-40.490±1.008	0.374±0.051
15	Control	50.817±0.607	-43.605±0.875	0.324±0.033
16	Control	59.980±1.290	-48.161±1.266	0.232±0.054
22	Control	63.250±0.860	-51.429±2.345	0.352±0.117
26	Control	54.694±1.472	-53.699±2.408	0.497±0.052
28	Control	61.116±1.809	-44.645±1.435	0.310±0.028
29	Control	57.258±1.416	-51.356±2.444	0.480±0.097
30	Control	59.975±0.872	-50.492±0.631	0.430±0.072
Mean	Control	55.905±6.209	-49.333±3.972	0.443±0.157

Table 45. Replaced and non-replaced hip sagittal kinematic and kinetic variables.

Subject	Group	Hip Contact Angle (deg)	Hip Extension ROM (deg)	Peak Hip Flexion Moment (Nm/kg)
4	Replaced	58.359±1.623	-52.218±2.429	0.490±0.048
5	Replaced	56.559±1.578	-50.319±3.787	0.286±0.060
6	Replaced	63.856±0.692	-48.377±0.744	0.561±0.041
9	Replaced	53.701±0.569	-46.477±2.656	0.696±0.030
17	Replaced	64.909±2.085	-59.058±3.421	0.262±0.083
18	Replaced	64.942±1.169	-46.531±2.401	0.049±0.067
19	Replaced	64.755±2.197	-48.466±1.942	0.197±0.059
20	Replaced	57.572±0.845	-53.760±1.951	0.642±0.067
21	Replaced	63.663±1.539	-45.384±1.671	0.698±0.074
23	Replaced	68.270±1.297	-47.546±1.371	0.096±0.068
24	Replaced	61.074±1.245	-51.553±2.020	0.520±0.046
25	Replaced	56.643±0.625	-47.928±2.718	0.409±0.044
27	Replaced	59.945±2.123	-49.050±1.690	0.501±0.053
4	Non-Replaced	55.025±3.103	-51.826±6.097	0.611±0.068
5	Non-Replaced	50.459±1.587	-47.050±3.771	0.380±0.065
6	Non-Replaced	63.561±0.914	-51.023±1.913	0.297±0.058
9	Non-Replaced	52.195±1.234	-49.949±1.611	0.221±0.020
17	Non-Replaced	60.967±0.368	-51.614±1.095	0.214±0.046
18	Non-Replaced	64.128±0.466	-53.510±0.987	0.261±0.078
19	Non-Replaced	59.639±1.348	-42.206±1.500	0.417±0.108
20	Non-Replaced	56.376±0.376	-46.537±0.702	0.377±0.036
21	Non-Replaced	65.092±1.477	-45.999±2.354	0.779±0.094
23	Non-Replaced	67.530±0.787	-51.501±1.355	0.161±0.029
24	Non-Replaced	55.353±0.574	-46.041±1.794	0.332±0.119
25	Non-Replaced	57.480±0.606	-54.740±1.787	0.426±0.040
27	Non-Replaced	59.396±1.123	-46.780±1.024	0.419±0.099
Mean	Replaced	61.096±4.328	-49.744±3.705	0.416±0.220
Mean	Non-Replaced	59.015±5.156	-49.137±3.627	0.377±0.169

Table 46. Control hip frontal plane kinematic and kinetic variables.

Subject	Group	Peak Hip Adduction Angle (deg)	Loading Response Peak Hip Abduction Moment (Nm/kg)	Push-Off Peak Hip Abduction Moment (Nm/kg)
1	Control	8.600±1.098	-0.738±0.044	-0.594±0.042
3	Control	14.296±0.414	-0.607±0.049	-0.535±0.119
7	Control	16.006±0.468	-0.952±0.032	-0.586±0.013
8	Control	12.716±0.516	-0.427±0.079	-0.288±0.078
10	Control	11.554±1.285	-0.572±0.208	-0.600±0.104
11	Control	7.412±0.700	-0.683±0.085	-0.342±0.068
12	Control	9.453±1.140	-0.930±0.041	-0.412±0.038
14	Control	12.990±1.191	-0.824±0.028	-0.389±0.064
15	Control	6.151±0.314	-0.812±0.057	-0.396±0.020
16	Control	10.060±0.644	-0.595±0.041	-0.479±0.065
22	Control	12.283±0.786	-0.858±0.068	-0.611±0.067
26	Control	-3.928±1.034	-0.402±0.037	-0.317±0.066
28	Control	7.057±0.680	-0.706±0.059	-0.311±0.000
29	Control	7.595±1.674	-0.345±0.048	-0.358±0.047
30	Control	9.539±0.570	-0.709±0.022	-0.617±0.074
Mean	Control	9.452±4.678	-0.677±0.187	-0.456±0.124

Table 47. Replaced and non-replaced hip frontal plane kinematic and kinetic variables.

Subject	Group	Peak Hip Abduction Angle (deg)	Loading Response Peak Hip Abduction Moment (Nm/kg)	Push-Off Peak Hip Abduction Moment (Nm/kg)
4	Replaced	11.651±1.025	-0.984±0.035	-0.913±0.106
5	Replaced	11.600±0.913	-1.231±0.008	-0.906±0.039
6	Replaced	10.170±0.764	-0.570±0.068	-0.650±0.032
9	Replaced	12.268±0.838	-1.005±0.054	-1.018±0.049
17	Replaced	0.650±1.044	-0.939±0.009	-0.686±0.038
18	Replaced	4.838±1.108	-0.599±0.056	-0.308±0.057
19	Replaced	12.723±1.379	-0.715±0.065	-0.369±0.048
20	Replaced	4.071±1.053	-1.182±0.053	-0.846±0.057
21	Replaced	5.004±1.081	-0.524±0.136	-0.527±0.047
23	Replaced	9.274±1.791	-0.814±0.069	-0.563±0.039
24	Replaced	4.962±0.527	-0.910±0.049	-0.798±0.025
25	Replaced	2.521±0.533	-1.016±0.013	-0.854±0.030
27	Replaced	4.146±0.614	-0.857±0.053	-0.917±0.007
4	Non-Replaced	5.524±1.418	-0.601±0.050	-0.559±0.072
5	Non-Replaced	8.499±0.904	-0.665±0.047	-0.494±0.080
6	Non-Replaced	20.408±0.811	-1.150±0.067	-1.084±0.050
9	Non-Replaced	15.426±0.410	-0.818±0.034	-0.601±0.038
17	Non-Replaced	3.396±0.678	-0.413±0.022	-0.344±0.061
18	Non-Replaced	7.688±0.716	-1.093±0.055	-1.017±0.036
19	Non-Replaced	6.870±0.685	-1.108±0.035	-0.971±0.084
20	Non-Replaced	9.665±0.669	-0.715±0.077	-0.551±0.059
21	Non-Replaced	-1.201±0.696	-0.833±0.028	-0.870±0.076
23	Non-Replaced	-0.440±0.982	-0.487±0.059	-0.183±0.021
24	Non-Replaced	7.806±0.811	-0.588±0.065	-0.262±0.007
25	Non-Replaced	8.902±0.783	-0.695±0.045	-0.503±0.074
27	Non-Replaced	15.809±1.304	-0.993±0.074	-0.619±0.081
Mean	Replaced	7.221±4.161	-0.873±0.223	-0.719±0.224
Mean	Non-Replaced	8.335±6.172	-0.781±0.243	-0.620±0.288

