Influence of Cruciate Retaining, Posterior Stabilized and Bi-Cruciate Stabilized Total Knee Replacement Designs on Gait Mechanics during Ramp and Level Walking

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DEDICATION

This dissertation is dedicated to my family who has been by my side throughout this journey. A special feeling of gratitude to my loving parents, Hongjie Wen and Linbing Liu, who celebrated every success of my life and supported me with all the endeavors. There are a lot of things I could not have accomplished without their help and support. I also want to thank my husband, Jin Dong, for being understanding and encouraging of my career. Finally, to my daughter, Chloe who made me stronger, better and more fulfilled than I could have ever imagined. I love you to the moon and back.

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ABSTRACT

Twenty-five, 5 Bi-cruciate stabilized (BCS), 10 Cruciate Retaining (CR) and 10 Posterior Stabilized (PS), total knee replacement (TKR) patients and 10 healthy controls performed uphill and downhill walking on different slopes using a force platform and an instrumented ramp system. Studies one and study two examined the knee biomechanics and knee joint muscle EMG activity of TKR patients and healthy control during uphill and downhill walking at 0° (level walking), 5°, 10° and 15°, respectively. Study three compared knee biomechanics of patients with three different types of TKR implants to healthy controls during walking up and down on a 10° ramp. Study one found TKR patients had lower peak knee extension moment (KEM) than healthy controls in all uphill walking conditions. The replaced limbs showed lower peak KEM in 10° and 15° uphill walking than non-replaced limbs. The peak loading-response internal knee abduction moment (KAbM) was greater in level walking compared to 10° and 15° uphill walking. Study two showed that replaced limbs of TKR patients had lower peak loading-response and push-off KEM, and quadriceps electromyography (EMG) activity than non-replaced and matched limb of healthy controls in downhill walking. Greater peak KEM, quadriceps EMG activity were found in downhill walking compared to level walking. Study three showed peak KEM was lower in BCS patients than healthy controls and it was lower in replaced limbs than non-replaced limbs during the 10° uphill walking. Peak loading-response KAbMs were similar between the replaced limbs of three TKR groups and healthy controls in both uphill and downhill walking. Moreover, the replaced limbs had lower peak loading-response and push-off KEMs than non-replaced limbs in downhill walking. Additionally, peak loading-response KAbM was greater in non-replaced limbs of BCS and PS patients compared to that in their replaced limb. Uphill walking may have the potential to become a safe exercise for

unilateral TKR patients, however, downhill walking may not be appropriate to be included in the early-stage rehabilitation exercise protocols for TKR patients. Future studies should investigate rehabilitation strategies to improve the symmetrical knee loading of BCS and PS patients, therefore postponing or avoiding another TKR surgery.

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CHAPTER I

INTRODUCTION

Background

Knee osteoarthritis (OA) is one of the most common causes of disability and continues to increase in prevalence as the population over 65 years has steadily increased (114). It has been reported that knee OA occurs in 10% of men and 13% of women 60 years of age or older (124). In addition, 46% of U.S. adults suffer from painful knee OA in at least one leg by the age of 85 years (81). Pain and other symptoms of knee OA greatly limit the patients' ability to perform daily activities such as walking, running, squatting, and stair ambulation. Total knee replacement (TKR) or total knee arthroplasty is an operative intervention for end-stage knee OA (123). According to the Agency for Healthcare Research and Quality, more than 700,000 TKR surgeries were performed in the U.S. in 2013 (82). Furthermore, the average cost for a TKR is $16,497 per surgical procedure and the total national costs reached 11.6 billion dollars in 2013 (82). However, previous studies (8, 83) reported that TKR patients cannot fully restore their physical function to the level of their healthy peers. Thus, an understanding of functional limitations of TKR patients would help physical therapists optimizing rehabilitation protocols and help manufacturers improving total knee prosthesis designs.

A TKR surgery is the resurfacing of the joint articulating surfaces (116). The distal end of the femur and proximal surface of the tibia are cut and replaced by a femoral component and a tibial component. The metal femoral component curves around the distal end of the femur, and is grooved so that the patella can slide up and down smoothly during knee flexion and extension. The tibial component is made by a flat metal platform and a stem that inserts into the tibia. A strong and durable cushion is placed between the two components (116). One of the controversies in TKR surgery is whether to sacrifice, retain or replicate the posterior cruciate ligament (PCL). If the PCL is healthy enough to maintain knee stability from extension to flexion, the cruciate-retaining (CR) knee implant is used (116). Posterior-stabilized (PS) prosthesis is one of the most commonly used types of implants in a TKR surgery when the PCL is removed. The cam-post concept that aims to replicate the function of the PCL is implemented in such a TKR design.

In a healthy knee, the PCL causes posterior translation of the femur relative to the tibia when the knee flexion angle increases. As the knee is flexed, the femur is pulled posteriorly relative to the tibia, which is called a rollback phenomenon. However, previous fluoroscopic studies (18, 86, 105) have reported that both CR and PS implants have less posterior femoral condyle translation relative to the tibia than healthy knees in a deep knee bend. Paradoxical anterior translation of the femur on the tibia may even occur in CR implants (105). Some studies have reported that PS implants are able to reduce the paradoxical anterior translation of the femur (18, 117) while many other studies indicated that the normal knee anteroposterior translation cannot be achieved in the PS implants (83, 86, 112).

A recent TKR design, bi-cruciate stabilized (BCS) implant, intends to reproduce the normal knee function during walking by implementing a tibial post and two femoral cams, which substitutes for both ACL and PCL. The addition of an anterior femoral cam aims to prevent excessive posterior movement of the femur on the tibia. BCS implants more closely restore the femoral rollback characteristics of the normal knee compared to either the CR or the PS implant (55, 113). When the knee was fully extended, the femur in a BCS implant is more anterior relative to the tibia compared to a PS implant due to the contact between the anterior femoral cam and the tibial post (119). However, higher complication and revision rates of the BCS implant were observed compared to PS and CR implants (20).

Gait analysis has been widely used to identify biomechanical abnormalities of the lower extremities. It is important to understand how biomechanical parameters of gait such as ground reaction force (GRF), temporal-spatial variables, kinematics, kinetics, and electromyographic data are altered during walking after a TKR surgery. Some studies have reported smaller peak knee flexion angle and knee flexion range of motion (ROM) in TKR patients during stance phase compared to healthy controls (12, 69, 85). Other studies also reported that peak external knee extension moment was significantly lower in TKR patients compared to healthy controls (12, 62, 69, 85). However, only a few studies have compared biomechanical parameters between the patients with different types of TKR implants in their gait analyses (49, 111) and no differences were found between the PS and CR implants in knee kinematics and kinetics during level walking (49, 111). The peak knee flexion angle during early stance phase was similar between PS (15.2°) and CR (16.9° $p>0.05$). Catani et al. (17) performed gait analysis for 16 patients who received a unilateral BCS implant. They reported that changing patterns of kinematics and kinetics at the knee joint were similar between the replaced and non-replaced limb of BCS patients. However, they only analyzed the curve patterns of knee kinematics and kinetics in the sagittal plane and did not provide detailed discrete peak values regarding knee biomechanical variables during stance phase.

Walking on a sloped surface is a challenging task in daily activities, which requires different gait adaptations when compared to level walking (32, 56, 58, 73, 94, 110). The incline angle used in previous studies were as low as 3° (28, 32) and as high as 22° (58). Previous studies have reported that the second peak vertical GRF in uphill walking (58, 73, 110) and the fist peak vertical GRF in downhill walking (58, 73, 110) were significantly greater than those in level walking. During uphill walking, the knee flexion angle at heel strike (32, 36, 57, 58, 60, 73) and the maximum knee flexion during early stance (28, 60, 73) were increased with an increase in the incline angle. However, previous literatures (28, 58, 73) showed that during uphill walking knee flexion ROM was smaller than level walking due to a more flexed knee position during the early stance phase on the incline. The peak knee extension moment (KEM) has also been shown to increase significantly during uphill walking compared to level walking (32, 73), and muscle activity of knee extensors also increased simultaneously (27, 59). Greater peak knee flexion angles were reported during downhill walking compared to level walking (56, 58, 73, 94). In addition, the peak KEM increased significantly during downhill walking compared to level walking (43, 58, 73, 94) and changes in muscle activity patterns were directly associated to the changes in the knee moments (27, 59). Furthermore, Haggerty et al. (32) reported the peak internal knee abduction moment during stance phase of uphill walking on a 10° incline was less than that of level walking at 1.34 m/s. Ehlen et al. (25) also reported that uphill walking at 0.75 m/s reduced the external knee adduction (internal knee abduction) moment compared with level walking at 1.5 m/s in obese participants.

Statement of Problems

Walking on inclined surfaces is an inevitable part of daily living and has been integrated into rehabilitation protocols after TKR surgery (75). To our knowledge, only one previous study (90) has reported knee kinematics and kinetics in the sagittal plane during downhill walking in TKR patients. There is a clear gap in the literature about the gait pattern adapted and key biomechanical variables in TKR patients during ramp walking. Moreover, when considering downhill walking, no study has reported lower extremity kinematics and kinetics in the frontal and transverse planes. Additionally, no research has been carried out to understand the effects of TKR on EMG activity of the muscles surrounding the knee joint of the replaced and non-replaced limbs during uphill and downhill walking. Finally, no studies have explored the effects of different types of TKR implants on gait dynamics during level, uphill and downhill walking. Therefore, the purposes of studies were as follows:

Study One: The purpose of this study was to compare knee biomechanics and knee joint muscle EMG activity of the replaced limb to the non-replaced limb of TKR patients and healthy controls during walking at level ground and on inclined surfaces of 5°, 10° and 15°.

Study Two: The purpose of this study was to compare knee biomechanics and knee muscles EMG activity of the replaced limb to the non-replaced limb of TKR patients and healthy control during walking at level ground and on decline surfaces of 5°, 10° and 15°.

Study Three: The purpose of this study was to compare knee biomechanics of patients with BCS, CR and PS TKR implants and healthy controls during walking uphill and downhill on a 10° ramp.

Significance of the study

Although many studies have investigated the knee joint mechanics of ramp walking, those studies have been focused only on young healthy populations without any knee pathology. It is unclear whether TKR patients and young healthy participants are similar in knee kinetics when walking on inclined surfaces. Since both uphill and downhill walking caused significant increases in knee joint loading in young healthy populations, the investigation of how TKR patients alter their gait characteristics on sloped surfaces is necessary (53). Moreover, uphill walking has been integrated into rehabilitation protocols after TKR surgery (75), and therefore, a comprehensive understanding of the biomechanics is warranted. The information from such a study may help physical therapists create appropriate rehabilitation protocols for TKR patients and optimize total knee prosthesis designs.

Research Hypotheses

Study One

We hypothesized that:

1) the peak KEM would be lower in replaced limbs of TKR patients compared to healthy controls, and peak loading-response knee abduction moment (KAbM) in replaced limbs of TKR patients would be similar compared to matched limb of healthy controlss;

2) Compared to non-replaced limbs, the replaced limbs would have lower peak KEM and similar peak loading-response KAbM

3) The peak KEM and quadriceps EMG activity would increase and the knee flexion ROM would decrease with an increase in the incline angle in replaced and non-replaced limbs of TKR patients.

Study Two

We hypothesized that:

1) the peak KEM would be lower in replaced limbs of TKR patients compared to healthy controls, and peak KAbM in replaced limbs of TKR patients would be similar compared to matched limb of healthy controlss;

2) The peak KEM would be lower and peak KAbM would be similar in the replaced limbs compared to their non-replaced limbs;

3) The peak KEM, quadriceps EMG activity and knee flexion ROM would increase across all comparisons between level ground and 15° slope in both replaced and non-replaced limb of TKR patients.

Study Three

We hypothesized that

1) TKR patients, no matter what type of implants they have, would have lower peak KEM and similar peak KAbM in replaced limb compared to their non-replaced limbs and the limbs of healthy controls during both uphill and downhill walking.
2) Knee biomechanics would be similar between three TKR implants during level walking and walking on 10° incline and decline surfaces.

Delimitations

The inclusion criteria included for healthy adults was:

- Men and Women between the ages of 50 and 75 years

The exclusion criteria for healthy adults were:

- Knee pain during daily activities.
- Diagnosed with any type of lower extremity joint osteoarthritis as reported by the patient.
- Any lower extremity joint replacement.
- Any lower extremity joint arthroscopic surgery or intra-articular injection.
- Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) as reported by the patient.
- BMI greater than 38 kg/m^2
- Inability to walk without a walking aid.
- Neurologic disease (e.g. Parkinson’s disease, stroke) as reported by the patient.
- 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.

The inclusion criteria for TKR were:

- Men and Women between the ages of 50 and 75
- Total knee replacement in one knee with either one of CR, PS, or BCS
- At least 6 months post TKR surgery.
- No more than 5 years post TKR surgery.

The exclusion criteria included for TKR were:

- Diagnosed osteoarthritis at the ankle or hip joint of the TKR side and any major spinal disorder including osteoarthritis as reported by the patient.
- Diagnosed osteoarthritis at the contralateral ankle, knee or hip of the TKR side as reported by the patient.
- Any additional 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) as reported by the patient.
- BMI greater than 38 kg/m^2
- Inability to walk without a walking aid.
- Neurologic disease (e.g. Parkinson’s disease, stroke) as reported by the patient.
- Any visual conditions affecting gait or balance
- Any major lower extremity injuries/surgeries.
- 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.

Limitations

- All data were collected in a laboratory setting.
- The foot tracking markers were placed on the shoe. The foot movement within the shoe may not be capture precisely
- The accuracy of 3D kinematics data collecting was highly related to the accuracy of the placement of reflective anatomical markers on the surface of the joints.
- The ramp set-up required placement prior to participants coming to the lab. Thus, level walking always followed ramp walking conditions.

CHAPTER II

LITERATURE REVIEW

Introduction

This chapter includes three main topics. The first section contains the literature review on characteristics of three total knee replacement (TKR) designs: cruciate retaining (CR), posterior stabilized (PS), and bi-cruciate stabilized (BCS) TKR. The second section discusses the differences and similarities of in vivo kinematics, functional assessment, and gait biomechanics among the three TKR designs. The third section compared lower extremity biomechanics of uphill and downhill walking to level walking in healthy and TKR participants.

A TKR is the resurfacing of the joint articulating surfaces. During TKR surgery, the knee joint structures are retained (e.g., the posterior cruciate ligament (PCL) in CR TKR), replaced by artificial structures (e.g., the distal end of the femur), or discarded (e.g., the anterior cruciate ligament (ACL) and PCL in PS and BCS TKR). The distal end of the femur and proximal surface of the tibia are cut and replaced by a femoral component and a tibial component. The metal femoral component curves around the distal end of the femur, and it is grooved so that the patella can slide up and down smoothly as the knee flexes and extends (116). The tibial component is made by a flat metal platform and a stem that inserts into the tibia. A strong and durable cushion is placed between the two components (116).

The primary objective of TKR are to improve joint alignment and to achieve pain-free knee movements with sufficient range of motion (30). Most patients reported the significant reduction in knee pain after they had TKR surgery (16, 39), however, there are still 20% of patients that suffer unfavorable pain after TKR surgery (14). Moreover, according to the results of a self-administered and validated knee function questionnaire, 52% of patients at least 1 year post TKR surgery, reported some degree of limitation when doing functional activities (e.g., squatting, kneeling, turning and cutting, moving laterally, carrying loads, leg strengthening) (83). Compared to only 22% of age- and gender-matched control participants with no knee disorders reported functional impairments (83). These results indicate that the improvements in TKR were needed in prosthetic designs or surgery procedure to restore the normal knee function. As a consequence, the manufacturers are always trying to reproduce normal knee functions and structure in their TKR designs (83).