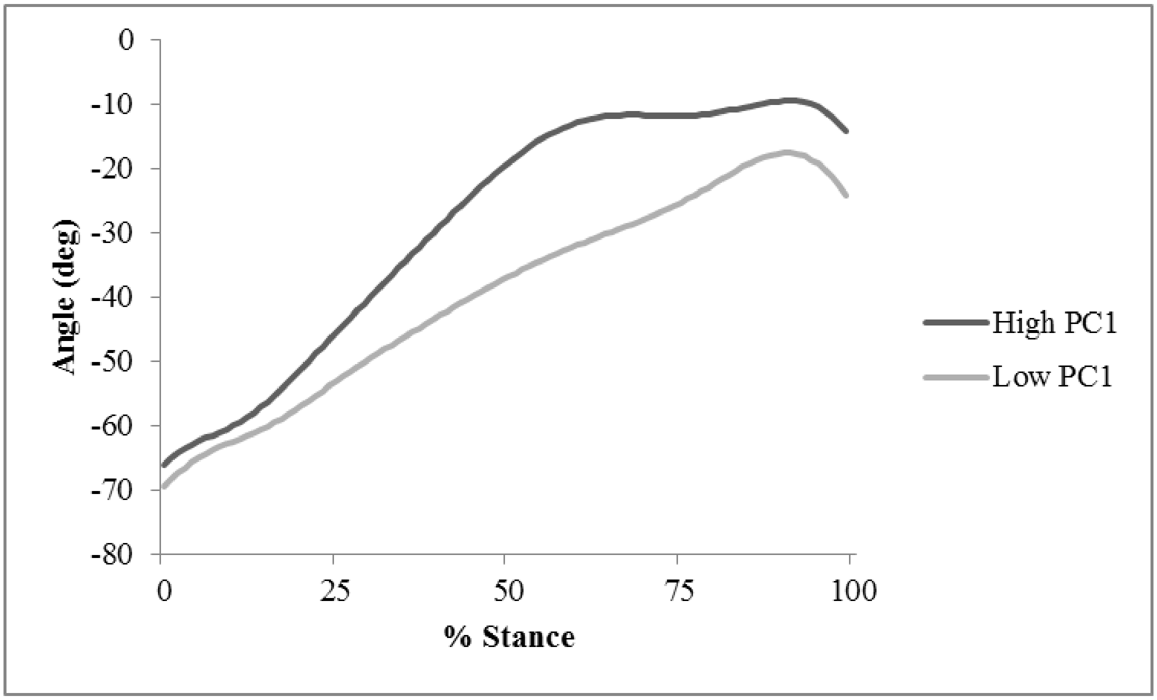


Figure 14a. Waveform reconstructions of sagittal knee angle based on the mean waveform ±1 standard deviation of the first PC score times the loading vector for PC1.

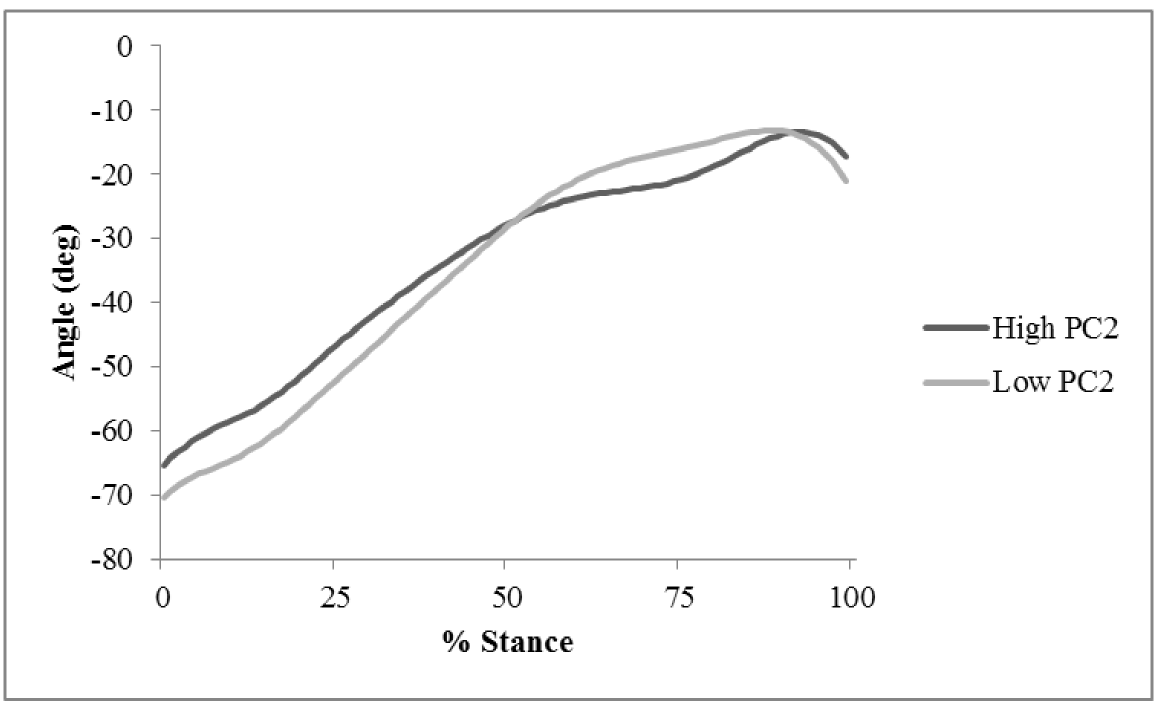


Figure 14b. Waveform reconstructions of sagittal knee angle based on the mean waveform ±1 standard deviation of the second PC score times the loading vector for PC2.

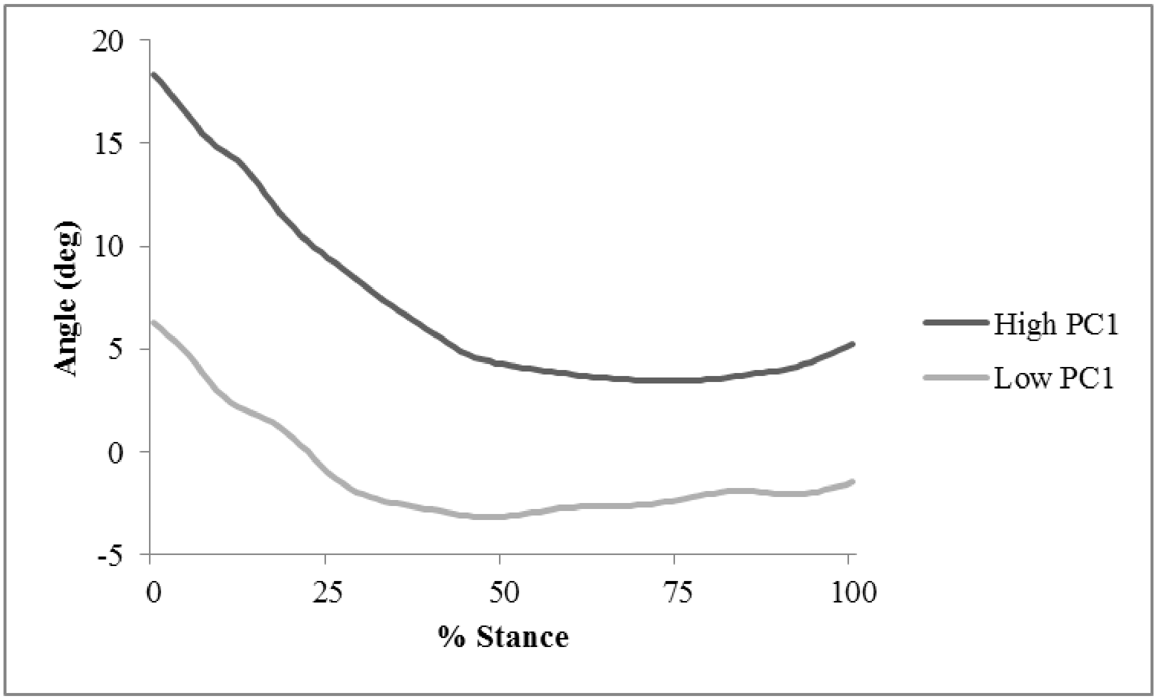


Figure 14c. Waveform reconstructions of frontal knee angle based on the mean waveform ±1 standard deviation of the first PC score times the loading vector for PC1.