Characteristics of different total knee replacement designs

One of the controversies with TKR surgery is whether to sacrifice, retain or replicate the posterior cruciate ligament (PCL) (13, 47, 115). The presence of the PCL helps the knee joint maintain its normal kinematics and it is also capable of absorbing the anteroposterior shear loading to stabilize the knee joint (98). In all TKR surgeries, the anterior cruciate ligament (ACL) is removed if it is still intact (108), since the destruction of the ACL and reduction in its integrity were commonly found in patients with severe knee OA (22).

Cruciate retaining prosthesis

If the PCL is healthy enough to maintain knee stability from extension to flexion, CR knee implant will be used (116). It does not require the removal of the PCL and assumes that the PCL can maintain natural knee function, joint stability, femoral rollback, knee range of motion, quadriceps efficiency, and the shear force reduction on the tibiofemoral joint (63, 66, 76, 98, 105). However, systematic reviews in 2005 (47), 2013 (116) and 2015 (115) could not find significant differences in clinical and functional outcomes between PCL retention and PCL sacrifice in TKR surgery with a minimum of 1-year follow up. In a meta-analysis, the sacrifice of the PCL showed two degrees greater knee flexion range of motion than the PCL retaining TKR

(115). Furthermore, the Knee Society functional score of PCL sacrificing TKR patients was also 2.4 point higher than that of CR TKR patients (115).Thus, based on current research no significant differences can be found between PCL retaining and sacrificing TKR designs.

Posterior stabilized prosthesis

As a normal knee flexes, the lateral femoral condyle rolls back farther posteriorly than the medial femoral condyle due to its larger radius of curvature (24). The PCL plays an important role in maintaining femoral rollback and internally rotating the tibia relative to the femur during flexion (6). PS TKR design normally includes an intercondylar cam and box that houses the articulating post of the PS tibial insert. It uses the implant to provide ligament stability in the posterior direction and is designed to provide femoral rollback by the cam-post engagement. The cam-post mechanism has been implemented to replicate the physiological functions of the PCL since the early 1970s (45). Figure 1 (106) shows a model representing cam-post contact for in vivo knee flexion position of a patient.

PS was designed to stabilize the anteroposterior knee motion by mechanical interaction between the femoral cam and the tibial post as the PCL is sacrificed. In an in vivo fluoroscopic study (106), the PS implanted knees (NexGen, Zimmer, Warsaw, IN) were able to achieve 112.5° and 142.5° maximum weight-bearing flexion and passive flexion angles, respectively. Both medial and lateral contact points between the tibia and femur move posterior when the knee was flexed from 30° to maximum knee flexion angle. The tibia was internally rotated from 1.1° to 6.0° when the knee was flexed 90° from full extension (180°). The initial contact between femoral cam and tibial post was observed when the knee flexed at 91.1°. It was suggested that a later initial cam-post engagement might point to a greater knee flexion in the implant (106).

The average roll-forward motions were 4 mm and 6 mm for medial and lateral femoral condyles respectively in a PS implant (Legacy Knee Posterior Stabilized TKR, Zimmer Inc. Warsaw, IN) when patients stand up from a squatting position (65). The average weight-bearing knee range of motion for 18 participants was 110.7°, while the non-weight bearing knee range of motion reached 135.6°, which was similar to another study (106). The maximum tibial external rotation was about 6.3° during the squatting-to-standing activity.

If the TKR is posteriorly unstable, paradoxical anterior translation of the femur on the tibia and lift-off of its lateral condylar may occur, which is different from knee kinematics in a healthy knee (11). Some studies have shown PS implants reduce the paradoxical anterior sliding of the femur (18, 117), whereas many studies indicated the patients with PS implants cannot achieve normal knee function (83, 86, 88, 112). Patients with PS TKR showed less posterior femoral rollback of the lateral condyle compared to normal knee, but more normal tibiofemoral axial rotation, and greater weight-bearing flexion than those with CR TKR (18).

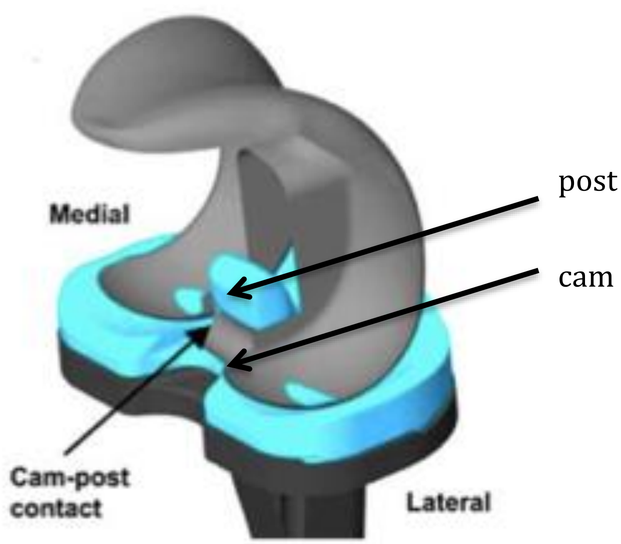

Figure 1 A model representing initial cam-post engagement in vivo pose of a patient (106).

Bi-cruciate stabilized prosthesis

A recent knee implant design, BCS, intends to reproduce the normal knee function by implementing a two cam-post mechanism, which substitutes for both ACL and PCL (Figure 2) (119). The main additional mechanical feature of the BCS is an anterior femoral cam which aims to prevent excessive posterior movement of the femur on the tibia. In addition, a BCS also includes an asymmetrical geometry of the tibial plateau, a concave medial compartment and a convex lateral compartment. Normally, the posterior aspects of the femoral cam and the post on the tibia contact with each other when the knee flexes to 50°-60°. In order to limit anterior tibia translation to mimic the function of the ACL, the anterior aspect of the femoral cam and the tibial post are engaged during the first 20° of knee flexion. The medial concave surface stabilizes the knee joint in the anteroposterior direction, in the meanwhile, the convex lateral surface promotes an external rotation of the femur during the knee flexion (17). However, higher complication and revision rates of the BCS knee implant were observed compared to other older prosthesis, e.g., PS and CR implants (20).

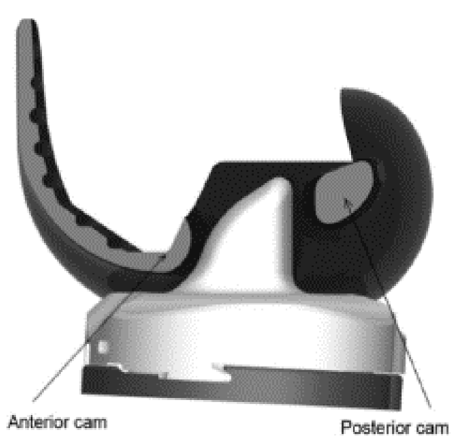

Figure 2 The journey (Smith and Nephew, Memphis, TN) bi-cruciate stabilized total knee replacement showing the anterior and posterior cams of the femoral component, and the post on the tibia (119).

In the healthy knee, lateral femoral condyle has greater posterior rollback motion relative to the medial condyle, leading to an external rotation of the femur during knee flexion (24). Komistek et al. (52) reported an average posterior rollback of medial and lateral femoral condyles were 3.4 mm and 19.2 mm, respectively in normal knees, during a deep knee bend with progressive knee flexion. In addition, the average external tibiofemoral rotation of healthy knees was 16.8° during knee flexion (52). The BCS implant showed posterior femoral rollback and axial rotation patterns similar to those of the normal knee, but different in magnitude. (119)

In a fluoroscopy study (118), from full extension to maximum knee flexion, the BCS implant had a posterior rollback of medial and lateral femoral condyles of 14 mm and 23 mm respectively. In addition, the average external rotation from full extension to maximum flexion was 10.8°, which is less than that in normal knee (52). Catani et al. (17) recruited 16 patients who underwent BCS TKR (Journey, Smith & Nephew, London, UK) at 6 months postoperatively. They investigated in vivo kinematics during stair-climbing, chair-rising/sitting, and step-up/down using fluoroscopy, and also performed gait analysis using a motion capture system. During the stair-climbing, chair-rising/sitting, and step-up/down, the anteroposterior translations were 9 mm, 10 mm and 6.9 mm between medial femoral condylar and tibia, and were 14.3 mm, 18.5 mm and 13.9 mm between lateral femoral condylar and tibia, respectivley. Kuroyanagi et al. (55) reported that in those with a BCS implant knee (Journey, Smith & Nephew, Memphis, TN), the external rotation range of motion reached 10° and 9° during lunge and kneeling, respectively. When the knee was flexed 100° from a full extension position, posterior rollback of medial and lateral condyles were 5mm and 11mm, respectively.

Comparisons between three total knee replacement designs

In this review, the comparisons were only made between CR, PS and BCS TKR no matter whether the prosthesis design was fixed bearing or mobile bearing.

In vivo kinematics

Healthy controls vs. TKR

Individuals with TKR experienced less posterior translation in femoral condyles with increasing knee flexion compared to those healthy knees (18, 86, 105). The patella tendon angle was often evaluated in the fluoroscopic study to explain the anteroposterior translation of the femur on the tibia. The patella tendon angle was defined as the angle between the patellar tendon and the tibial longitudinal axis (Figure 3) (86). When the knee is fully extended, the patellar tendon angle is positive, indicating the femur is anterior relative to the tibia and pushing the tendon forward. As the knee flexion angle increases, the patellar tendon angle becomes negative as the femoral condyles roll back on the tibial plateau. A more negative patellar tendon angle indicates a more posterior femoral translation.

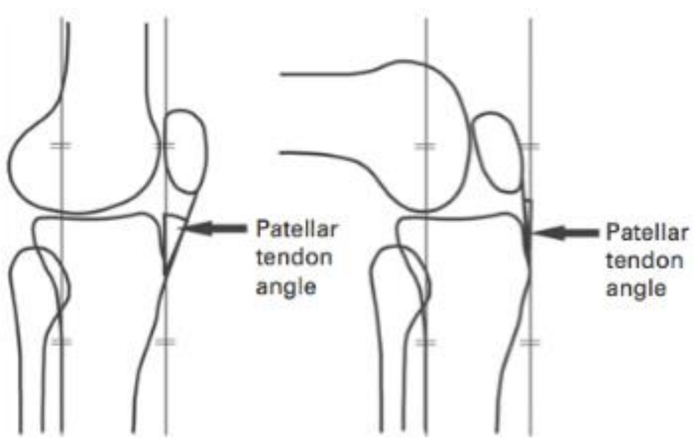

Figure 3 The patellar tendon angle is positive when the knee is full extension, while it becomes negative when the knee is flexed (86).

In a fluoroscopy study (105), five different CR prosthetic designs, Porous Coated Anatomic (Howmedica), Ortholoc (Wright Medical Technology), Genesis (Smith & Nephew), Anatomic Modular Knee (Depuy), and Miller-Galante 2 (Zimmer) were compared to healthy controls when they performing a single-leg deep knee bend. In healthy knees, the contact point between the femur and tibia was located 6 mm anterior to the midline in the sagittal plane of the tibiofemoral joint at full extension. However, the contact point translated to 2 mm posterior to the midline as the knee flexion increased. In contrast to the healthy knees, at full extension the contact point of CR knees started 10 mm on average posterior to the midline, and then translated to 5 mm anterior to the midline in the sagittal plane during knee flexion. CR knees experienced femoral anterior translation during knee flexion, which were opposite to the healthy knee. The five CR TKRs also showed 20% lower in maximum weight-bearing knee flexion compared to healthy knees.

Pandit et al. (86) recruited 55 patients and divided them into four study groups according to four different implants they received, CR Scorpio (Stryker SA, Montreux, Switzerland), PS Scorpio (Stryker SA, Montreux, Switzerland), CR Sigma (DePuy, Johnson and Johnson, Leeds, UK) and PS Sigma (DePuy, Johnson and Johnson, Leeds, UK). Patellar tendon and knee flexion angles were compared between TKR knees and healthy knees using fluoroscopy during three different exercises: (1) leg extension against gravity: in a semi-supine position, participants with the support of their thigh and upper body extended the knee from 90° to full extension; (2) leg flexion against gravity: in a standing up position, participants flexed knee from full extension to 90° while the femur remained perpendicular to the ground; and (3) step-up on single foot to a 25 cm high platform . For exercise one, as the knee extended from 90° to full extension, the patellar tendon angle was increased from -1° to 20° for normal knee, while it was increased approximately from 7° to 12 ° for all the TKR patients. For exercise two, the changing pattern of patellar tendon angle for the normal knee was similar to that for exercise one. The patellar tendon angles of all the implants were significantly lower in extension and higher in flexed position compared to that of healthy knee ($p<0.001$ for all comparisons). All TKR groups demonstrated a smaller patellar tendon angles in the extension compared to healthy knee during the step-up movement ($p<0.01$). The study showed a similar trend for all three exercises. As the knee flexion angle increases, the TKR groups experienced less change in patellar tendon angle compared to the normal knee indicating TKR had less posterior translation in the femoral condyles relative to the tibia than the healthy knee.

Ward et al. (119) compared the patellar tendon angle during knee flexion, extension and step-up movements using the fluoroscopy between the BCS (Journey, Smith and Nephew), PS (Genesis II, Smith and Nephew) and healthy controls. The patellar tendon angle in the BCS was closer to that in the healthy knee when knee was near full extension during the leg extension (control: 15°; BCS: 16°; PS: 13°) and flexion (control: 20°; BCS: 18°; PS: 15°) compared to the PS implant. The engagement of the anterior cam (post contact with anterior femoral cam) of the BCS partially restored the mechanical function of the ACL by preventing excessive posterior translation of the femur on tibia plateau near full extension.

B. H. van Duren et al. (113) reported similar results to those found in Ward's study (119). Ten patients with BCS implant (Journey, Smith & Nephew, Memphis, TN) were evaluated fluoroscopically during step-up and lunge movement. The maximum knee flexion angle achieved in BCS implant was 124.7°, which was 11.5% less than the angle achieved by the healthy knee ($p<0.05$). The average angle of engagement of the anterior cam-post (post contact with anterior femoral cam) and posterior cam-post (post contact with posterior femoral cam) were 12.6° and

45.4° respectively. The patellar tendon angle in BCS was 10° less than that in the healthy knee during both step-up and lunge throughout the range of knee flexion ($p<0.05$). Although BCS showed a similar tibiofemoral anteroposterior motion to the healthy knee, the consistent lower patellar tendon angle in BCS compared to the healthy knee indicates that the absolute position of the femur component relative to the tibia throughout the range of knee flexion was too posterior.

Although the BCS TKR were more internally rotated compared to CR and PS TKRs, the healthy knees demonstrated 5° greater tibia internal rotation than BCS when the knee was flexed to 70° from fully extension (80). BCS and PS TKRs were similar in tibiofemoral anteroposterior translation patterns that both medial and lateral condyles moving posterior gradually as knee flexion increased (119). For the healthy knees, the femur was positioned at a more anterior position relative to the tibia during the knee flexion compared to the implanted knees (80, 113). CR TKR exhibited different sliding patterns compared to other TKR designs and healthy knees, which is probably due to the lack of intrinsic anteroposterior stabilizers (117). Overall, BCS TKRs more closely restore the femoral rollback characteristics of healthy knees than the CR TKR or PS TKR (55, 113).

Posterior stabilized vs. cruciate retaining design

In general, CR knees have shown less posterior femoral rollback than PS knees (9, 18, 117). Victor et al. (117) examined the differences in knee kinematics between CR and PS TKRs (Genesis II, Smith & Nephew, Memphis, TN) during a weight-bearing deep lunge and step-up/down on a 30-40 cm riser. No significant differences were detected in knee range of motion between CR and PS implants either passively or during the deep lunge activity. The anteroposterior position of the femur was strong correlated with maximum knee flexion angle of PS knees ($R^2 = 0.89$, $p = 0.006$). The rollback was greater and more consistent in PS knees compared to CR knees during the lunge. In the step up/down activity, CR knee demonstrated a mean of 4 mm anterior translation in medial condylar, while PS knee had a mean of 3 mm posterior translation. Lateral condylar translated 2 and 10 mm posteriorly in CR and PS knees, respectively, during the step-up/down activity.