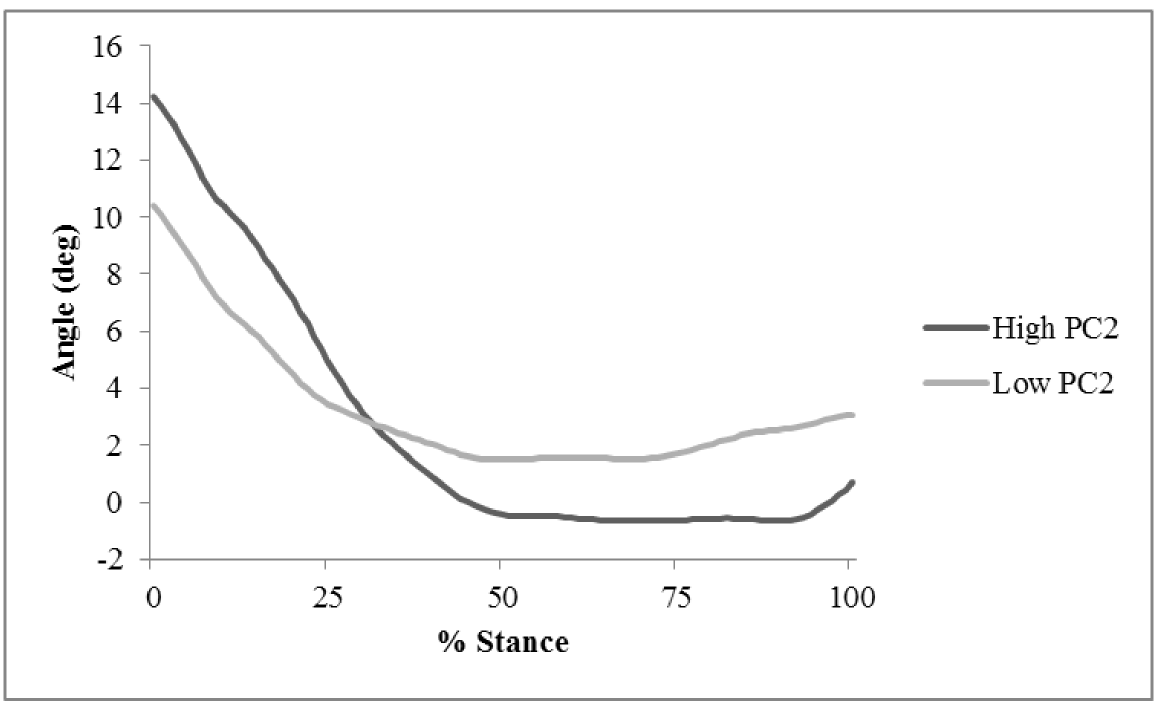


Figure 14d. Waveform reconstructions of sagittal knee angle based on the mean waveform ±1 standard deviation of the second PC score times the loading vector for PC2.

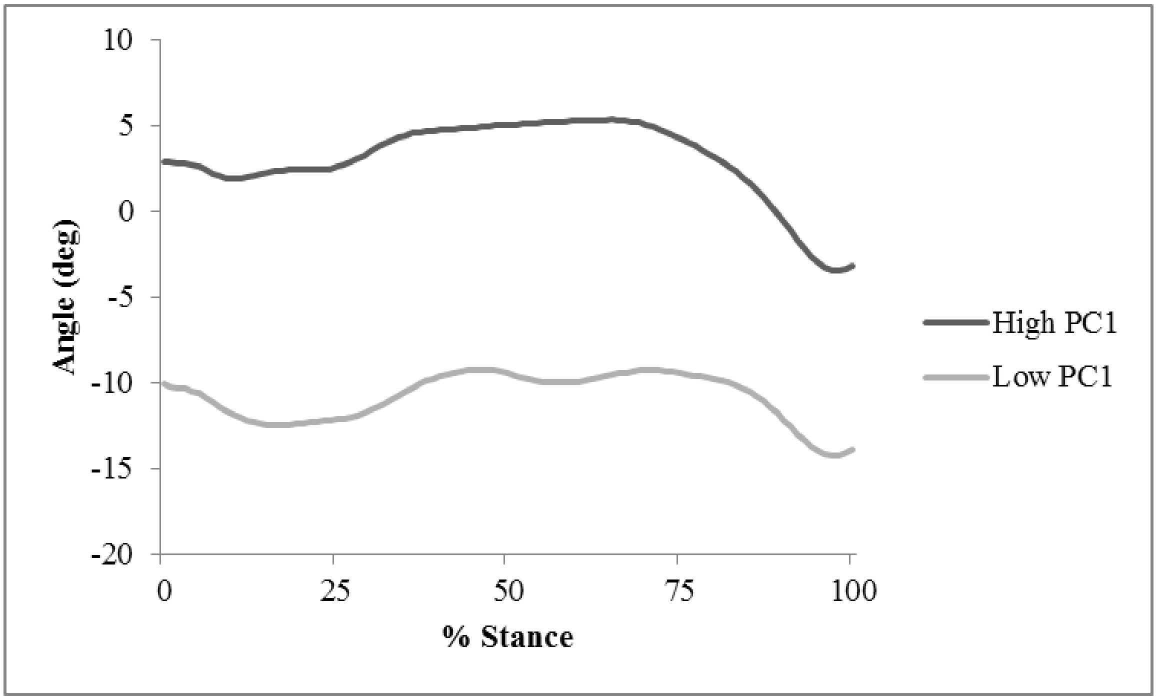


Figure 14e. Waveform reconstructions of transverse knee angle based on the mean waveform ±1 standard deviation of the first PC score times the loading vector for PC1.

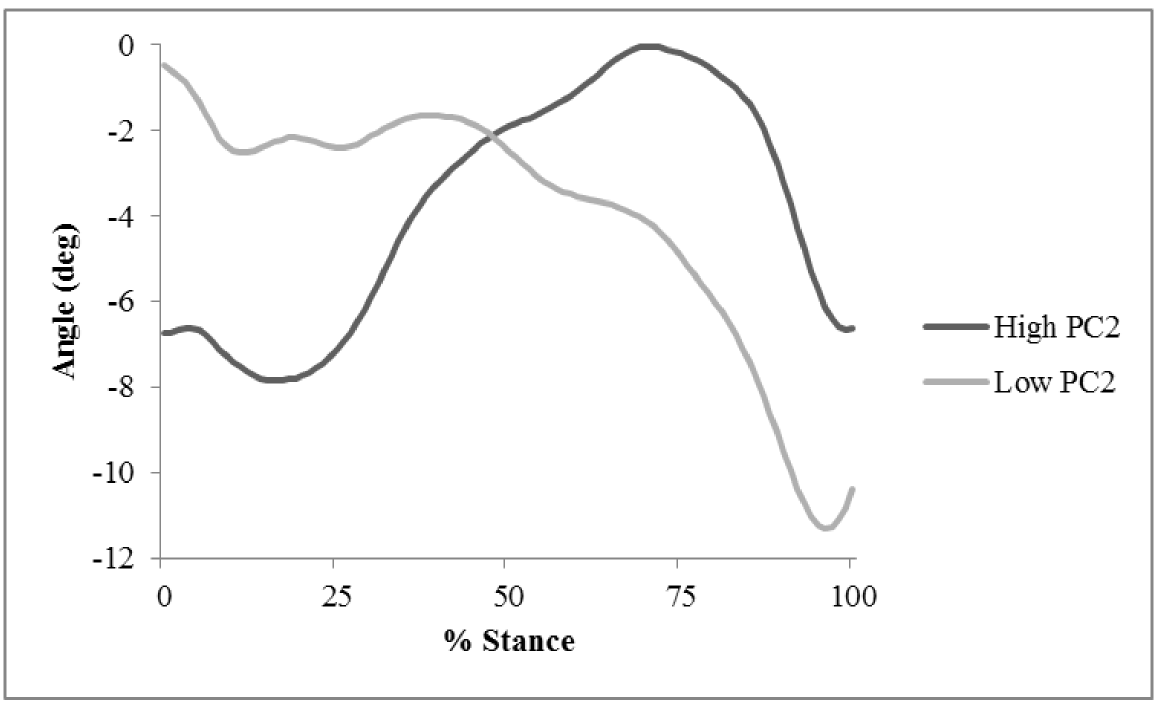


Figure 14f. Waveform reconstructions of sagittal knee angle based on the mean waveform ±1 standard deviation of the second PC score times the loading vector for PC2.

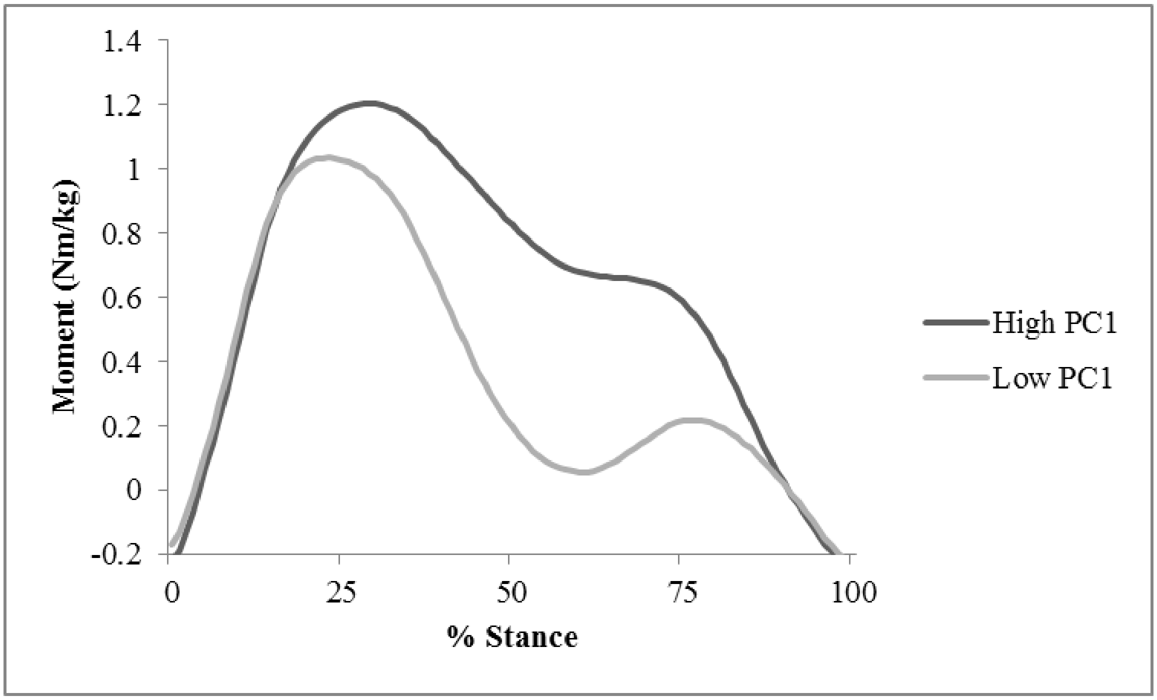


Figure 14g. Waveform reconstructions of sagittal knee moment based on the mean waveform ±1 standard deviation of the first PC score times the loading vector for PC1.

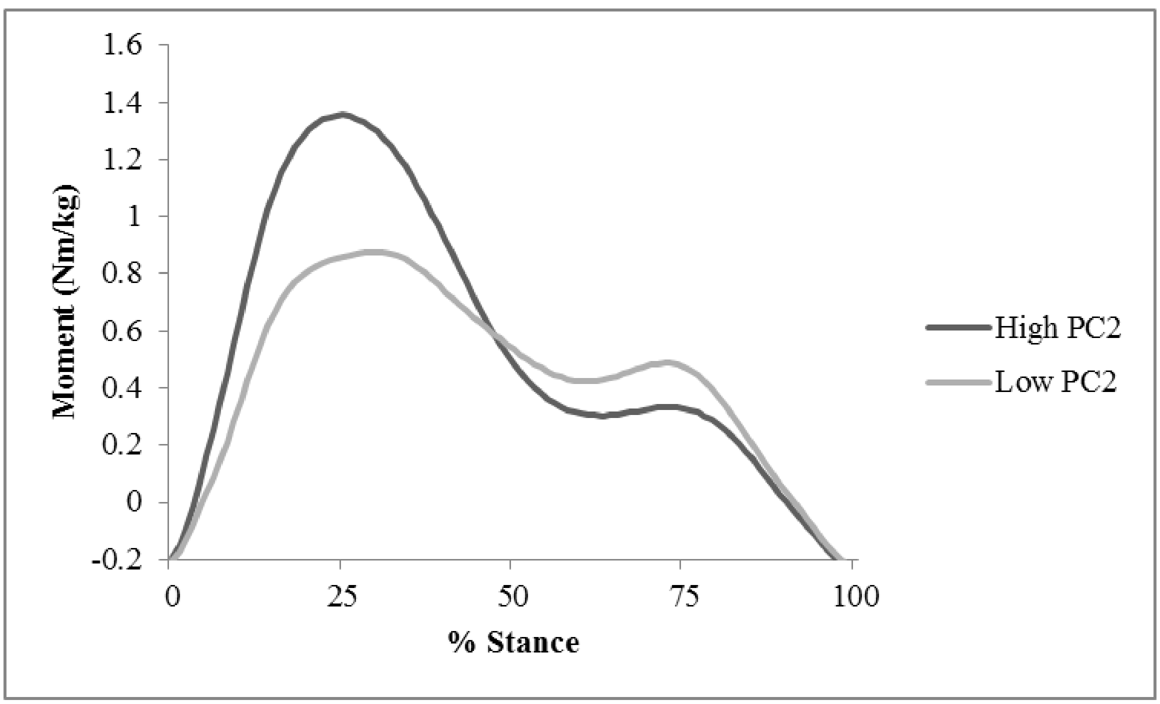


Figure 14h. Waveform reconstructions of sagittal knee moment based on the mean waveform ±1 standard deviation of the second PC score times the loading vector for PC2.