Cates et al. (18) investigated in vivo knee kinematics for 30 TKR patients. Fifteen of them had been implanted a CR TKR (NexGen CR-Flex high-flexion TKR, Zimmer, Warsaw, Ind), 15 participants had a PS TKR (Legacy LPS-Flex high-flexion TKR, Zimmer, Warsaw, Ind). All participants performed a deep knee bend during fluoroscopic examination at least 6 months post-surgery. Both CR and PS implants had the anteroposterior translation and average weight-bearing ROM that were similar between two designs (p = 0.782), although the ROM was 5° greater for CR knees compared to PS knees. On the medial femoral condyles, CR knees exhibited 3.2 mm less posterior femoral rollback than PS knees (p = 0.028). In addition, the internal rotation angle for CR knees was 3° greater than that of PS knees at maximum knee flexion (p = 0.011).

Bi-cruciate stabilized vs. posterior-stabilized design

Both BCS and PS demonstrated posterior rollback in the femoral condyles during knee flexion, when the knee was fully extended. The patella tendon angle in BCS was greater than that in PS indicating that the femur in BCS is more anteriorly relative to the tibia compared to PS (119). Thirteen patients with a BCS implant (Journey, Smith and Nephew, Memphis, TN) and 15 patients with a PS implant (Genesis II, Smith and Nephew) participated in a fluoroscopic study at seven weeks post-surgery (119). They were asked to perform leg extension and flexion against gravity and step-up on a 25 cm riser. The BCS group had a 3° greater patellar tendon angle when the knee was close to full extension compared to the PS group (p=0.02). The patellar tendon angle was also 4° greater in BCS compared to PS during the step-up when the knee was flexed to 10° ($p<0.04$).

Functional outcomes

It is important to understand differences in functional outcomes between different TKR designs. There are some tests that can be used to estimate participant’s physical function, such as, a 6-minutes walking test, timed up and go test, and timed stair ascent and descent. Normally, the knee society scoring system (99) and knee flexion and extension range of motion were also measured in the functional test. The Western Ontario and MacMaster Universities Osteoarthritis Index (WOMAC) survey, Total Knee Function Questionnaire (121), Short Form-36 (SF-36) (120), consisting of physical and mental components have also been used to evaluate specific and general health-related quality of life. In general, the PS (21) and BCS (20, 96) showed higher complication and revision rate than the CR design.

Posterior stabilized vs. cruciate retaining design

Several studies have reported non-significant differences between CR and PS TKR in functional measurements (19, 48, 51, 64). However, patients with PS implants showed greater knee range of motion than patients with CR implants (38, 70, 111).

Conditt et al. (21) compared the functional outcomes between patients receiving a CR TKR and PS TKR (AMK, DePuy, Warsaw, IN). All participants completed the Total Knee Function Questionnaire, SF-36, and knee society scoring system, and the knee range of motion was measured at one year post-surgery. CR and PS TKR groups showed same range of motion (121°) at one-year follow-up. The patients with PS TKR reported that lower functional score in squatting (-1.2 vs. 0,4), kneeling (-1.3 vs. -0.1) and gardening (-0.7 vs. 1.2) than the patients with CR TKR ($p<0.05$ for all comparisons) in Total Knee Function Questionnaire, which indicating patients with PS TKR experienced greater functional limitations compared to patients with CR TKR. Moreover, the patients with PS designs experienced a higher frequency of swelling or tightness of their replaced knee than the patient with CR TKR ($p < 0.05$) on a five-point scale ranging from never experiencing swelling or tightness to greater than once per week.

Chaudhary et al. (19) examined self-reported pain, function, and health-related quality of life using the WOMAC and the RAND 36-Item Health Survey of 100 patients with either a PS or CR (SCORPIO, Stryker Orthopedics, Mahwah, New Jersey) implant. The active knee flexion and extension range of motion of each participant were measured with a goniometer. PS and CR groups had similar pain, function and quality of life scores, and knee range of motion over a two-year postoperative period. Two hundred and fifty patients received a CR in one knee and a PS implant in the contralateral knee (51). At the time of two-year follow-up, there were no differences in knee society scoring system and knee range of motion. Harato et al. (38) reported that patients with PS implant (Genesis II, Smith and Nephew, Memphis, TN) had significantly greater knee range of motion (3.3°) than CR implant at a minimum of 5 years post-surgery. No significant differences were found between PS and CR groups in postoperative WOMAC evaluation or SF-12 mental and physical scores. Maruyama et al. (70) recruited 20 patients who had a CR TKR implanted in one knee, and a PS TKR in the contralateral knee (DePuy, Johnson & Johnson, Warsaw, IN). In a 2-year post-surgery, the PS knees showed 7.4° greater knee range of motion compared to CR knee ($p<0.05$). van den Boom et al. (111) also reported a 7° greater knee range of motion in PS compared to CR knee ($p = 0.038$).

Bi-cruciate stabilizing (BCS) vs. Posterior Stabilized (PS)

No significant differences were found between BCS and PS TKR for patient satisfaction, knee society scoring system and Hospital for Special Surgery knee score (96, 97). However, the improvement in knee range of motion in BCS compared to PS was not consistent (97). Furthermore, BCS exhibited higher incidence of complications and residual pain compared to the PS design (20, 96).

Patients who received either the BCS implant (Journey BCS; Smith & Nephew, Memphis, TN) or the PS implant (Genesis II, Smith & Nephew, Memphis, TN) participated in a function assessment study (97). There were no significant differences in maximal knee flexion on radiographs. Both implants achieved a medium maximal flexion angle of 125° at the two-year follow-up. BCS and PS groups also exhibited similar results with the Knee Society Scoring system, the Patella Scoring System, the Knee Injury and Osteoarthritis Outcome Score questionnaire, and visual analog scale satisfaction at a two-year follow-up. However, in the BCS group, 26 patients reported 41 adverse device effects, versus 13 patients reported 16 adverse device affects in PS group.

Sanz-Ruiz et al. (96) recruited 73 patients with a PS implant (LCS Complete RPS Knee System, DePuy Orthopedics, Warsaw, IN) and 77 patients with a BCS implant (Journey, Smith & Nephew, Memphis, TN). The patients in BCS group (116.3°) demonstrated a significant greater knee range of motion than those in PS group (107.1°, $p = 0.007$) at one-year follow-up, also at seven-year follow-up (BCS: 115.9° vs. PS:105.8°, $p = 0.022$). However, at the end of seven-year follow-up, the BCS group showed higher WOMAC function subscale than PS group ($p = 0.002$). Unfortunately, the residual pain in the WOMAC pain subscale ($p = 0.013$) and iliotibial band syndrome incidence (BCS: 6.6% vs. PS: 0%, $p = 0.02$) were also higher in the BCS TKR compared to the PS TKR (96).

Gait analysis

Gait analysis has been widely used to identify the biomechanical abnormalities of lower extremities. It is important to understand how biomechanical parameters of gait, ground reaction force (GRF), temporal-spatial variables, kinematic and kinetic, are altered after TKR during walking. Slight differences were detected in gait parameters between different implant designs.

Healthy controls vs. TKR patients

Temporal-spatial variables including gait velocity, stride length, and cadence provide basic information about recovery of walking after TKR, which are easy to collect and analyze in a laboratory or clinical setting. Significant differences were reported between TKR patients and healthy controls in temporal-spatial variables (5, 12, 62, 85). Alnahdi et al. (5) found no differences in walking speed between patients at six months post-surgery (1.27 m/s) and one year (1.31 m/s) after TKR ($p = 0.29$). However, the healthy control participants (1.43 m/s) walked significant faster than the TKR patients ($p = 0.001$). Levinger et al. (62) reported the TKR patients walked significantly slower (TKR: 1.18 m/s vs. healthy controls: 1.37 m/s, $p<0.001$) with shorter stride length (TKR: 1.23 m vs. healthy controls: 1.36 m, $p<0.001$) and reduced cadence (TKR: 115.2 steps/min vs. healthy controls: 121.27 steps/min, $p=0.002$) at a12-months follow-up compared to the healthy controls. Benedetti et al. (12) also demonstrated that stride length, cadence and walking speed in TKR patients at six-months (106.7 cm; 95.2 steps/min; 0.85 m/s), one-year (112.2 cm; 103.2 steps/min; 0.97 m/s), and two years (112 cm; 102.4 steps/min; 0.96 m/s) follow-up exams were lower than those obtained from healthy controls (130.9 cm; 111.8 steps/min; 1.22 m/s; $p<0.001$ for all comparisons). TKR patients at a two-month follow-up session walked (TKR: 0.7 m/s vs. healthy controls: 1.3 m/s, $p<0.001$) significantly slower with reduced stride length (TKR: 0.9 m vs. healthy controls:1.4 m, $p=0.003$)

and cadence (TKR: 85 steps/min vs. healthy controls:110 steps/min, $p=0.002$) compared to healthy controls (85). According to the findings in previous literatures, the gait temporal-spatial parameters of TKR patients do not approach those values of healthy older adults over a two-year post-surgery period.

GRF is a measure of overall external loading applied to human body during movements, and is commonly reported as a percentage of body weight (BW). The asymmetry between peak vertical GRF in the replaced and non-replaced limb was reported in a study of Quervain et al. (54). They showed that the replaced limb had a lower peak vertical GRF (1.06 BW) compared to non-replaced limb (1.1 BW) when patients walked at 1.14 m/s at a two-year postoperative test ($p=0.008$). The asymmetry loading between limbs may explain why approximately 40% of patients who had one knee replaced have to replace the contralateral knee within ten years (74).

Joint kinematic variables including peak knee flexion, adduction angles and knee flexion range of motion (ROM) were some common variables reported in TKR related gait biomechanical analysis. Some studies reported smaller peak knee flexion angle and knee flexion ROM in TKR patients during stance phase compared to healthy controls (12, 68, 85). Benedetti et al. (12) reported TKR patients compared to healthy controls at 12-months follow-up had reduced peak knee flexion angle during weight acceptance phase (TKR: 11.5° vs. healthy controls: 16.7°, $p=0.001$) and at toe-off (TKR: 33.9° vs. healthy controls: 38.2°, $p=0.04$). As a consequence, the total knee flexion ROM was less in TKR patients compared to healthy controls (TKR: 48.8° vs. healthy controls: 57.1°, $p<0.0001$), respectively. Mandeville et.al (68) demonstrated that TKR patients at six-months post-surgery had significant less peak knee flexion angle during weight acceptance phase compared to healthy controls (10.63° vs. 16.09°, respectively $p<0.0125$). Ouellet et al.(85) also found TKR patients at two-months post-surgery had reduced peak knee flexion angle during stance phase compared to the healthy individuals (35° vs. 47° respectively, p<0.05). However, Levinger et al. (62) reported that there were no significant differences in peak knee flexion angle during stance (20.97° vs. 20.96° respectively, p=1.00) and total knee flexion ROM (51.07° vs. 59.24 respectively, p=0.078) between TKR patients at 12-months follow-up and healthy controls.

Previous studies reported that peak knee external extension moment was significantly lower in TKR patients compared to healthy controls (12, 62, 68, 85). Levinger et al. (62) stated that TKR patients at 12-month post-surgery showed lower peak KEMKEM than healthy controls (-0.77 Nm/kg vs. -1.97 Nm/kg respectively, p=0.002). In addition, the patients walked significantly slower compared to the control group (1.18 m/s vs. 1.37m/s respectively, p<0.001). Benedetti et al. (12) also showed that TKR patients at two-year post-surgery had reduced walking speed (0.96m/s vs. 1.22 m/s respectively, p<0.001) and peak KEMKEM (-1.3 Nm/kg vs. -2.6 Nm/kg respectively, p<0.001) compared to healthy control. In addition, Ouellet et al. (85) found the peak KEMKEM was 18% lower in TKR patients at two-month post-surgery compared the healthy controls (p = 0.008) and the patients walked significantly slower than healthy controls (0.7m/s vs. 1.3m/s respecitvely). Mandeville et al. (68) analyzed TKR patients at six-month post-surgery and found that TKR patients had lower walking speed (1.05 m/s vs. 1.21 m/s respectively, p<0.0125) and lower knee internal flexion moment (external extension moment) at weight acceptance compared to healthy controls (0.7 NM/kg vs. 1.22 NM/kg respectively, p<0.0125). Comparisons between studies are difficult, since the time from surgery plays an important role in recovery, and in the reviewed studies, it varied from two months (85) to two years (12). The findings in previous literature showed that there were deficits in sagittal plane knee kinematics and kinetic after replacement compared to healthy controls. Since the walking speed can significantly influence the knee kinematics and kinetics (41), smaller peak knee flexion angle, ROM and KEMKEM may due to the lower walking speed in TKR patients compared to healthy controls.

In order to understand the success of surgery, frontal plane knee kinematics and kinetics are also compared between TKR patients and healthy controls, since those variables are strongly associated with the progression and severity of medial compartment knee OA (123). Previous studies (69, 72) have shown that peak knee adduction angle in TKR patients is similar to that in healthy controls. Mandeville et al. (69) did not find significant differences in knee adduction angle at first peak of vertical GRF between TKR patients at six-month post-surgery (5.81°) and healthy controls (5.46°). McClelland et al. (72) also reported no difference in peak knee adduction angle during stance phase between TKR patients at 12-month post-surgery (4.54°) and control group (4.55°) ($p = 0.981$). Orishimo et al. (84) reported that peak knee adduction angle during stance phase significantly decreased at six-month follow-up compared to preoperative (3.6° vs. 9.7° repectively, $p=0.001$). TKR surgery is successful at restoring peak knee adduction during stance to healthy levels, as peak knee adduction angle in TKR patients were similar to healthy controls. This angle directly changes the length of the frontal plane moment arm. The frontal plane GRF and its moment arm relative to the knee joint center are two main factors related to the knee adduction moment (44). A reduction in this moment arm may lead subsequent decrease in the knee adduction moment. However, no studies examined the differences in frontal plane moment arm between TKR patients and healthy controls.

The external knee adduction moment (internal abduction moment) has been considered as a surrogate measure for medial compartment knee joint loading (125). Increased medial knee joint loading may cause increased stress and accelerated wear on the joint replacement (35). In

Mandeville et al (69) showed no significant difference for peak knee adduction moment at first peak of vertical GRF between TKR patients at six-month follow-up (3.01 Nm/kg) and healthy controls (3.07 Nm/kg). However, McClelland et al. (71) found peak knee adduction moment during stance phase was greater in healthy control (3.59 Nm/kg) compared to TKR patients (2.91 Nm/kg, $p<0.001$) at 12-month follow-up. Orishimo et al. (84) stated peak knee adduction moment in the braking phase of walking was decreased to 85% of preoperative levels at six-month postoperative ($p = 0.037$). Previous studies have reported similar (68) or smaller (72) peak knee adduction moment during stance in TKR patients compared to healthy controls. In addition, peak knee adduction moment was significantly reduced following knee replacement compared to pre-operative (84). As the results, TKR surgery improved knee moment and subsequent loading in the frontal plane.