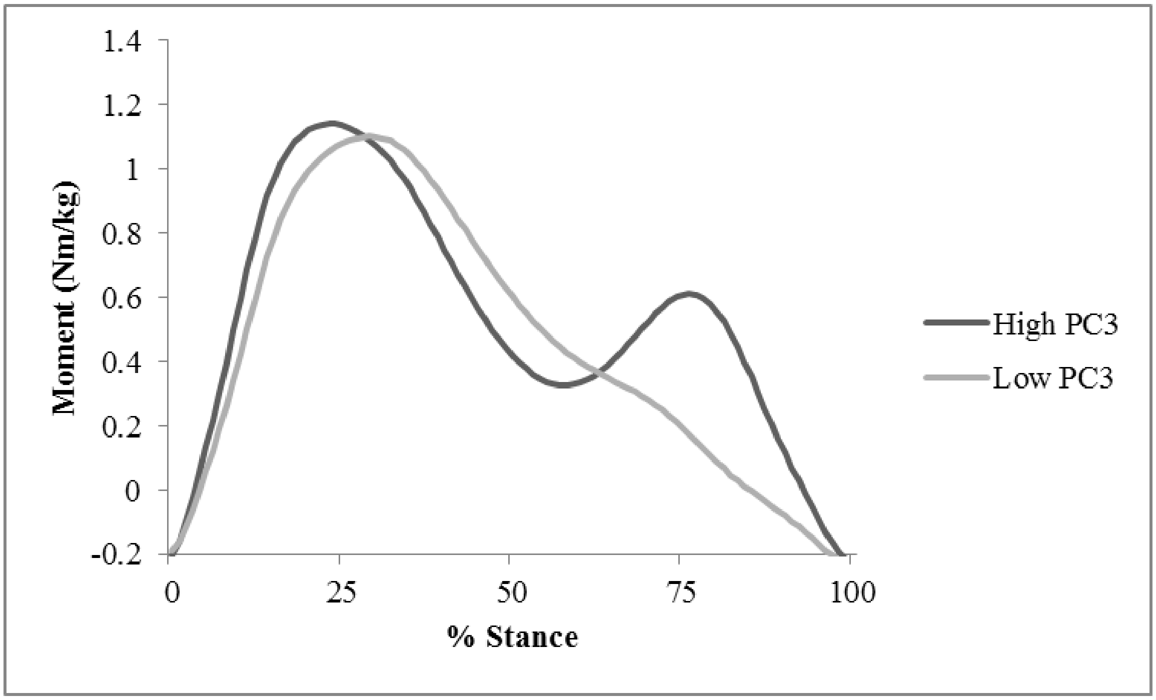


Figure 14i. Waveform reconstructions of sagittal knee moment based on the mean waveform ±1 standard deviation of the third PC score times the loading vector for PC3.

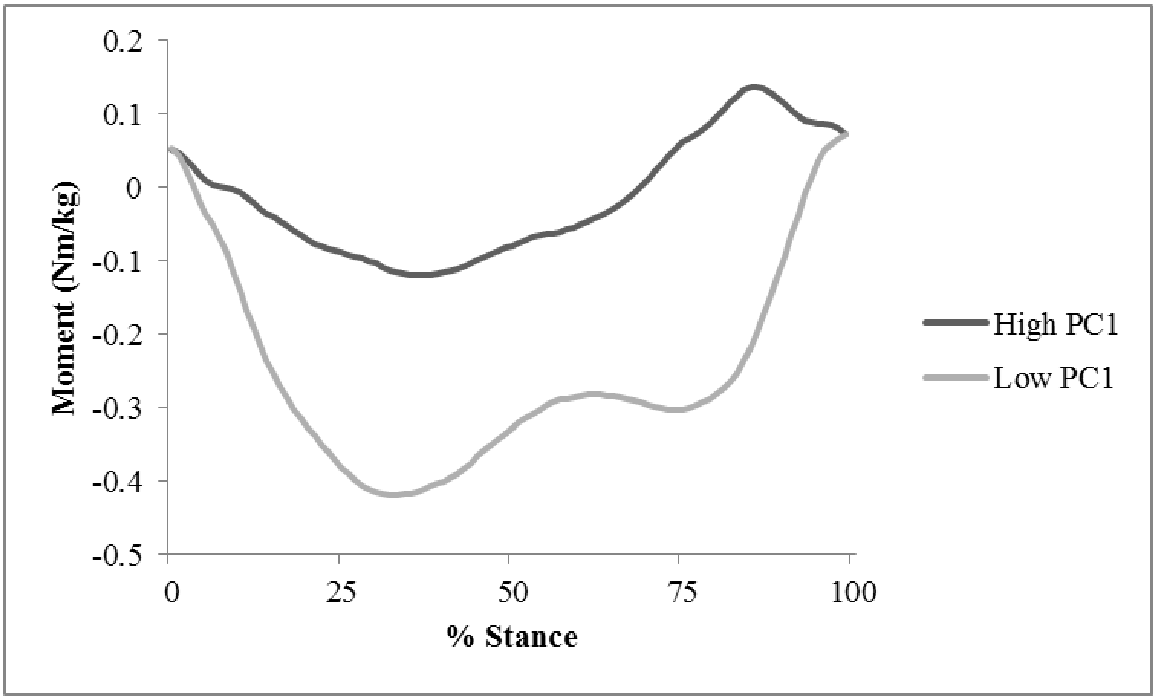


Figure 14j. Waveform reconstructions of frontal knee moment based on the mean waveform ±1 standard deviation of the first PC score times the loading vector for PC1.

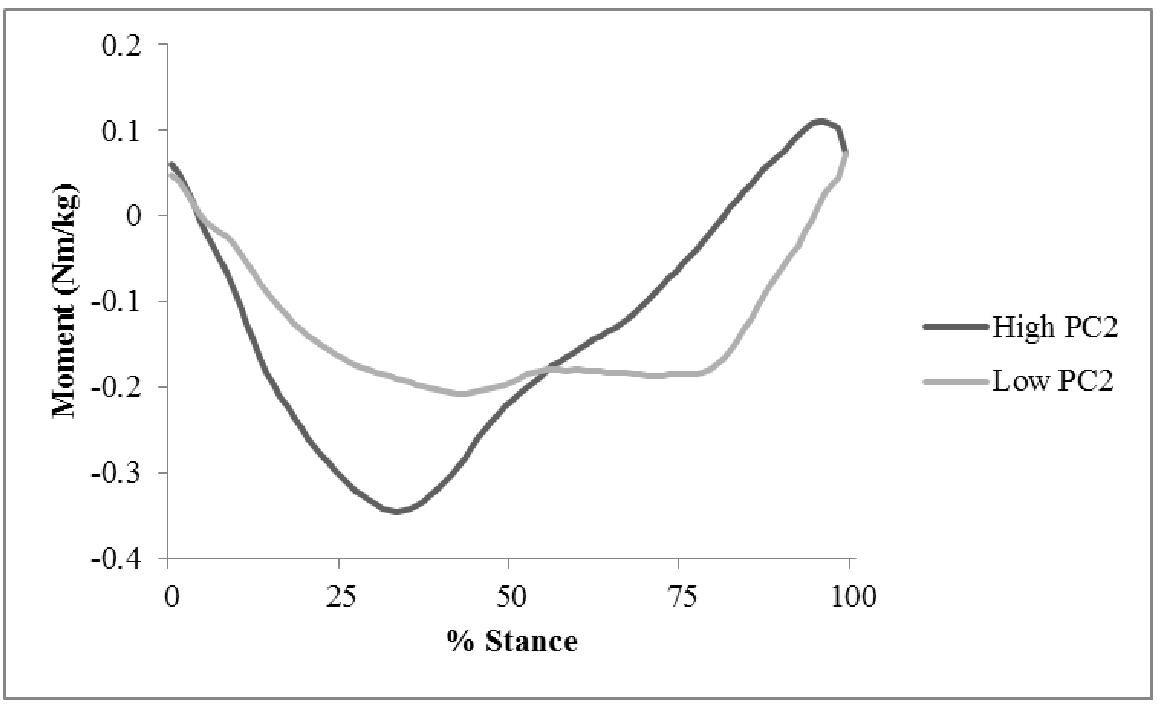


Figure 14k. Waveform reconstructions of frontal knee moment based on the mean waveform ±1 standard deviation of the second PC score times the loading vector for PC2.