The patients with either CR or PS implant showed gait impairment compared to healthy controls (46). However, gait analysis disclosed most BCS patients can replication of nearly normal walking patterns (17). Eleven and nine patients with CR at the average 25.9 month post-surgery and PS at the average 42.6-month post-surgery (Genesis I, Smith & Nephew, Memphis, TN), respectively, were compared to ten healthy controls in a gait analysis study (46). Three-dimensional knee angles were monitored by an electrogoniometer. Compared to healthy controls, PS knee were 45% and 24% lower in the peak knee flexion angles during stance and swing phase, respectively. Moreover, the PS knee also showed 56% less external rotation range of motion during swing phase compared to the healthy controls.

Catani et al. (17) tested sixteen patients who received a unilateral BCS TKR (Journey, Smith & Nephew, London, UK) at 6 months post-surgey and compared their replaced and non-repalced limbs in level walking. Sixty percent of patients were able to restore normal hip, knee and ankle flexion in entire gait cycle. However, knee adduction moment was smaller in BCS knees compared to normal knee. Unfortunately, they only analyzed the curves of knee kinematics and kinetics in sagittal plane and did not provide detailed information regarding other key kinematics and kinetics variables.

Posterior stabilized (PS) vs. cruciate retaining (CR) design

Some studies have examined the key gait characteristics in PS and CR TKRs and no significant differences were found between the two implants in major knee biomechanics parameters (10, 15, 46, 109). Eighteen patients who had either a PS or CR implant (Depuy PFC Sigma, Depuy, Inc., Warsaw, IN) in one knee for at least two years of follow-up from surgery performed level walking and stair ascent/descent (49). Compared to CR knee, the PS knee exhibited 7% and 12% greater in peak knee flexion angle during stance ($p=0.02$) and swing phase ($p=0.002$) in stair descent, respectively.

Bolanos et al. (15) recruited 14 patients with a PS implant (Insall-Burstein II, Zimmer, Warsaw, IN) in one knee and a CR implant (Biomet, Warsaw, IN; Howmedica, Rutherford, NJ)in the contralateral knee. No significant differences were found between the PS and CR knees regarding the EMG muscle activity during level walking, stair ascent and descent, and isokinetic strength of the quadriceps and hamstring. In addition, no significant differences were found between PS and CR in both knee kinematics and kinetics during level walking and stair ambulation.

Twenty-four patients who received either PS or CR unilateral TKR (AGC, Biomet, Inc., Warsaw, IN) were participated in a gait analysis study at 6-9 months post-surgery(111). Compared to PS knees, CR knees showed a 5° and 3.3° greater in maximum knee flexion and flexion range of motion during stance phase ($p<0.004$ for all comparisons). No significant differences were seen between two implant groups in any knee kinetic parameters preoperatively, postoperatively and the difference between pre- and post-operative values.

Biomechanics of ramp walking

Ramp Walking in Healthy Adults

Locomotion on sloped surface is a challenge in daily environment that requires different muscle activations and increased metabolic cost (100) when compared with level walking. Gait analysis on inclined surfaces and declined surfaces are crucial to understand the rehabilitation requirements (57, 61, 75) and total knee prosthesis design (31, 102). The influences of slope on human walking have been studied in terms of kinematics, kinetics and EMG on both ramps and treadmills.

Spatiotemporal Gait Parameters

When compared with level walking, ramp walking, whether uphill or downhill, shows many differences in common spatial-temporal variables including stride length, cadence, and velocity. Kawamura et al. (50) recruited 17 healthy young men and asked them to walked at their preferred self-selected speed on slopes of 3°, 6°, 9° and 12°. They reported that during uphill walking, participants showed increases in step length at 6° (70 cm) and 9° (71 cm) slopes compared with level walking (68 cm) respectively ($p<0.05$ for all comparisons). However, the step length during 12° uphill walking (69 cm) was similar to that during level walking (68cm, $p>0.05$). During downhill walking, the step length decreased for 9° (63 cm) and 12° (58 cm) slopes compared to level walking (68 cm) ($p<0.05$ for all comparisons). They also reported the velocity in up (1.2 m/s) and downhill (1.1m/s) walking decreased significantly at an inclination of 12° compared to level walking (1.28 m/s, $p<0.01$).

Similar spatiotemporal gait adaptations during uphill walking were found in a group of older adults with a mean age of 77.8 years (26). Decreases in step length (63.1 cm vs. 64.3cm, $p=0.01$), cadence (111.6 steps/min vs. 117 steps/min, $p<0.001$) and velocity (0.89 m/s vs. 0.96 m/s, $p<0.001$) were detected when walking on a 10° incline compared to level walking.

Although most studies performed in a controlled laboratory setting, Sun et al. (107) investigated the gait characteristics of urban pedestrians under a nature conditions. Compared to downhill walking, people had a faster speed (1.155m/s vs. 1.13m/s, $p<0.005$), a slower cadence (112.16 steps/min vs. 115.31 steps/min, $p<0.001$) and a longer step length (61.4 cm vs. 58.7 cm, $p<0.001$) during uphill walking. Moreover, they reported moderate correlation between spatiotemporal gait parameters (walking speed: $R^2 = 0.734$, $p<0.01$; cadence: $R^2 = 0.684$, $p<0.02$; and step length: $R^2 = 0.598$, $p<0.025$) and slope angle. For uphill walking with increasing slope by 1°, the walking speed, cadence and step length decreased by 0.014 m/s ($p<0.01$), 1.01 steps/min ($p<0.02$) and 0.2cm ($p<0.025$), respectively. In addition, downhill walking demonstrated strong correlation between step length and slope angle ($r^2 = 0.826$, $p<0.005$). Increasing slope by 1° was expected to decrease step length during downhill walking by 0.75 cm ($p<0.005$). In general, the step length (26, 107), cadence (26, 107) and walking speed (26, 50, 107) decreased with increasing slope during uphill walking. During downhill walking, the step length also decreased with increasing slope (50, 107).

Ground Reaction Force

Vertical and anteroposterior ground reaction forces (GRF) were commonly investigated during uphill and downhill walking. The vertical GRF for uphill and downhill walking was similar in shape and temporal occurrence of peaks to those for level walking, but some significant differences were reported in the peak magnitudes. The findings from previous literature in the first peak vertical GRF, the loading peak, during uphill walking were not consistent between studies. Mclntosh et al. (73) recruited 11 healthy male university students and asked them to walk up and down on 0°, 5°, 8° and 10° inclines at self-selected speeds. During uphill walking on a 10° incline, the first peak vertical GRF was nearly 19.3 % greater than that during level walking ($p<0.05$). In a study by Lay et al. (58), nine healthy adults performed uphill and downhill walking at a self-selected speed on a custom ramped walkway at 0°, 8.5° and 21°. The first peak vertical GRFs were greater in uphill walking at 8.5° (1.08BW) and 21° incline (1.11BW) than that in level walking (1.05BW), but the differences were non-significant ($p>0.05$), which was probably due to the limited number of participants. However, Uto et al. (110) reported the first peak GRF was 1.1 BW and 1.08 BW when participants walked uphill on 5° and 10° inclines at self-selected speeds, which were lower than that during level walking (1.14 BW, $p<0.01$ for all comparisons).

Compared to level walking, there was a significant increase in the second peak vertical GRF, or the propulsive peak in uphill walking (58, 73, 110), Mclntosh et al. (73) reported the second peak vertical GRF was about 31.8% greater during uphill walking on a 10° incline than during level walking. Lay et al. (58) also demonstrated that the second peak vertical GRF was greater in uphill walking on a 8.5° incline (1.17 BW) compared to that in level walking (1.09 BW, $p<0.05$). In the Uto et al.'s study (110), the second peak vertical GRF was 1.16 BW and 1.12 BW when participants walked up on 5° and 10° inclines, respectively, which were greater than during level walking (1.09 BW, $p < 0.015$ for all comparisons).

The first peak vertical GRF increased significantly as the angle of incline increased for downhill walking (29, 56, 58, 73, 94, 110). Previous studies have showed the second peak vertical GRF in downhill walking was similar (73, 94),or smaller (56, 58, 110) than during level walking.

However, Mclntosh et al. (73) found that, during downhill walking at self-selected speed on a 10° incline, the first peak vertical GRF was 47.7% greater than that in level walking, but the second peak vertical GRF was similar between downhill and level walking. Lay et al. (58) also reported that the first peak vertical GRF was greater during downhill walking on a 9° decline (1.19 BW) than during level walking (1.05 BW/kg, $p<0.05$) at self-selected speed. However, the second peak vertical GRF were lower in downhill walking on 8.5° (0.96BW) and 21° (0.89 BW) declines compared to that in level walking (1.09 BW, $p<0.05$ for all comparisons) at self-selected speed. In the Uto et al.'s study (110), the first peak vertical GRF were 1.25 BW and 1.29 BW when participants walked down at self-selected speed on 5° and 10° declines, respectively, which were greater than that in level walking (1.14 BW, $p < 0.001$ for all comparisons). The second peak GRF was lower in downhill walking at self-selected speeds on 5° and 10° declines (0.99 BW and 0.89 BW) compared to that in level walking (1.1 BW, $p<0.001$ for all comparisons).

The general patterns in the anterior-posterior GRF and the magnitudes of peaks for uphill, downhill and level walking were dramatically different. During uphill walking, the peak braking force was negligible, while the propulsive force increased remarkably (29, 58, 73). Lay et al. (58) reported that compared to level walking, that the uphill walking at self-selected speed on a 10° incline demonstrated a 81.3% decrease in braking force and a 76.8% increase in propulsive force ($p<0.05$ for all comparisons). During downhill walking at self-selected speed, the peak braking GRF increased significantly, while the peak propulsive GRF decreased as the angle of incline increased (29, 58, 73, 94). In the Lay et al.'s study(58), compared to level walking, the downhill walking on a 10° decline at self-selected speed showed a 111% increase in braking force and a 50.8% decrease in propulsive force ($p<0.05$ for all comparisons).

Joint Kinematics

Uphill walking

Joint kinematics was commonly reported in slope walking literature. Hip flexion at heel strike during uphill walking was significantly greater during level walking (28, 32, 36, 57, 58, 60, 73, 87), and gradually increased from about 30° at 0 incline to 56° at 10° incline (32, 73). The peak hip extension angle did not show remarkable differences between uphill and level walking (28, 58, 60, 73, 94). Hip extension range of motion during uphill walking at 10° (73) and 8.5° (58) incline showed approximately 30° and 15° greater than those in level walking, respectively.

During the uphill walking, the knee flexion angle at heel strike (32, 36, 57, 58, 60, 73) and the maximum value during early stance (28, 60, 73) were considerably increased with an increase in incline angle. Lay et al. (58) reported that the knee flexion angles at heel strike was 21.3° and 48.4° during uphill walking at 8.5° and 21° inclines, which were significantly greater than that in level walking (3.56°, $p<0.05$ for all comparisons). Compared to level walking, the peak knee flexion angle during early stance was approximately 20° greater during uphill walking at 8.5°(58), 9°(28) and 10°(73) incline. However, previous literatures (28, 58, 73) showed that during uphill walking knee flexion ROM was smaller than level walking, since the participants were kept at a flexed position during the early stance phase.

During uphill walking, the ankle joint was dorsiflexed throughout the entire stance phase due to the incline, however it was plantarflexed during early stance phase in level walking (28, 32, 36, 58, 60, 73). The previous literatures also reported that the ankle angles at heel strike showed 2.3° (36), 4.5° (58) and 9.8° more dorsiflexed during uphill walking at 8°, 8.5° and 11° incline compared to that in level walking, respectively. The ankle dorsiflexion ROM during stance phase was smaller in uphill walking compared to level walking (28, 58, 73). Since ankle plantarflexion angle at toe off was similar between uphill and level walking, the ankle plantarflexion ROM was 8° greater in uphill walking at 8.5° incline compared to level walking (28, 32, 58, 73).

Only a few studies reported the frontal and transverse plane lower extremity kinematics. During the uphill walking, the hip adduction (32, 36) and internal rotation angles (36) at heel strike were slightly greater than those during level walking. Haggerty et al. (32) and Han et al. (36) reported 2.2° and 3° greater in hip adduction angle at heel strike during uphill walking at 8.5° and 16° inclines, respectively ($p<0.05$ for all comparisons). Han et al. (36) reported compared to level walking, uphill walking had greater knee adduction angle at heel strike and mid-stance ($p<0.05$), however, Haggerty et al. (32) did not find any differences between uphill and level walking in peak knee adduction angle. In horizontal plane, Han et al. (36) reported compared to level walking, hip internal rotation, knee external rotation and ankle external rotation at heel strike were 3.17° greater, 3.49° lower and 4.83° lower in uphill walking at 8° incline respectively ($p<0.05$ for all comparisons).

Downhill walking

During downhill walking, hip flexion angle at heel strike was slightly smaller than during level walking (56, 58, 60, 73, 94). There were no significant differences between downhill and level walking in peak hip extension angle and hip extension ROM (58, 73, 94). Knee flexion at heel strike did not show any differences between downhill and level walking; however, the peak knee flexion was greater in downhill walking compared to level walking during stance phase (56, 58, 73, 94). The downhill walking on a 10° decline showed an approximate 20° increase in peak knee flexion angle compared to level walking during the stance phase (56, 73, 94). Kuster et al. (56) and Redfern et al. (94) reported compared to level walking, the peak knee flexion angles was 17° and 41° greater during walking downhill at 10° and 20° decline respectively. In addition, the knee flexion ROM were greater during downhill walking than during level walking, indicating that the knee was kept at a more flexed position during downhill walking compared to level walking (56, 58, 87, 94). For ankle joint, previous literature reported smaller plantarflexion angle at toe off during downhill walking compared to level walking (32, 56, 58, 73). Kuster et al. (56) showed plantarflexion angle at toe off and the plantarflexion ROM were 8° and 6° smaller in downhill walking at 10° incline compared to level walking, respectively ($p<0.05$). No studies have reported the lower extremity kinematic in frontal and transverse plane during downhill walking.

Joint Kinetics

Uphill walking

Joint kinetics has been investigated during incline walking to provide comprehensive understanding of the demands placed on the lower extremity. Hip sagittal plane moment demonstrated similar pattern under all incline conditions. During uphill walking, the peak hip extensor moment in early stance increased significantly compared to level walking (28, 42, 58, 73). Lay et al. (58) reported the peak hip extension moment in early stance was 1.1 Nm/kg during uphill walking at 8.5° incline, which was 103% greater than that in level walking ($p<0.05$). Mclntosh et al. (73) showed the peak hip extension moment increased approximate 60% during uphill walking on a 10° incline compared to level walking.

The peak internal hip abduction moment for uphill walking (32, 73) was reported to be significantly lower than that of level walking. The peak hip abduction moment decreased approximate 54% during uphill walking at 10° incline compared to level walking (73). Haggerty et al (32) also reported that the peak hip abduction moment was 1.01 Nm/kg during uphill walking at 8.5° incline, which was 20% less than that in level walking.

The patterns of knee moment were similar between uphill and level walking. During uphill walking, the peak KEM in early stance was slightly greater than level walking (32, 58, 73). Haggerty et al. (32) reported that the peak KEM was 1.01 Nm/kg during uphill walking at 8.5° incline, which was 36% greater than that in level walking (0.74 Nm/kg, $p<0.05$). However, Lay et al. (58) reported non-significant difference in peak KEM between uphill and level walking.

In addition, Haggerty et al. (32) reported the peak knee internal abduction moment during stance phase of uphill walking on a 10° incline at 1.34 m/s was 22% lower than that of level walking at the same speed ($p = 0.002$). The internal KAbM has been considered as an indicator for the medial knee loading, since it is highly associated with medial compartment tibiofemoral contact force (125). The decrease in the internal KAbM during uphill walking may indicate the reduced loading in the medial compartment of tibiofemoral joint. Thus, using uphill walking for rehabilitation has the potential to benefit the TKR patients, the medial knee osteoarthritis patients, and people with varus knee alignment. Since no other studies reported frontal plane knee moments during incline walking, it is unknown whether the peak internal knee abduction would decrease as the degree of the incline increased when participants walked at their self-selected speeds.

The pattern and maximum ankle plantarflexion moment in uphill walking are similar to those of level walking (28, 58, 73). Lay et al. (58) reported the peak ankle plantarflexion moment was 1.94 Nm/kg during late stance phase in uphill walking at a 8.5° incline, which is 18% greater than that in level walking ($p<0.05$). Other studies did not report significant difference in ankle moment between uphill and level walking.

Downhill Walking

The differences in hip sagittal plane moment between downhill and level walking were negligible (43, 56, 58). The peak internal hip abduction moment for downhill walking (73) was significantly lower than that of level walking. Mclntosh et al. (73) reported that the peak hip joint abduction moment was approximate 0.3 Nm/kg during downhill walking at a 10° incline, which was about 50% less than that in level walking ($p<0.05$).

The patterns of knee moment were similar between downhill and level walking. The KEMKEM was dramatically increased during mid and late stance in downhill walking (43, 58, 73, 94). Kuster et al. (56) reported the peak KEMKEM during downhill walking at 10° decline was 2.6 Nm/kg, which was nearly twice as much as that obtained in level walking 1.2 Nm/kg ($p<0.05$) when participants walked at the same step frequency 120 steps/min. Redfern et al. (94) also found that the peak KEMKEM was 1.7 Nm/kg during downhill walking at 20° decline, which was significantly greater than that in level walking 0.4 Nm, and the participants walked at their self-selected speed for both conditions. Lay et al. (58) reported that the peak KEMKEM in early stance was 0.88 Nm/kg during downhill walking at self-selected speed on a 8.5° decline, which was 100% greater than that in level walking (0.44 Nm/kg, $p<0.05$).

During the downhill walking, the plantarflexion moment demonstrated two distinct peaks (56, 73), and the magnitude of the second peak in late stance was lower than that of level walking (56, 58). No study has reported lower extremity kinetics in frontal and transverse plane during downhill walking.

Electromyography analysis

Some studies reported muscle electromyography (EMG) activity patterns to provide insights into neuromuscular control strategies for slope walking in healthy individuals (3, 27, 33, 57, 59).

Lay et al. (59) analyzed the activities of the gluteus maximus (GM), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semimembranosus (SM), medial gastrocnemius (MG), soleus (SOL), and tibialis anterior (TA) during uphill, level and downhill walking at grade of 21°. They reported that during uphill walking, the mean EMG activity of all muscles except TA increased 211% on average compared to level walking in the stance phase. Furthermore, the burst duration of the GM, BF, SM, RF and VM also increased markedly during uphill walking compared to level walking. The increasing in hip extensor muscles (GM, BF and SM) and ankle plantar flexor muscles (MG and SOL) activity and duration from level to uphill walking corresponds to the increased magnitudes of hip extension and ankle plantarflexion moments, respectively (58). The quadriceps (RF and VM) also showed higher activity during uphill walking compared to level walking, however the difference between uphill and level walking in KEM were non-significant. The increased RF and VM activity were needed to counteract the increased BF and SM activity to maintain the KEMKEM. RF, VM and TA activity were significantly greater during downhill walking than during level walking. In addition, the burst duration of the RF, VM, SOL and MG increased progressively during downhill walking compared to level walking. During downhill walking, the larger peak KEMKEM was observed compared to level walking, and quadriceps (RF and VM) activities were in agreement with the findings in knee kinetics (58).

Other slope walking studies reported similar results. Franz et al. (27) investigated EMG patterns of the GM, BF, RF, VM, MG and SOL during level, uphill and downhill treadmill walking at a grade of 9°. During uphill walking, the mean EMG activity of all muscles increased 203% on average compared to level walking. The knee extensors, RF and VM, increased approximately 178% on average in downhill walking compared to level walking. Alexander et al. (2) also examined the function of BF, RF, vastus lateralis (VL), TA, lateral gastrocnemius (LG) during slope walking at inclination angles of -18°, -12°, -6°, 0, 6°, 12° and 18°. Knee (RF, VL) extensor muscle activities increased significantly during both uphill and downhill walking compared to level walking. Hip (BF) and ankle (LG) muscle activities were higher in uphill walking than those in level walking. Lange (57) also reported that the mean and peak muscle activities of VM, VL, and BF increased 96% and 113% on average, respectively, as the incline increased from 0 to 13°. Haight el al. (33) investigated the EMG patterns of SOL, LG, VL, VM, BF and SM during level and uphill treadmill walking at 6° incline at 1.5m/s and 0.75 m/s respectively. The differences between two test conditions in EMG magnitude and duration were not significant due to the distinct walking speeds they chose.

In conclusion, the second peak vertical GRF in uphill walking and the first peak vertical GRF in downhill walking were significantly greater than those in level walking. In addition, hip and knee flexion, and ankle dorsiflexion angles at heel strike were greater in uphill walking compared to level walking. During uphill walking, hip extension and ankle plantarflexion ROM were greater than level walking, while knee flexion ROM was lower in uphill walking compared to level walking. Greater peak knee flexion angle and smaller plantarflexion angle at toe off were reported during downhill walking compared to level walking. For joint kinetics, hip, knee and ankle extension moment increased significantly in uphill walking compared to level walking and muscle activity of hip and knee extensors also increased accordingly. The knee joint moment increased significantly during downhill walking compared to level walking, and muscle activity patterns were changed directly associated to changes in the joint moments.

Ramp Walking in TKR Adults

Although several studies provide valuable information on how biomechanical gait parameters can change when walking on different inclined surfaces, those studies have been focused only on young healthy participants (3, 36, 42, 43, 56, 58, 59, 73, 94). Since both uphill and downhill walking caused significantly increase in knee joint loading, the investigation of how TKR patient altered their gait characteristics on sloped surfaces is necessary (53). Haggerty et al. (32) reported in young healthy participants, the peak knee internal abduction moment during stance phase of uphill walking on a 10° incline was lower than that of level walking. It is unclear whether TKR patients and the young healthy participants are similar in knee frontal plane kinetics during the incline walking.

Reynolds (90) compared knee biomechanical characteristics between TKR patients and age matched healthy individuals during downhill walking at their self-selected speeds on an incline of 7° in her dissertation. During downhill walking, the knee range of motion (ROM) and peak knee flexion angle of replaced limbs for TKR patients were 11.9 % and 26.3 % smaller than those of healthy participants, respectively. In addition, the peak KEMKEM of replaced knees was 22.7 % lower than their non-replaced knees and 36.2% lower than healthy controls. This study only investigated downhill walking and did not report the changes of biomechanical parameters in frontal and transverse plane as the results of inclines.

Currently, a limited number of studies have explored kinematics, kinetics and EMG for both uphill and downhill walking in TKR patients. To our knowledge, only one previous study (90) has reported kinematics and kinetics for downhill walking in TKR patients. There is a clear gap in the literature about the gait pattern adaption and key biomechanics variables in TKR patients during slope walking. In addition, walking on inclined surfaces is an inevitable part of daily living and it has been integrated into rehabilitation protocol after TKR (75), therefore, a comprehensive biomechanical analysis is warranted. The information from such a study may help physical therapists creating appropriate rehabilitation protocols and optimizing total knee prosthesis designs.

CHAPTER III

MATERIALS AND METHODS

Participants

Healthy adults between the ages of 50 and 75 years were recruited through flyers within the University of Tennessee campus and surrounding communities. The participants who met the inclusion and exclusion criteria were invited to participate in the research study.

Inclusion Criteria:

- Men and Women between the ages of 50 and 75

Exclusion Criteria:

- Knee pain during daily activities.
- Diagnosed with any type of lower extremity joint osteoarthritis as reported by the patient.
- Any lower extremity joint replacement.
- Any lower extremity joint arthroscopic surgery or intra-articular injection.
- Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) as reported by the patient.
- BMI greater than 38 kg/m^2
- Inability to walk without a walking aid.
- Neurologic disease (e.g. Parkinson's disease, stroke) as reported by the patient.
- 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.

TKR patients were referred to the principal investigator via phone interviews carried out at the Tennessee Orthopedic Clinics. TKR procedures were all performed by the same surgeon and with either one of three TKR designs: Cruciate-Retaining (CR, Journey II, Smith& Nephew, Memphis, TN, USA), Posterior Stabilized (PS, Persona, Zimmer, Warsaw, IN, USA), and Bi-cruciate Stabilized (BCS, Journey II, Smith & Nephew, Memphis, TN, USA). TKR participants who met the specific criteria for participation (Table 2) were invited to participate in the research study.

Inclusion Criteria

- Men and Women between the ages of 50 and 75
- Total knee replacement in one knee with either one of CR, PS and BCS
- At least 6-months from TKR.
- No more than 5-years from TKR.

Exclusion Criteria

- Diagnosed osteoarthritis at the ankle or hip joint of the TKR side and any major spinal disorder including osteoarthritis as reported by the patient.
- Diagnosed osteoarthritis at the contralateral ankle or hip of the TKR side as reported by the patient.
- Any additional lower extremity joint replacement.
- Any lower extremity joint arthroscopic surgery or intra-articular injection.

- Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) as reported by the patient.
- BMI greater than 38 kg/m^2
- Inability to walk without a walking aid.
- Neurologic disease (e.g. Parkinson's disease, stroke) as reported by the patient.
- 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.

All participants signed an informed consent document approved by the Institutional Review Boards at The University of Tennessee, Knoxville.

Instrumentation

A twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) were used to acquire three-dimensional (3D) kinematics of the trunk, pelvis, thigh, shank, and feet of the participants. Participants were asked to wear tight fitting workout clothing (i.e. spandex) and a pair of standardized laboratory running shoes (Noveto, Adidas, USA) during the experiment. Reflective anatomical markers were placed bilaterally on the 2^{nd} toe, 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 tracking markers on a semi-rigid thermoplastic shell was placed on the lateral aspect of shanks, thighs, pelvis and posterior trunk. Four discrete tracking markers were place on the heel counter of the shoe.

A customized ramp system was used in the study which consists of a walkway that is 1 m wide and 3 m long and bolted on to two force platforms (BP600600 and OR-6-7, 1200Hz, American Mechanical Technology Inc., Watertown, MA, USA). The instrumented ramp measures the ground reaction forces (GRF) and the moments of forces during ramp walking. The inclined angle of ramp surface can be adjusted to 5°, 10° and 15°. The walkway ends with a platform (Figure 4).

Figure 4 15° ramp set-up for data collection.

Gait speeds during ramp walking was monitored by two sets of photocells (63501 IR, Lafayette Instrument Inc., IN, USA) and two electronic timers (54035A, Lafayette Instrument Inc., IN, USA). The photocells were placed 3 meters apart for level walking, and 1.5 meters apart at shoulder height for ramp walking.

A 16-channel surface EMG system (1200 Hz, Trigno^{TM} Wireless EMG System, Delsys, INC, Natick MA, USA) was used to monitor the following muscles on both sides of the body:

vastus medialis (VM), vastus lateralis (VL), long head of biceps femoris (BF), semitendinosus (ST) and medial gastrocnemius (MG). Both GRF and EMG data were sampled simultaneously with the 3D kinematic data using the VICON system and Nexus software package (2.5, Vicon Motion Analysis Inc., Oxford, UK).

Experimental procedures

TKR patients were asked to complete the 2011 Knee Society Scoring System (KSS) (99) and Knee injury and Osteoarthritis Outcome Score (KOOS) (93). KSS is a questionnaire aimed to assess patient satisfaction, expectations and functional abilities following TKR. KOOS is a self-reported questionnaire consisted of five subscales: knee related pain, other symptoms, function in daily living, function in sport and recreation, and knee related quality of life. Both healthy and TKR patients completed an information sheet which collects demographic and injury history

information, and the physical activity readiness survey (PAR-Q). Following completion of the surveys, participants performed 3 minutes of walking on a treadmill at a self-selected speed as warm-up.

EMG electrodes were placed bilaterally on the VM, VL, BF, ST and MG of both TKR and healthy participants. The skin of the electrode attachment sites was shaved and cleaned with alcohol swab before the application of the electrodes. The placement of the EMG electrodes on the selected muscles were based on the recommendations of Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) (40). To obtain baseline EMG values of the selected muscles for the purpose of normalization, participants were asked to perform three trails in each of related functional tests. For VM and VL, a half squat (bend knee to about 45° was used. For BF and ST, a leg curl (flex to 90°) from a standing position was performed for one leg at a time. For MG, a bilateral calf raise from a standing position was used. A rest period of one minute between testing movements was also provided.

All participants performed five trials in each of 14 test conditions. Condition one and two were walking uphill and downhill respectively on the 5° ramp with right foot contacting the force platform. Condition three and four were walking uphill and downhill respectively on the 5° ramp with left foot contacting the force platform. Condition five and six were walking uphill and downhill respectively on the 10° ramp with right foot contacting the force platform. Condition seven and eight were walking uphill and downhill respectively on the 10° ramp with left foot contacting the force platform. Condition nine and ten were walking uphill and downhill respectively on the 15° ramp with right foot contacting the force platform. Condition 11 and 12 were walking uphill and downhill respectively on the 15° ramp with left foot contacting the force platform. Condition 13 and 14 were level walking with the right and left foot contacting the force platform, respectively. The testing order of three ramp incline conditions (5°, 10°, 15°) was randomized first, and then followed by the randomization of right and left foot within each incline condition. The ramp conditions were tested first due to the need for its setup prior to participants coming to the lab to reduce the total testing time. Participants were asked to practice ramp and level walking trials at a self-selected speed for each ramp condition. The left and right sides of level walking conditions were also randomized. Participants were asked to perform practice ramp and level walking trials at a self-selected speed for each ramp incline condition. Once participants were comfortable on ramp walking during the practice trials (about three trials each), the participants were asked to perform uphill, downhill and level walking at their respective speed range (mean ± 5%) obtained in the practice trials. Participants had to repeat a trial if they did not make a full contact within the force platform with the targeted foot, and were not able to reach the pre-determined speed range. A handrail was provided for balance purposes if needed, but participants were not encouraged to use it. A numerical visual analog pain scale (VAS) was used to assess pain in both knees for healthy and TKR patients prior to the warm-up, and at the end of each test condition.

Data Analyses

Visual3D biomechanical analysis software suite (C-Motion, Inc., Germantown, MD, USA) was used to compute the 3D kinematic and kinetic variables. An X-y-z Cardan rotational sequence was used for the 3D angular computations and a right hand rule was used to determine the conventions of angular kinematic and kinetic variables. Positive values indicate knee extension ROM, knee adduction ROM. For kinetic variables, positive values indicate knee extension and adduction moments. Raw GRF were filtered alone using a fourth-order low-pass Butterworth filter with a cut-off frequency of 50 Hz for GRF data. Kinematic and GRF data were smoothed at cutoff frequencies of 8 Hz, respectively, using a fourth-order zero-lag Butterworth low-pass filter. Peak angles and moments were determined using a customized program (VB_V3D, MS Visual BASIC, Microsoft, Redmond, WA, USA) and selected variables were further organized for statistical analysis and reports using another customized program (VB_Table, MS Visual BASIC, Microsoft, Redmond, WA, USA). The GRFs were normalized to the participant's body weight (BW). Joint moments were calculated as internal moments in the proximal segment and normalized to the participant's body mass yielding a unit of Nm/kg. Body segment masses were estimated based on Dempster's regression (23) and segment moment of inertias were estimated based on the Hanavan model (37).

The EMG data was analyzed using the Visual3D. Raw EMG signals for functional test trails and motion trials were filtered with a Butterworth band-pass filter with 10 Hz and 450 Hz cutoff frequencies and then full wave rectified (1). A moving root mean square (RMS) was used to filter the rectified EMG signals using a 60-millisecond moving window. The maximum value of the RMS EMG signals of three functional test trails was used to normalize the filtered EMG signals of the testing movement trails. The mean RMS was calculated as the mean of the normalized RMS signal during the stance phase of walking (89).