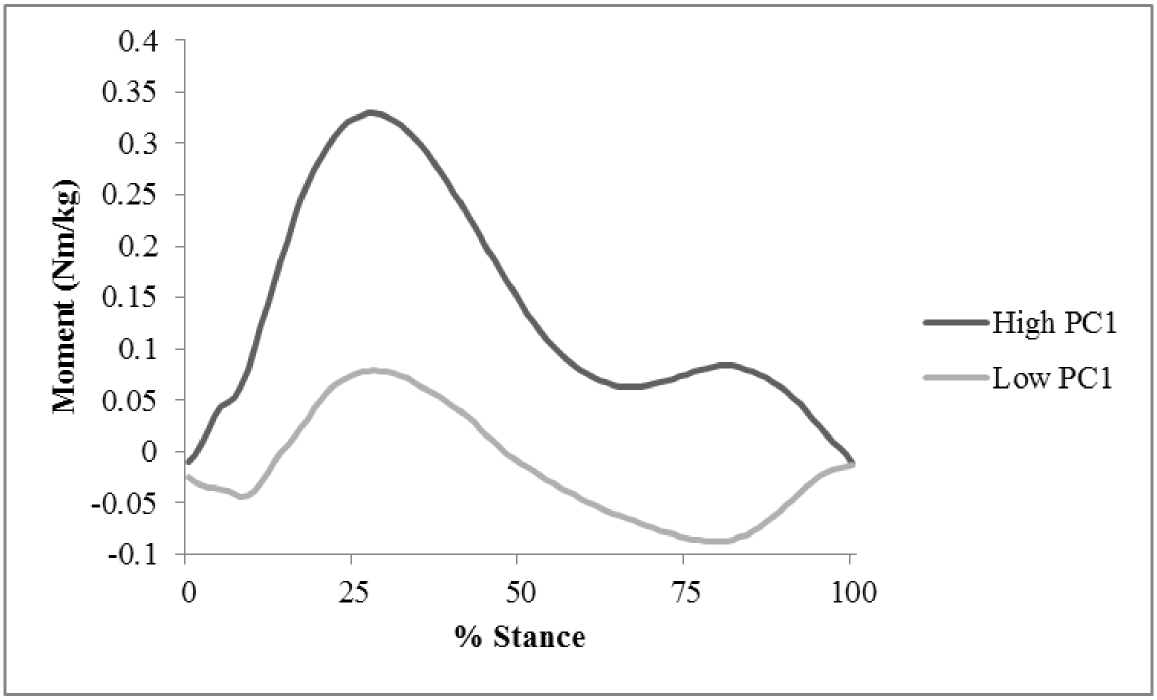


Figure 14l. Waveform reconstructions of transverse knee moment based on the mean waveform ±1 standard deviation of the first PC score times the loading vector for PC1.

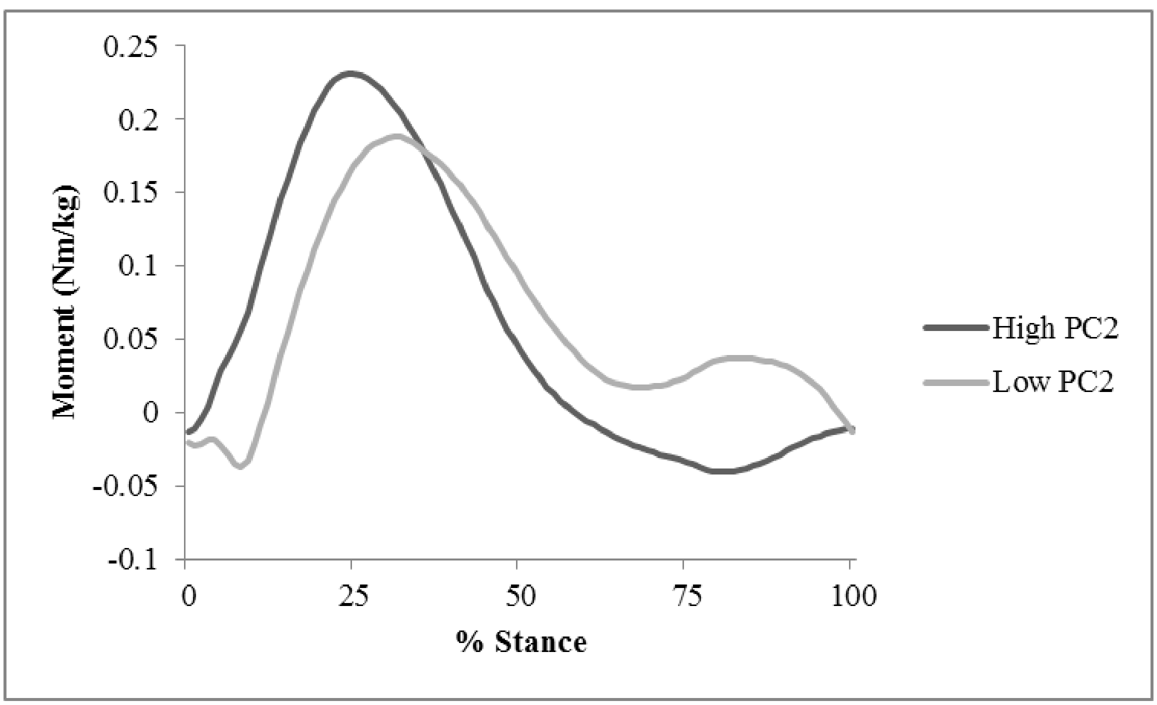


Figure 14m. Waveform reconstructions of transverse knee moment based on the mean waveform ±1 standard deviation of the second PC score times the loading vector for PC2.

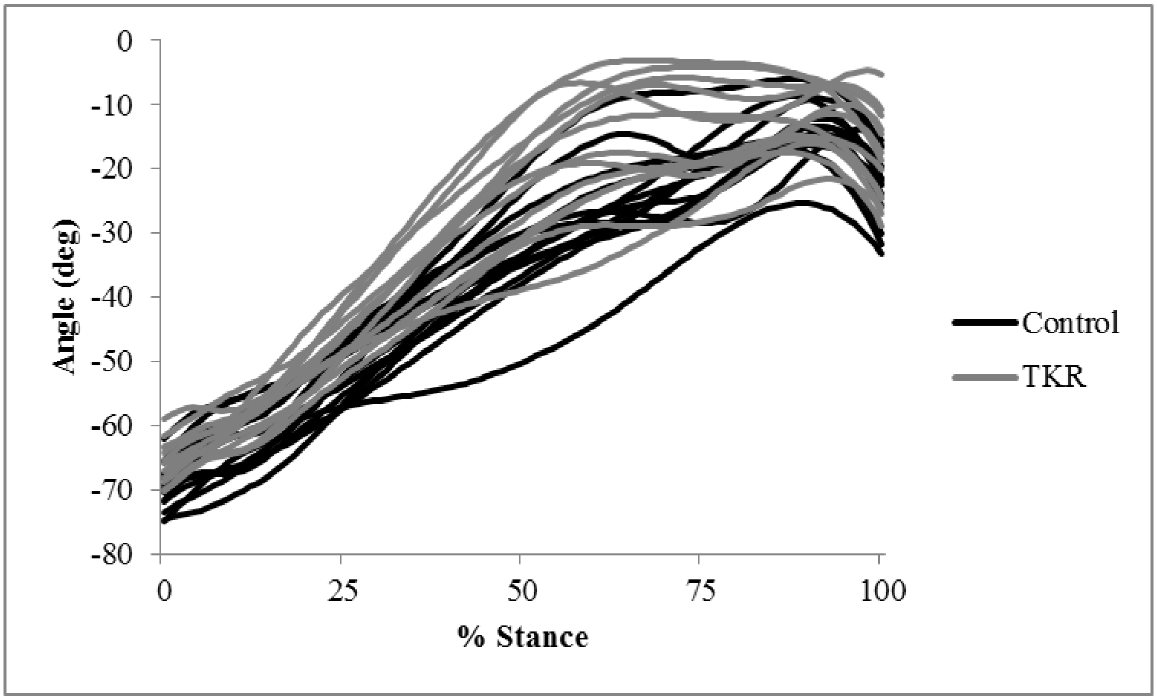


Figure15. Individual waveforms of sagittal plane knee angle for control and TKR.