Statistical Analyses

A web-based software tool, GLIMMPSE (http://glimmpse.SampleSizeShop.org/), was used to estimate sample size. An *a priori* power analysis, using results of peak knee flexion angle (90), peak KEM (32, 33, 90), and peak KAbM (32), showed that a minimum of 14 participants were needed for each group in order to obtain an alpha of 0.05 and beta of 0.80.

In study one, a one-way analysis of variance (ANOVA) was used to identify differences in demographic and survey data between TKR patients and healthy controls. A 2 x 4 (group: TKR patients and healthy controls x incline slope: 0°, 5°, 10° and 15°) two-way ANOVA was used to examine the difference in walking speed between TKR patients and healthy controls in all walking conditions. A 2 x 2 x 4 (limb: replaced, non-replaced limb x group: TKR and healthy controls x incline slope: 0°, 5°, 10° and 15°) mixed model analysis of variance (ANOVA) was used to examine the interactions and main effects during uphill walking (24.0, IBM SPSS, Chicago, IL). The left and right limb of healthy controls were randomly selected to match with TKR replaced and non-replaced limb, respectively. Limb 1 of healthy controls was matched with replaced limb of TKR patients; limb 2 of healthy controls was matched with non-replaced limb of TKR patients. An a priori alpha level was set to 0.05. When the ANOVA results revealed a significant three-way interaction, two-way ANOVAs (limb x group, slope x group and limb x slope) were performed. When two-way ANOVAs showed significant interaction or main effect, post-hoc comparisons with Bonferroni adjustments were used to detect differences between limbs and angles (adjusted $p<0.0125$ for differences detected between incline angles, $p<0.00625$ for slope x group and limb x slope interactions, and $p<0.0125$ for limb x group interaction).

In study two, a one-way ANOVA was used to identify differences in demographic and survey data between TKR patients and healthy controls. A 2 × 4 (group: TKR and healthy controls x decline slope: 0°, 5°, 10° and 15°) two-way ANOVA was used to examine the difference in walking speed between TKR patients and healthy controls. In addition, a 2 × 2 × 4 (limb: replaced and non-replaced limb × group × slope) mixed-design ANOVA was used to examine the interactions and main effects on VAS and biomechanics variables during downhill walking (24.0, IBM SPSS, Chicago, IL). The left and right limb of healthy controls were randomly selected as limb 1 and 2 to match with TKR replaced and non-replaced limb, respectively. An *a priori* alpha level was set to 0.05. When the ANOVA results revealed a significant three-way interaction, two-way ANOVAs were followed. When two-way ANOVA showed significant interaction or main effect, post-hoc comparisons with Bonferroni adjustments were used to detect differences between limb and angles (adjusted $p<0.0125$ for differences detected between slopes, $p<0.00625$ for interactions).

In study three, a one-way ANOVA was used to identify differences in demographic and survey data between TKR patients with three different implants and healthy controls (24.0, IBM SPSS, Chicago, IL). A 2 × 4 (limb: replaced and non-replaced limb × group: BCS, CR, PS and healthy) ANOVA was used to examine the difference in VAS and biomechanics variables during uphill and downhill walking respectively. The left and right limb of healthy controls were randomly selected to match with TKR replaced and non-replaced limbs, respectively. An *a priori* alpha level was set to 0.05. When ANOVA showed significant interaction or main effect, least significant difference (LSD) post-hoc comparisons were used to detect differences between limb and groups.

CHAPTER IV

KNEE BIOMECHANICS DURING UPHILL WALKING ON DIFFERENT SLOPES IN TOTAL KNEE REPLACEMENT OLDER ADULTS

Abstract

The purpose of this study was to compare knee biomechanics and knee joint muscle EMG activity of the replaced limb to the non-replaced limb of total knee replacement (TKR) patients and healthy controls during walking on level ground and inclined surfaces of 5°, 10° and 15°. Twenty-five TKR patients and ten healthy controls performed five walking trials on different slopes on a force platform and an instrumented ramp system. A 2 x 2 x 4 (limb x group x incline slope) mixed model ANOVA was used to examine selected variables. The peak KEM was greater in 15° uphill walking compared to level, 5° and 10° uphill walking. TKR patients had lower peak KEM and smaller knee extension range of motion than healthy controls in all walking conditions. The replaced limb showed lower peak KEM in 10° and 15° uphill walking than non-replaced limb and smaller knee extension ROM in 10° uphill walking. Knee extension and abduction ROM increased with increased incline angles. The greater peak loading-response vertical ground reaction force was found in level walking compared to three levels of uphill walking. The peak loading-response KAbM was greater in level walking compared to 10° and 15° uphill walking. Uphill walking may have the potential to become a safe exercise for unilateral TKR patients.

Keywords: total knee arthroplasty, inclined surface, knee joint moment

Introduction

Total knee replacement (TKR) or total knee arthroplasty is an operative intervention for end-stage knee osteoarthritis (OA) (123). According to the Agency for Healthcare Research and Quality, more than 700,000 TKR surgeries were performed in the United States in 2013 (82). The average cost for a TKR is $16,497 per surgical procedure and the total national costs reached 11.6 billion dollars in 2013 (82). The primary goals of TKR are to improve joint alignment and achieve pain-free knee movements with sufficient range of motion (ROM) (30). Most patients report a significant reduction in knee pain and improvement in ROM after TKR surgery (16, 39), however, 20% of patients still suffer unfavorable pain after their surgery (14). Previous studies (8, 83) reported that TKR patients cannot fully restore their physical function to the level of their healthy peers. Thus, an understanding of functional limitations of TKR patients would help physical therapists optimizing rehabilitation protocols and help manufacturers improving total knee prosthesis designs.

Uphill walking is an inevitable part of daily living and causes higher knee joint loading compared to level walking (4). Several studies have reported knee biomechanical gait parameters during uphill walking at different angles in young healthy populations (3, 36, 42, 43, 56, 58, 59, 73, 94). During the uphill walking, the knee flexion angle at heel strike (32, 36, 57, 58, 60, 73) and the peak knee flexion angle during early stance (28, 60, 73) were increased with an increase in incline angle. However, previous literatures have (28, 58, 73) showed that during uphill walking knee flexion ROM was smaller than level walking due to a more flexed knee position during the early stance phase on the incline.

During uphill walking, the peak KEM (32, 58, 73) in early stance were greater than those in level walking in young healthy populations. Haggerty et al. (32) reported the peak internal

KAbM during the stance phase of 10° uphill walking at 1.34 m/s was 22% less than that of level walking at the same speed. The decrease in the KAbM during uphill walking may indicate reduced loading in the medial compartment of tibiofemoral joint (125). Thus, using uphill walking for rehabilitation has the potential to benefit the TKR patients, medial knee OA patients, and people with varus knee alignment. It is still unknown how the peak internal KAbM would change as the incline slope increases. Previous studies have reported muscle EMG activities of vastus lateralis (VL), biceps femoris (BF), and medial gastrocnemius (MG) increased markedly during uphill walking compared to level walking (2, 27, 57, 59), which also supported the findings in KEMs.

Although there is a lack of studies investigating ramp walking in TKR patients, previous studies have shown that during level walking patients with TKR typically have slower walking speed, less knee flexion ROM during stance, and reduced KEMs compared to healthy controls (12, 62). Since the walking speed can significantly influence the knee kinetics and kinematics (41), smaller peak knee flexion angle and ROM, and KEM may be due to the slower walking speed in TKR patients compared to healthy controls. Additionally, peak knee adduction angle (69, 72) and peak knee external adduction moment (72) in TKR patients were similar or smaller to those in healthy controls. Furthermore, peak KAbM was significantly reduced following knee replacement compared to pre-operation (84). These results suggest that TKR surgery seems to successfully improved knee loading conditions in the sagittal and frontal plane.

Previous gait analyses during uphill walking have only focused on young healthy populations (3, 36, 42, 43, 56, 58, 59, 73, 94). Currently, no studies have explored knee kinematics, kinetics, and EMG for uphill walking in TKR patients. There is a clear gap in the literature about the gait pattern adaption in TKR patients. Furthermore, uphill walking has been integrated into rehabilitation protocols after TKR surgery (75), therefore, a comprehensive biomechanical analysis of its benefit for this population is warranted. The information from such a study may help physical therapists creating appropriate rehabilitation protocols and optimizing total knee prosthesis designs. Thus, the purpose of this study was to compare knee biomechanics and knee joint muscle EMG activity of the replaced limb to the non-replaced limb of TKR patients and healthy controls during walking on level ground and inclined surfaces of 5°, 10° and 15°. We hypothesized that 1) the peak KEM would be lower in replaced limb of TKR patients compared to healthy controls, and peak loading-response KAbM in replaced limb of TKR patients would be similar compared to matched limb of healthy controls, 2) compared to non-replaced limb, the replaced limb would have lower peak KEM and similar peak loading-response KAbM, and 3) the peak KEM and quadriceps EMG activity would increase and the knee flexion ROM would decrease with an increase in the incline angle in replaced and non-replaced limb of TKR patients.

Materials and Methods

Participants

Twenty-five TKR patients were recruited from a local orthopedic clinic (68.8 ± 4.9 years, 1.70 ± 0.11m, 83.2 ±15.6 kg, 22.1 ± 11.72 months since surgery). The inclusion criteria for TKR patients were having a unilateral total knee replacement (conducted by a single surgeon) between 6 months and 60 months and between the ages of 50 and 75 years. Potential participants were excluded if they had any additional lower extremity joint replacements, any additional diagnosed OA of the hip or ankle, more than 75% radiographic joint space narrowing and chronic pain at the contralateral knee of the TKR side, BMI greater than 38, or neurological diseases. Ten older adults between the ages of 50 and 75 years without any lower extremity pathology participated in the study as healthy controls (69.1 ± 4.5 years, 1.74 ± 0.12 m, 75.0 ± 23 kg).

Instrumentation

A twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) were used to acquire three-dimensional (3D) kinematics of the trunk, pelvis, thigh, shank, and feet of the participants. Participants were asked to wear tight fitting workout clothing and a pair of standardized laboratory running shoes (Noveto, Adidas, USA) during the experiment. Reflective anatomical markers were placed bilaterally on the 2nd toe, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and acromion processes. A cluster of four reflective tracking markers on a semi-rigid thermoplastic shell was placed on the lateral aspect of shanks, thighs, pelvis and posterior trunk. Four discrete tracking markers were place on the lateral and posterior heel counter of the shoe.

A customized instrumented ramp system was used in the study to measure the ground reaction forces (GRF) and the moments of forces during ramp walking (Figure 5). The ramp consists of a walkway that is 1 m wide and 3 m long and with two separate walking surfaces/structures bolted on to two force platforms (BP600600 and OR-6-7, 1200Hz, American Mechanical Technology Inc., Watertown, MA, USA), and ends with a platform. The inclined angle of ramp surface can be adjusted to 5°, 10° and 15°. Gait speeds were monitored by two sets of photocells (63501 IR, Lafayette Instrument Inc., IN, USA), and two electronic timers (54035A, Lafayette Instrument Inc., IN, USA), placed 3 meters apart for level walking, and 1.5 meters apart at shoulder height for ramp walking.

A 16-channel surface EMG system (1200 Hz, Trigno^{TM} Wireless EMG System, Delsys, INC, Natick MA, USA) was used to monitor the muscle EMG activities on following muscles on both sides of the body: VL, BF and MG. The skin of the electrode attachment sites was shaved and cleaned with alcohol swab before the application of the electrodes. The placement of the EMG electrodes on the selected muscles were based on the recommendations of SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) (40). Both GRF and EMG data were sampled simultaneously with the 3D kinematic data using the VICON system and Nexus software package (2.5, Vicon Motion Analysis Inc., Oxford, UK).

Figure 5 The setup of ramp at a 15° incline for experimental data collection.

Experimental Procedures

TKR patients were asked to complete the 2011 Knee Society Scoring System (KSS) (99) and Knee injury and Osteoarthritis Outcome Score (KOOS) (93). KSS is a questionnaire aimed to assess patient satisfaction, expectations, and functional abilities following TKR surgery. KOOS is a self-reported questionnaire consisted of five subscales: knee related pain, other symptoms, function in daily living, function in sport and recreation, and knee related quality of life. Both healthy controls and TKR patients completed an information sheet which collects demographic and injury history information, and the physical activity readiness survey (PAR-Q). Following completion of the surveys, participants performed a 3 minutes of walking on a treadmill at a self-selected speed as warm-up.

To obtain baseline EMG values of the selected muscles for the purpose of normalization, participants were asked to perform three trails in each functional test (34). For VL, a half squat (bend knee to about 45°) was used. For BF, a leg curl (flex knee to 90°) from a standing position was performed for one leg at a time. For MG, a bilateral calf raise from a standing position was performed. A rest period of one minute between testing movements was also provided.

Participants were then fitted with markers as previously mentioned. All participants were asked to walk at 0° (level walking), and at 5°, 10°, 15° (uphill). The testing order of three ramp incline conditions (5°, 10°, 15°) was randomized first. Level walking was performed after ramp walking conditions. The testing order of right and left leg was randomized within each incline condition. The ramp conditions were tested first due to the need for its setup prior to participants coming to the lab to reduce the total testing time. Participants were asked to perform practice ramp and level walking trials at a self-selected speed for each ramp incline condition. Once participants were comfortable on ramp walking during the practice trials (about three trials each), the participants were asked to perform uphill and level walking at their self-selected speed range (mean ± 5%) obtained during the practice trials for each ramp condition. Participants was asked to repeat a trial if they did not make a full contact within the force platform with the targeted foot, and were not able to reach the pre-determined speed. A handrail was provided on the right side for balance purposes if needed, but participants were not encouraged to use it. A numerical visual analog pain scale (VAS) was used to assess pain in both knees for healthy and TKR patients prior to the warm-up, and at the end of each test condition.

Data Analyses

Visual3D biomechanical analysis software suite (version 2.6, C-Motion, Inc., Germantown, MD, USA) was used to compute the 3D kinematic and kinetic variables. An X-y-z Cardan rotational sequence was used in the 3D angular kinematics computations and a right-hand rule was used to determine the conventions of angular kinematic and kinetic variables. Joint moments were calculated as internal moments in the reference system of proximal segment and normalized to the participant's body mass yielding a unit of Nm/kg. Body segment masses were estimated based on Dempster's regression equations (23) and segment moment of inertias were estimated based on the Hanavan model (37). Positive values indicate knee extension angle and ROM, knee adduction angle and ROM. For kinetic variables, positive values indicate knee extension and adduction moments. Kinematic and GRF data were smoothed at a cutoff frequency of 8 Hz using a fourth-order zero-lag Butterworth low-pass filter. Raw GRF were filtered alone using a fourth-order low-pass Butterworth filter at a cut-off frequency of 50 Hz. Peak loading-response and push-off GRFs, peak knee extension, adduction angles, knee flexion, extension and adduction ROM, and peak knee extension and flexion moment and KAbM were determined and organized for statistical analysis using customized programs (VB_V3D and VB_Table, MS Visual BASIC, Microsoft, Redmond, WA, USA). The GRFs were normalized to the participant's body weight (BW) and joint moments were normalized to the participant's body mass (Nm/kg).

The EMG was analyzed using the Visual3D. Raw EMG signals were filtered with a band-pass filter with a high and low pass cutoff frequencies 10 Hz and 450 Hz and full wave rectified (1). A moving root-mean-square (RMS) filter was used to filter the rectified EMG signals using a 60-millisecond moving window. The maximum value of the RMS EMG signals of three functional test trails was used to normalize the filtered EMG signals of the testing movement trails. The mean RMS value was calculated for all muscles during the stance phase of movement trials (89).

Statistical Analyses

A one-way analysis of variance (ANOVA) was used to identify differences in demographic and survey data between TKR patients and healthy controls. A 2 x 4 (group: TKR patients and healthy controls x incline slope: 0°, 5°, 10° and 15°) ANOVA was used to examine the difference in walking speed between TKR patients and healthy controls in all walking conditions. A 2 x 2 x 4 (limb: replaced, non-replaced limb x group: TKR and healthy controls x incline slope: 0°, 5°, 10° and 15°) mixed model ANOVA was used to examine the interactions and main effects of peak loading-response and push-off GRFs, knee flexion and peak knee extension and flexion moment and peak KAbM during uphill walking (24.0, IBM SPSS, Chicago, IL). A 2 x 2 x 3 (limb x group x incline slope: 5°, 10° and 15°) mixed model ANOVA was used to examine the knee extension and abduction ROM. The left and right limb of healthy controls were randomly selected to match with TKR replaced and non-replaced limb, respectively. Limb 1 of healthy controls was matched with replaced limb of TKR patients; limb 2 of healthy controls was matched with non-replaced limb of TKR patients. An a priori alpha level was set to 0.05. When the ANOVA results revealed a significant three-way interaction, two-way ANOVAs were followed. When two-way ANOVAs showed significant interaction or main effect, post-hoc comparisons with Bonferroni adjustments were used to detect differences between limbs and angles (adjusted $p<0.025$ for differences detected between limbs and groups, $p<0.0125$ for differences detected between incline angles, $p<0.00625$ for slope x group and limb x slope interactions, and $p<0.0125$ for limb x group interaction). In order to focus on effects on TKR patients and streamline result reporting, when there was a significant limb effect in 3-way or 2-way interaction, we only reported related TKR group results.

Results

There were no differences of age, height, and mass between TKR patients and healthy controls (Table 1). TKR patients had greater BMI than healthy controls ($p=0.014$). Sub-scales of symptom, pain, activity of daily life, sport/recreation, and quality of life of KOOS were significant lower in TKR patients compared to healthy controls ($p<0.047$ for all comparisons).

Participants walked significantly faster on level ground than on 5°, 10° and 15° ramp respectively ($p<0.002$ for all comparisons, Table 2). They also walked faster on 5° and 10° ramp respectively than on 15° ramp ($p<0.007$ for all comparisons). TKR patients had higher VAS scores than healthy controls ($p<0.012$ for all comparisons, Table 2).

A significant limb×slope×group interaction was detected in knee extension ROM ($p=0.01$, Table 3). In follow-up ANOVAs, a significant limb×slope interaction was found for TKR patients ($p=0.015$) and a significant slope×group interaction was found in replaced limb ($p=0.019$). Post hoc comparisons showed that the non-replaced knee had greater extension ROM than the replaced knee in 10° uphill walking ($p=0.049$). Knee extension ROM increased significantly as the incline angle increased in both replaced and non-replaced limb of TKR patients and both limb of healthy controls ($p<0.002$ for all comparisons). Both replaced and non-replaced limbs of TKR patients had smaller knee extension ROM than their respective matched limb of healthy controls in all the uphill walking conditions ($p<0.016$ for all comparisons). Knee flexion ROM decreased ($p<0.001$ for all comparisons) and knee adduction ROM increased

($p<0.011$ for all comparisons) as the incline angle increased in both limb of TKR patients, respectively.

The peak loading-response vertical GRF was greater in level walking compared to all three uphill conditions respectively ($p<0.002$ for all comparisons, Table 4). It was also greater in 5° compared to 15° uphill walking ($p=0.038$). The peak push-off vertical GRF was smaller in level walking compared to 5° ($p=0.028$) and 10° ($p=0.012$) uphill walking respectively.

Significant limb×slope interaction ($p=0.006$), group ($p=0.019$) and limb (0.008) main effects were found for peak KEM (Table 4). In replaced limb, the peak KEM was greater in 15° compared to level and 5° uphill walking ($p<0.012$), and it was greater in 10° compared to 5° uphill walking ($p=0.002$). In non-replaced limb, the moment was greater in 15° uphill walking compared to level, 5°, and 10° uphill walking respectively ($p<0.009$ for all comparisons). The moment was also greater in 10° compared to level and 5° uphill walking respectively ($p<0.001$ for all comparisons). It was also smaller in replaced limb compared to non-replaced limb in 10° ($p=0.002$) and 15° ($p<0.001$) uphill walking, respectively. TKR patients had lower peak KEM than healthy controls in all walking conditions ($p<0.021$ for all comparisons).

A significant limb x group interaction was found for peak knee flexion moment ($p=0.012$, Table 4). The moment was lower in replaced limb compared to and non-replaced limb ($p<0.039$). TKR patients had lower peak knee flexion moment than healthy controls ($p<0.025$). In addition, peak knee flexion moment significantly increased as incline angle increased ($p<0.001$ for all comparisons).

A significant incline slope main effect was observed for peak loading-response KAbM ($p=0.009$) and peak push-off KAbM ($p<0.001$, Table 4). The peak loading-response KAbM was greater in level walking compared to 10° ($p=0.013$) and 15° ($p=0.003$) uphill walking. The peak push-off KAbM was greater in level walking compared to all uphill walking conditions respectively ($p<0.001$ for all comparisons). It was also greater in 5° compared to 10° and 15° uphill walking respectively ($p<0.029$ for all comparisons).

Only slope main effect was significant for all examined muscles (Table 5). BF muscle activity was lower in level walking compared to all uphill conditions ($p<0.004$ for all comparisons). It was also lower in 5° compared to 10 and 15° uphill walking respectively ($p<0.011$ for all comparisons). For MG muscle, the EMG activity significantly increased as the incline angle increased from 0° to 15° ($p<0.001$ for all comparisons). VL muscle activity was also significantly increased as the incline angle increased from 0° to 15° ($p<0.004$ for all comparisons).

Discussion

The purpose of this study was to compare knee biomechanics and knee muscle EMG activity of replaced limb to the non-replaced limb of TKR patients and matched limb of healthy controls during walking on inclined surfaces of 0°, 5°, 10° and 15°. The first hypothesis was that the peak KEM would be lower in replaced limb of TKR patients compared to healthy controls, and peak loading-response KAbM in replaced limb of TKR patients would be similar compared to their non-replaced limb and matched limb of healthy controls. The results were in agreement with the first hypothesis. There was a significant group effect for peak KEM. Replaced limb of TKR patients showed lower peak KEM than the matched limb of healthy controls in all walking conditions. Interactions and post-hoc comparisons did not demonstrate any differences between replaced, non-replaced and matched limb of healthy controls for both peak loading-response and push-off KAbM.

Comparison between TKR patients and healthy controls

Both the replaced and non-replaced limb of TKR patients had reductions in peak KEM compared to matched limb of healthy controls in all test conditions. Compared to matched limb of healthy controls, the peak KEM was 32.7%, 42.3%, 41.8% and 38.4% lower in replaced limb and 38.6%, 44.5%, 27.8% and 27.4% lower in non-replaced limb in level and three uphill walking conditions, respectively. These findings showed that the deficits of both replaced and non-replaced limb are apparent compared to matched limb of healthy controls in both level and uphill walking. Previous studies have reported there were deficits in sagittal plane knee kinetic and kinematics in the replaced and non-replaced limb of TKR patients compared to healthy controls during level walking (12, 62, 68, 85). Benedetti et al. (12) showed that TKR patients at two-year follow-up walked 21% slower and had 50% lower peak KEM in replaced limb compared to healthy controls.

Although no differences in walking speed and peak vertical GRF between TKR patients and healthy controls were found across walking conditions, reduced KEM may be partially due to the smaller knee extension ROM of TKR patients compared to healthy controls in all uphill walking conditions. Compared to matched limb of healthy controls, the knee extension ROM was 59.6%, 39.1% and 25.7% smaller in replaced limb and 65.5%, 25.8% and 20.0% smaller in non-replaced limb in uphill walking conditions. In level walking, some studies reported smaller knee flexion ROM in replaced limb of TKR compared to healthy controls (12, 68, 85). In this study, the differences between replaced and matched limb of healthy controls in knee flexion ROM during level and uphill walking were small and insignificant. Since no studies have explored uphill walking in TKR patients, this study provides novel data in knee kinetics and kinematics for uphill walking for this population.

Both TKR had similar peak loading-response KAbM compared to healthy controls in all walking conditions, which supports our hypothesis. The loading-response KAbM has been considered as a surrogate measure for medial compartment knee joint loading (125). Increased medial knee joint loading may cause increased stress and accelerated wear on the joint replacement (35). Before the surgery, patients usually suffered severe knee OA and normally had a greater peak loading-response KAbM than matched limb of healthy controls in level walking (123). Similar peak loading-response KAbM in replaced limb compared to matched limb of healthy controls in both level and uphill walking indicated that TKR surgery successfully reduced the peak loading-response KAbM and subsequent frontal plane knee loading.

Comparison between replaced and non-replaced limb of TKR patients

The second hypothesis was that compared to non-replaced limb, the replaced limb would have lower peak KEM and similar peak loading-response KAbM. The results of this study support the hypothesis. The peak KEM was lower in replaced limb compared to non-replaced limb in 10° and 15° uphill walking. The limb main effect was not significant for both peak loading-response and push-off KAbM.

Compared to the non-replaced limb, the replaced limb showed 25% and 26.2% lower peak KEM only in 10° and 15° uphill walking. These differences were coupled with a significant reduced knee extension ROM (12.6%) in 10° uphill walking. These results suggest that asymmetry in knee loading were exacerbated in the more demanding uphill walking conditions. The asymmetry after unilateral TKR in uphill walking was similar to the findings from a previous study in level walking and stair ascent. Mizner and Snyder-Mackler (79) reported that knee excursion (knee flexion ROM) was 42% smaller in the replaced limb compared to the non-replaced limb. During stair ascent, the peak KEM of the replaced limb was also lower than the non-replaced limb of TKR patients (101). However, the peak KEM for the replaced limb was not significantly different from that in the non-replaced limb in level walking in present study, which was also supported by findings of previous studies (77, 79). Uphill walking places more demand on the knee joint and surrounding muscles, therefore it may exaggerate the strength deficit of knee muscles in the replaced limb compared to the non-replaced limb. After unilateral TKR, knee OA often progresses in the non-replaced limb. A previous study reported that 40% of patients with unilateral TKR had to replace the other knee within the 10 years (74). Greater sagittal plane knee moments in non-replaced limb may cause higher loading on the knee and expedite knee OA progression of the non-replaced limb. In addition, the peak knee flexion moment during late stance phase was 30%, 17%, 19.6% and 14% lower in the replaced limb compared to the non-replaced limb in level and uphill walking conditions, respectively. These finding may indicate that TKR patients experienced a reduction in both quadriceps and hamstrings muscle strength following surgery.

However, there were no significant differences in the EMG activations of the quadriceps between replaced and non-replaced limb respectively during uphill walking. The disagreement between the EMG activation and peak KEM may be partially due to the fact that these are two different types of measures. RMS EMGs reflect the mean muscle activation, whereas the peak knee moment provides a maximum effort of knee extension muscles. There is no universally agreed peak EMG measure. In addition, EMG activity were analyzed during the stance phase of walking, which does not include muscle activity prior to heel strike and after toe-off.

Comparison between different slopes in uphill walking

The third hypothesis was that the peak KEM would increase and the knee flexion ROM would decrease with an increase in the incline angle. The results of this study supported the hypothesis that there was a significant slope effect for all kinetic variables including peak KEM. The peak extension moment was greater in 15° compared to level , 5° and 10° uphill walking, and it was also greater in 10° compared to level and 5° uphill walking. The knee extension ROM increased and flexion ROM decreased significantly as the incline angle increased from 0° to 15° uphill walking. The quadriceps, hamstring and gastrocnemius muscle activities were also higher in uphill walking compared to level walking, providing support for the findings of knee extension and flexion moments.

There was a significant slope main effect for peak loading-response and push-off KAbM. The peak loading-response KAbM was greater in level walking compared to 10° and 15° uphill walking. Our findings were similar to the observation by Haggerty et al. (32). They reported that the peak KAbM in weight acceptance was greater in level walking compared to that in 10% (5.7°), 15% (8.55°) and 20% (11.4°) gradients on a force-instrumented treadmill at 1.34 m/s in young healthy participants. In the current study, the knee abduction ROM was also increased at the greater incline angles. However, Haggerty et al. (32) reported no change in knee abduction ROM as the treadmill gradient increased. Another previous study (91) also reported that KAbM was greater when walking on the ground than walking on the treadmill. Since both gait speed (92) and treadmill strongly influence the magnitude of the KAbM, it is hard to directly compare our findings to the previous study. Even though 5° uphill walking did not cause a decrease of peak loading-response KAbM, our results also indicated that the peak loading-response KAbM did not increase as the incline angle increased. These results suggest that uphill walking may not increase the medial joint loading and therefore, may have the potential to become a safe exercise for unilateral TKR patients and knee OA patients. However, the increased KEMs observed at the greater slopes should be a concern in using uphill walking on a 10° or steeper slope in rehabilitation exercises.

The loading-response peak vertical GRF was greater in level walking compared to all three uphill conditions, and it was also greater in 5° compared to 15° uphill walking. Participants walked faster on level ground than on inclined surfaces, which may cause higher peak vertical GRF during the weight acceptance phase in level walking compared to uphill conditions. However, Lay et al. (58) did not found significant differences in the loading-response peak vertical GRF between 0, 15% (8.55°) and 39% (21°) inclines.

There was also a significant slope effect for all knee kinematic variables. The findings of this study show good agreement with previous studies on uphill walking (3, 36, 42, 43, 56, 58, 59, 73, 94). These data revealed that in uphill walking, the knees are more flexed at heel strike and have more extension ROM as the incline angle increased. These changes are necessary to raise the lower limb for heel strike and then to push body up on the incline.

Certain limitations in this study should be noted. First, the TKR patient group had 15 more participants than the healthy control group. The assumption of equal variances is satisfied for all dependent variables, the unequal sample size would not influence the results of ANOVA. Second, EMG was normalized to the maximum value of the three functional test trails instead of maximal voluntary isometric contractions, which was a more common method to normalized EMG data. This was done to avoid causing discomfort and pain to the TKR patients in performing maximal contraction. Additionally, 6 out of 25 TKR patients used of the handrail on our ramp system for balance purposes, which may have effects on their knee kinematic and kinetic results. However, we performed a 2×2×4 (limb × groups: handrail user and non-handrail user × slopes) ANOVA on peak loading-response and push-off vertical GRF and peak KEM and the results showed no group effects or interactions involving group of these key variables.

Conclusion

In summary, TKR patients had lower peak KEM and smaller knee extension ROM than healthy controls. The replaced limb showed smaller knee extension ROM and lower peak KEM in uphill walking than non-replaced limb. Knee extension and abduction ROM increased significantly as the incline angle increased. The peak loading-response vertical GRF was significantly greater in level walking compared to uphill walking. The peak KEM was greater in uphill walking compared level uphill walking. The peak loading-response KAbM was greater in level walking compared to uphill walking. Uphill walking may have the potential to become a safe rehabilitation exercise for unilateral TKR patients. But it should be avoided walking on a 10° or steeper slope in rehabilitation exercises.

Chapter IV Appendix: Tables

Table 1 Descriptive statistics and survey data (mean ± stdv).