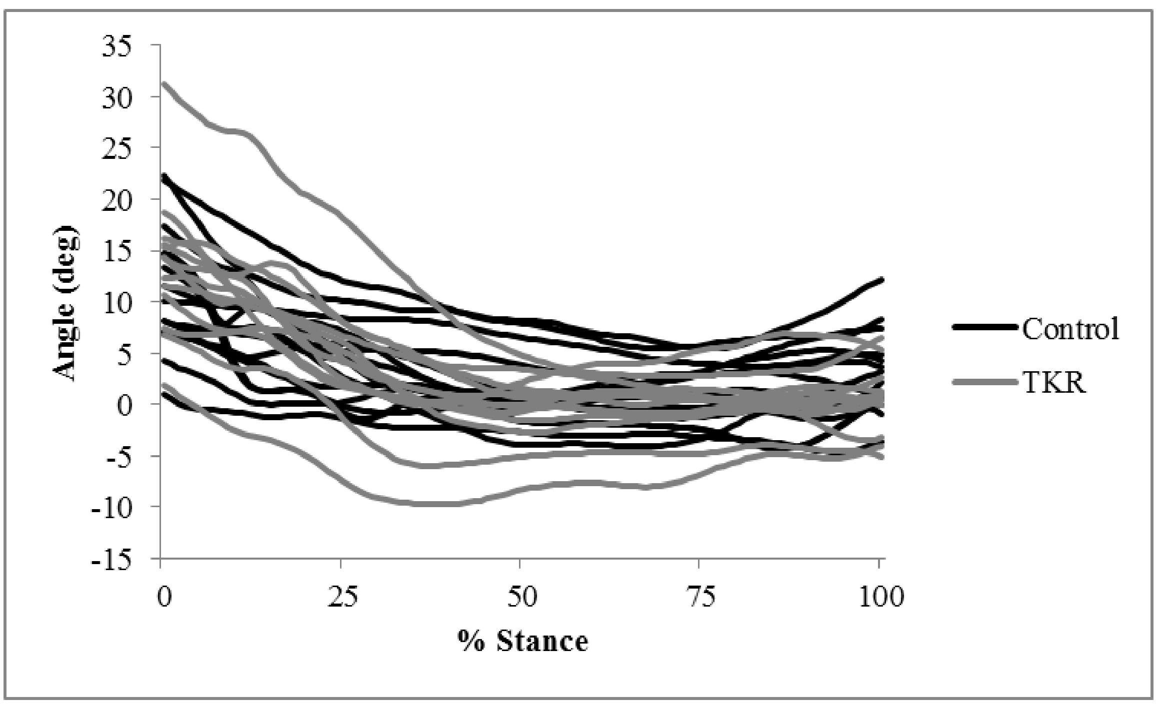


Figure 16. Individual waveforms of frontal plane knee angle for control and TKR.

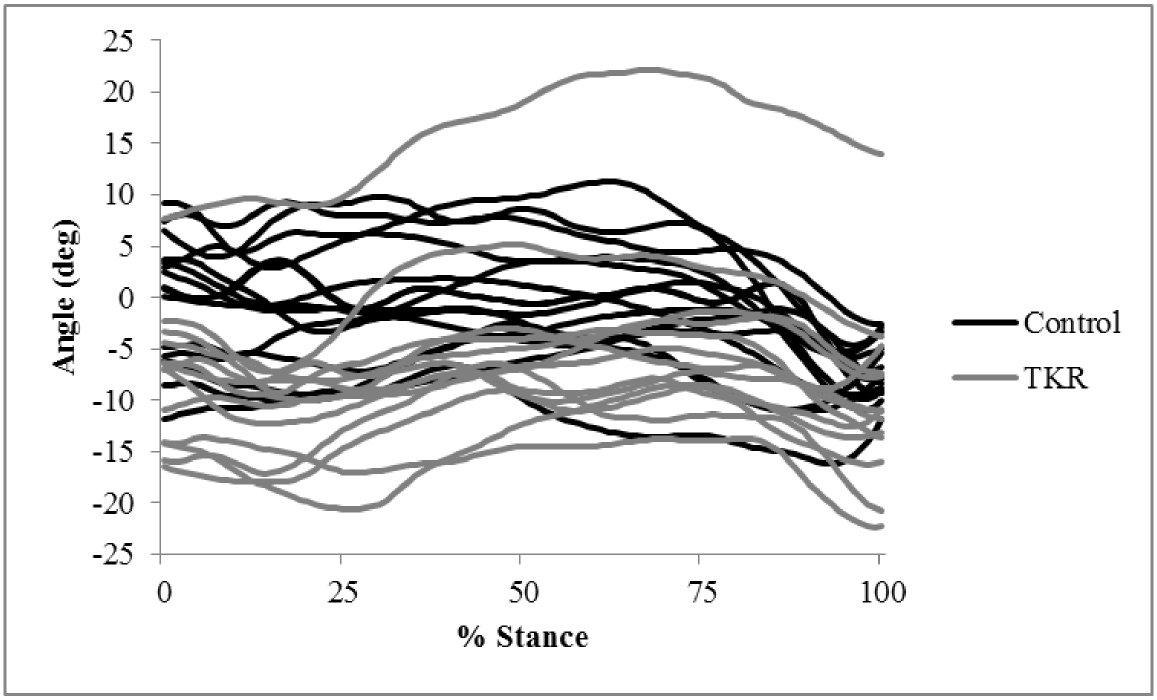


Figure 17. Individual waveforms of transverse plane knee angle in control and TKR.

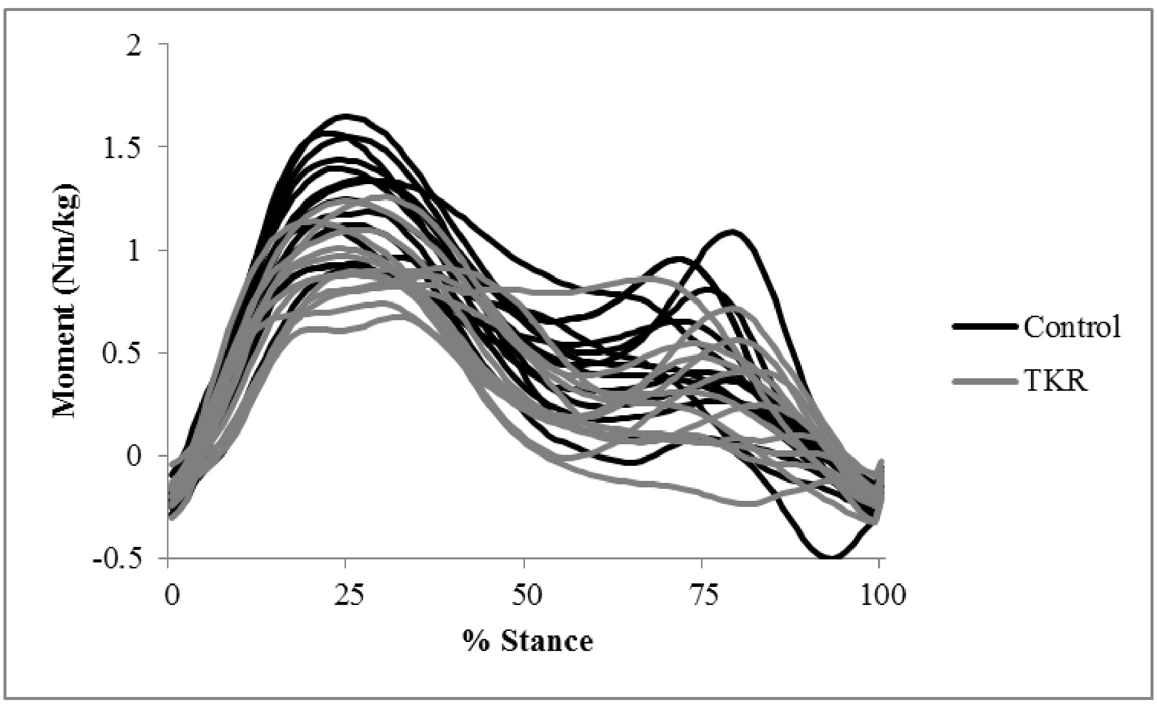


Figure 18. Individual waveforms of sagittal plane knee moment for control and TKR.

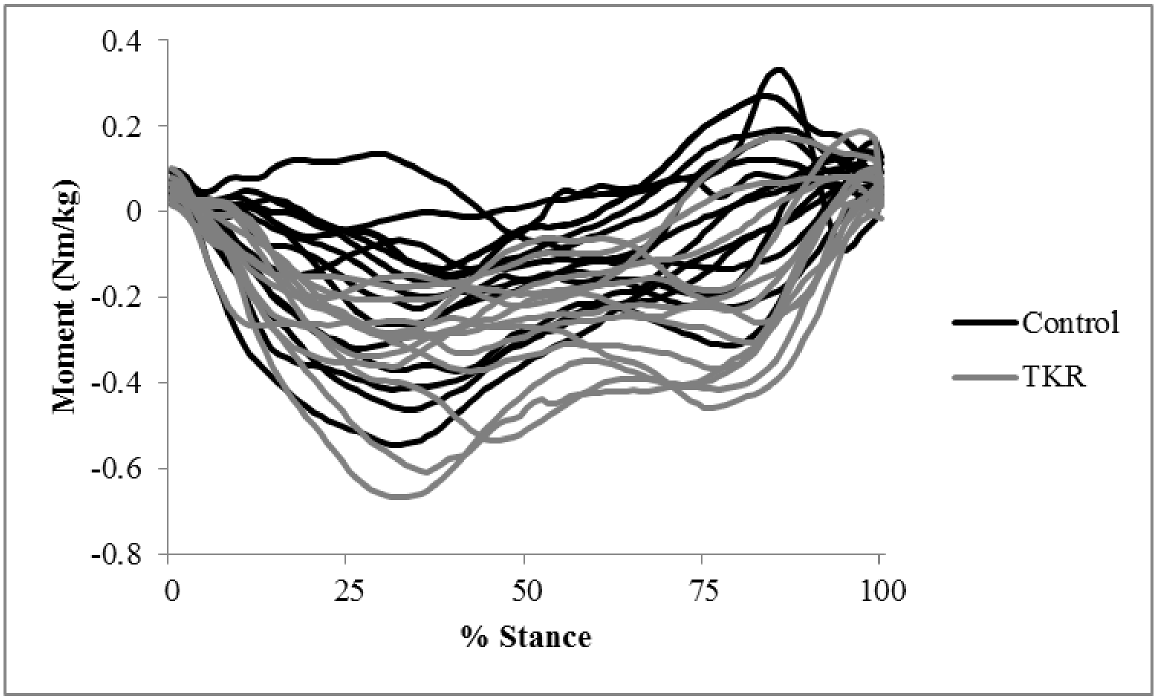


Figure 19. Individual waveforms of frontal plane knee moment for control and TKR.

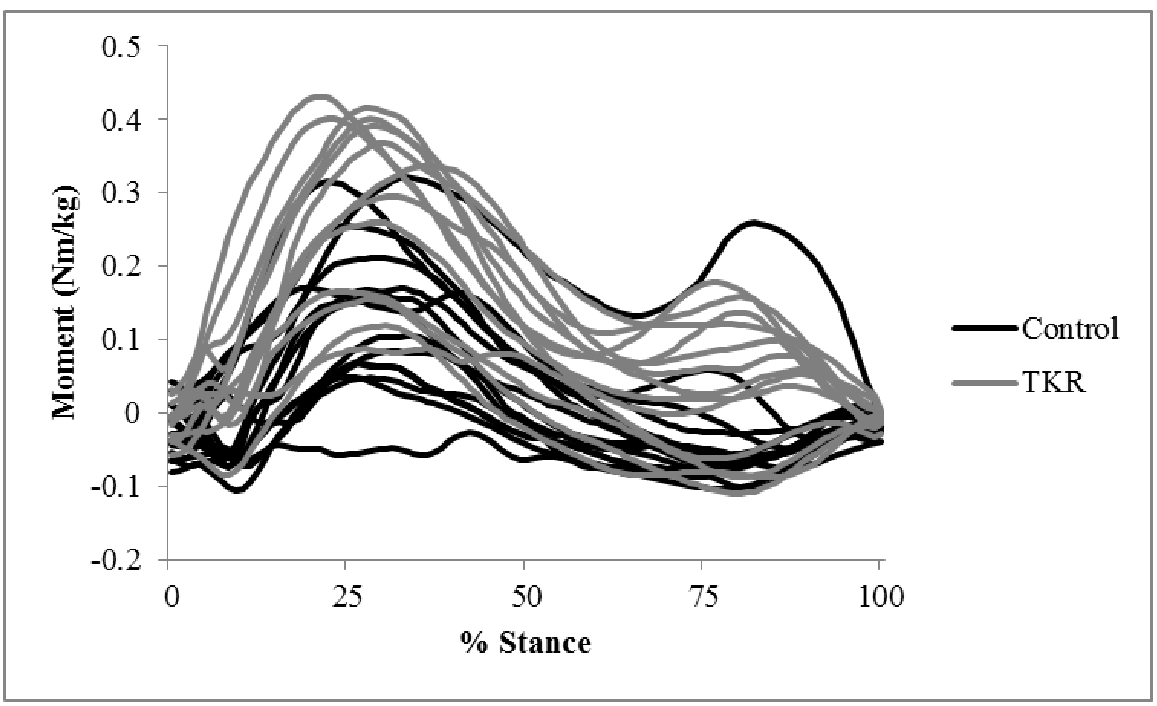


Figure 20. Individual waveforms of transverse plane knee moment for control and TKR.

VITA

Tyler Standifird was born in Orem, UT in 1984 to Ronald and Patricia Standifird. He was the youngest of six children and enjoyed following in the footsteps of his older siblings. He grew up in Highland, UT, where he graduated from Lone Peak High School in 2003. After graduation Tyler attended the University of Utah where he graduated with a degree in Exercise Physiology in 2009. In 2012, Tyler completed a Master's degree at Brigham Young University in Exercise Science while performing research in Biomechanics. Tyler completed his educational pursuits at the University of Tennessee where he earned a PhD in Biomechanics in 2015. Tyler has accepted a tenure track, assistant professor position at Utah Valley University in Orem, UT.