	TKR	Healthy	P_value
Age (years)	68.8±4.9	69.1±4.6	0.869
Height (cm)	170.2±10.6	174.4±12.0	0.309
Mass (kg)	83.2±15.5	75.0±23.0	0.231
BMI (kg/m^2)	28.7±4.2	24.1±4.4	**0.014**
KOOS			
Symptom	78.7±19.3	92.5±13.1	**0.047**
Pain	82.6±17.3	96.1±4.0	**0.001**
Activity of daily life	85.1±17.1	98.7±1.8	**0.001**
Sport/Recreation	50.0±23.0	87.5±14.2	**<0.001**
Quality of life	72±24.3	90.6±10.3	**0.003**

Table 2 Walking speed and VAS data (mean ± stdv).

			0°	5°	10°	15°
Walking Speed (m/s) $^{*\alpha\beta\gamma\varepsilon\zeta}$	TKR		1.06±0.15	1.00±0.15	0.98±0.16	0.94±0.14
	Healthy		1.17±0.20	1.05±0.19	1.02±0.17	0.96±0.17
VAS(mm)$^{@}$	TKR	Replaced	4±7	5.2±10	6.8±12	9.6±16
		Non-replaced	4.4±8	5.2±9	6±9	6±9
	Healthy	Limb1	0±0	0±0	0±0	0±0
		Limb2	0±0	0±0	0±0	0±0

$^{@}$: Significant Group main effect; *: significant incline slope main effect*: Significant Slope main effect
$^{\alpha}$: significantly different between 0° and 5°; $^{\beta}$: significantly different between 0° and 10°; $^{\gamma}$: significantly different between 0° and 15°; $^{\delta}$: significantly different between 5° and 10°; $^{\varepsilon}$: significantly different between 5° and 15°; $^{\zeta}$: significantly different between 10° and 15°;
TKR: total knee replacement, VAS: visual analog pain scale,
Limb 1 of healthy controls matched with the replaced limb of TKR patients
Limb 2 of healthy controls matched with the non-replaced limb of TKR patients

Table 3 Knee kinematics (°) during uphill walking (mean ± stdv).

Variable	Group	Limb	0°	5°	10°	15°
Knee extension ROM ^YZ	TKR	Replaced	-	4.4±6.6& bc	17.3±7.8& c	29.8±6.8&
		Non-replaced	-	3.9±6.1& bc	19.8±8.0&$ c	31.5±7.6&
	Healthy	Limb 1	-	10.9±6.8	28.4±5.4	40.1±7.5
		Limb 2	-	11.3±6.0	26.5±6.7	39.4±6.9
Knee flexion ROM * α β γ δ ε ζ	TKR	Replaced	-40.8±5.2	-34.5±5.4	-31.1±4.2	-28.9±4.7
		Non-replaced	-43.1±6.1	-36.8±5.4	-33.6±5.8	-28.6±6.8
	Healthy	Limb 1	-43.4±5.2	-41.3±5.3	-38.2±6.1	-35.7±6.8
		Limb 2	-44.7±7.2	-40.4±5.9	-37.0±5.5	-34.4±5.9
Knee Abduction ROM* β γ δ ε ζ	TKR	Replaced	-	-3.5±1.6	-5.1±3.4	-8.1±4.6
		Non-replaced	-	-3.6±1.5	-5.5±2.7	-8.1±4.2
	Healthy	Limb 1	-	-4.3±1.7	-7.4±2.6	-9.6±4.8
		Limb 2	-	-4.2±1.6	-7.1±4.1	-10.1±5.6

Positive values indicate knee extension, adduction and internal rotation angles and ROM.

*: Significant slope main effect

^: significant limb x slope x group interaction; X: significant limb x group interaction Y: significant slope x group interaction; Z: significant limb x slope interaction

a: significantly different from 5°, b: significantly different from 10°, c: significantly different from 15°

$: significantly different from replaced limb; &: significantly different from healthy controls

α: significantly different between 0° and 5°; β: significantly different between 0° and 10°; γ: significantly different between 0° and 15°; δ: significantly different between 5° and 10°; ε: significantly different between 5° and 15°; ζ: significantly different between 10° and 15°;

-: no comparable values

ROM: range of motion.

Table 4 GRF (BW) and knee moments (Nm/kg) during uphill walking (mean±stdv).

Variables	Group	Limb	0°	5°	10°	15°
Peak loading-response vertical GRF $^{*\alpha\beta\gamma\varepsilon}$	TKR	Replaced	1.03±0.09	1.00±0.09	0.98±0.08	0.97±0.08
		Non-Replaced	1.04±0.09	1.00±0.09	1.00±0.08	0.99±0.08
	Healthy	Limb 1	1.07±0.07	1.05±0.05	1.04±0.06	1.03±0.09
		Limb 2	1.09±0.07	1.05±0.05	1.04±0.06	1.04±0.08
Peak push-off vertical GRF $^{*\alpha\beta}$	TKR	Replaced	1.00±0.08	1.03±0.07	1.04±0.07	1.02±0.07
		Non-Replaced	1.02±0.07	1.04±0.07	1.05±0.09	1.04±0.08
	Healthy	Limb 1	1.05±0.05	1.07±0.04	1.08±0.07	1.08±0.07
		Limb 2	1.06±0.04	1.07±0.04	1.08±0.08	1.09±0.11
Peak KEM $^{Z *@\#}$	TKR	Replaced	0.33±0.21^{c}	0.30±0.22^{bc}	0.39±0.27	0.45±0.28
		Non-Replaced	0.35±0.24^{bc}	0.32±0.28^{bc}	0.52±0.32^{c}	0.61±0.33
	Healthy	Limb 1	0.49±0.29	0.52±0.31	0.67±0.39	0.73±0.43
		Limb 2	0.57±0.26	0.58±0.30	0.72±0.30	0.84±0.34
Peak knee flexion moment $^{*X\alpha\beta\gamma\delta\varepsilon\zeta}$	TKR$^{\&}$	Replaced	-0.14±0.14	-0.29±0.15	-0.37±0.15	-0.43±0.20
		Non-Replaced$^{\$}$	-0.20±0.15	-0.35±0.16	-0.46±0.19	-0.50±0.21
	Healthy	Limb 1	-0.28±0.12	-0.41±0.13	-0.53±0.14	-0.58±0.15
		Limb 2	-0.21±0.17	-0.35±0.17	-0.43±0.23	-0.51±0.23
Peak loading-response KAbM $^{*\beta\gamma}$	TKR	Replaced	-0.36±0.12	0.34±0.10	-0.32±0.10	-0.31±0.11
		Non-Replaced	-0.43±0.15	-0.38±0.18	-0.37±0.18	-0.36±0.18
	Healthy	Limb 1	-0.43±0.14	-0.42±0.11	-0.39±0.13	-0.37±0.14
		Limb 2	-0.43±0.15	-0.38±0.15	-0.38±0.18	-0.36±0.17
Peak push-off KAbM $^{*\alpha\beta\gamma\delta\varepsilon}$	TKR	Replaced	-0.28±0.11	-0.24±0.11	-0.23±0.11	-0.20±0.10
		Non-Replaced	-0.32±0.16	-0.28±0.16	-0.27±0.15	-0.27±0.15
	Healthy	Limb 1	-0.25±0.13	-0.24±0.14	-0.19±0.16	-0.21±0.14
		Limb 2	-0.27±0.18	-0.22±0.16	-0.19±0.18	-0.16±0.29

Positive moment values indicate knee extension, adduction and internal rotation moments.
$^{@}$: Significant group main effect; #: Significant limb main effect; *: Significant slope main effect, ^{b}: significantly different from 10°, ^{c}: significantly different from 15°, ^{X}: significant limb x group interaction ^{Y}: significant slope x group interaction ^{Z}: significant limb x slope interaction ^: significant limb x slope x group interaction, $^{\$}$: significantly different from replaced limb; $^{\&}$: significantly different from healthy controls
$^{\alpha}$: significantly different between 0° and 5°; $^{\beta}$: significantly different between 0° and 10°; $^{\gamma}$: significantly different between 0° and 15°; $^{\delta}$: significantly different between 5° and 10°; $^{\varepsilon}$: significantly different between 5° and 15°; $^{\zeta}$: significantly different between 10° and 15°;
GRF: ground reaction force, KEM: knee extension moment, KAbM: Knee Abduction moment,

Table 5 Root mean square of normalized EMG (mean±stdv)

			0	5	10	15
Long head of biceps femoris $^{*\alpha\beta\gamma\delta\varepsilon}$	TKR	Replaced	0.23±0.14	0.28±0.16	0.35±0.11	0.39±0.20
		Non-replaced	0.21±0.16	0.29±0.20	0.32±0.20	0.34±0.23
	Healthy	Limb 1	0.27±0.07	0.31±0.08	0.34±0.11	0.35±0.13
		Limb 2	0.29±0.11	0.35±0.14	0.42±0.19	0.49±0.27
Medial Gastrocnemius $^{*\alpha\beta\gamma\delta\varepsilon\zeta}$	TKR	Replaced	0.20±0.09	0.25±0.10	0.29±0.10	0.33±0.11
		Non-replaced	0.17±0.09	0.23±0.09	0.30±0.12	0.34±0.12
	Healthy	Limb 1	0.21±0.06	0.25±0.08	0.30±0.08	0.33±0.12
		Limb 2	0.24±0.08	0.26±0.08	0.31±0.07	0.35±0.10
Vastus Lateralalis $^{*\alpha\beta\gamma\delta\varepsilon\zeta}$	TKR	Replaced	0.21±0.12	0.24±0.13	0.29±0.14	0.35±0.16
		Non-replaced	0.17±0.09	0.21±0.10	0.27±0.13	0.38±0.18
	Healthy	Limb 1	0.23±0.05	0.25±0.04	0.32±0.07	0.36±0.10
		Limb 2	0.25±0.06	0.29±0.06	0.35±0.09	0.41±0.11

*: Significant slope main effect

$^{\alpha}$: significantly different between 0° and 5°; $^{\beta}$: significantly different between 0° and 10°; $^{\gamma}$: significantly different between 0° and 15°; $^{\delta}$: significantly different between 5° and 10°; $^{\varepsilon}$: significantly different between 5° and 15°; $^{\zeta}$: significantly different between 10° and 15°;

CHAPTER V

KNEE BIOMECHANICS DURING DOWNHILL WALKING ON DIFFERENT SLOPES IN TOTAL KNEE REPLACEMENT OLDER ADULTS

Abstract

The purpose of this study was to compare knee biomechanics and knee muscles EMG activity of the replaced limb to the non-replaced limb of total knee replacement (TKR) patients and healthy controls during walking on level ground and on decline surfaces of 5°, 10° and 15°. Twenty-five TKR patients and ten healthy controls performed five walking trials on different declined slopes on a force platform and an instrumented ramp system. A 2 × 2 × 4 (limb × group × incline slope) mixed model ANOVA was used to examine selected biomechanics variables. The replaced limbs of TKR patients had lower peak loading-response and push-off knee extension moment (KEM) than non-replaced and matched limb of healthy controls. No differences were found in loading-response and push-off knee internal abduction momentsbetween replaced, non-replaced and matched limb of healthy controls. Greater peak KEM, loading-response vertical ground reaction force (VGRF), knee flexion range of motion, quadriceps EMG activity were found in downhill walking compared to level walking. Finally, the push-off VGRF was lower in downhill walking compared to level walking. Downhill walking may not be appropriate to be included in the early-stage rehabilitation exercise protocol for TKR patients.

Keywords: total knee arthroplasty, declined surface, knee joint moment, knee adduction moment

Introduction

Total knee replacement (TKR) or total knee arthroplasty is a common surgical procedure for disabling knee osteoarthritis (OA) (123). It has been shown to be effective in reducing pain and improving range of motion (ROM) for patients suffering severe knee OA (16, 39). Recent studies have reported that TKR patients showed smaller knee flexion ROM, and reduced KEM during level walking compared to their healthy peers (12, 62). In addition, peak internal knee abduction moment (KAbM) was similar or lower in replaced limb of TKR patients compared to non-replaced and healthy controls (72).

The results of previous studies (56, 58, 87, 94) showed that the peak knee flexion and knee flexion ROM was greater in downhill walking compared to level walking during stance phase in young healthy individuals indicating that the knees are kept at a more flexed position during downhill walking compared to level walking. The loading-response vertical ground reaction force (VGRF) increased as the angle of slope increased for downhill walking (29, 56, 58, 73, 94, 110). The peak KEM was also greater in downhill walking compared to level walking (43, 58, 73, 94). Kuster et al. (56) reported the peak KEM during 10° downhill walking was nearly twice as much as that obtained in level walking when participants walked at the same step frequency. In addition, higher quadriceps EMG activities observed in downhill compared to level walking provided support for the findings of downhill walking having higher knee loading than level walking (27, 59). However, no study has reported knee kinematics and kinetics in frontal and transverse planes during downhill walking.

To our knowledge, only one previous study (90) has reported kinematics and kinetics for downhill walking in TKR patients. In Reynolds' thesis (90), the author compared knee biomechanical characteristics between TKR patients and age matched healthy individuals during downhill walking at their self-selected speed on a 7° slope. The knee flexion ROM and peak knee flexion angle of replaced limb for TKR patients were 11.9% and 26.3% respectively less than those of healthy participants. In addition, the peak KEM of replaced limb was 22.7% lower than their non-replaced limb and 36.2% lower than the matched limb of healthy controls.

Currently, no studies have explored knee kinematics, kinetics and EMG during downhill walking on different downhill slopes in TKR patients. Thoroughly investigating specific gait impairment after TKR surgery on different downhill slopes may help improve rehabilitation strategies. Thus, the purpose of this study was to compare knee biomechanics and knee muscles EMG activity of the replaced limb to the non-replaced limb of TKR patients and healthy control during downhill walking on decline surfaces of 0° (level walking), 5°, 10° and 15°. We hypothesized that 1) the peak KEM would be lower in replaced limb of TKR patients compared to healthy controls, and peak KAbM in replaced limb of TKR patients would be similar compared to matched limb of healthy controls; 2) peak KEM would be lower and peak KAbM would be similar in the replaced limb compared to their non-replaced limb; and 3) the peak KEM, quadriceps EMG activity and the knee flexion ROM and would increase across all slope comparisons between 0° and 15° in both replaced and non-replaced limb of TKR patients.

Materials and Methods

Participants

Twenty-five TKR patients between the ages of 50 and 75 years were recruited from a local orthopedic clinic (68.8 ± 4.9 years, 1.70 ± 0.11m, 83.2 ±15.6 kg, 22.1 ± 11.72 months since surgery). TKR patients were recruited if they had a unilateral total knee replacement (conducted by a single surgeon) between 6 months and 60 months. The exclusion criteria for potential participants were had any additional lower extremity joint replacements, any additional diagnosed OA of the hip or ankle, more than 75% radiographic joint space narrowing and chronic pain at the contralateral knee of the TKR side, BMI greater than 38 kg/m^2, or neurological diseases. Ten older adults between the ages of 50 and 75 years without any lower extremity pathology were recruited in the study as healthy controls (69.1 ± 4.5 years, 1.74 ± 0.12 m, 75.0 ± 23 kg).

Instrumentation

Three-dimensional (3D) kinematics were collected, using a twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK). Participants were asked to wear tight fitting workout clothing and a pair of standardized laboratory running shoes (Noveto, Adidas, USA) during data collection. Reflective anatomical markers were placed bilaterally on the 2nd toe, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and acromion processes. A cluster of four reflective tracking markers on a semi-rigid thermoplastic shell was placed on the lateral aspect of shanks, thighs, pelvis and posterior trunk. Four discrete tracking markers were place on the lateral and posterior heel counter of the shoe.

A customized instrumented ramp system was used in the study to measure the ground reaction forces (GRF) and the moments of forces during downhill walking (Figure 6). The ramp consists of a walkway that is 1 m wide and 3 m long and with two separate walking surfaces/structures bolted on to two force platforms (BP600600 and OR-6-7, 1200Hz, American Mechanical Technology Inc., Watertown, MA, USA), and ends with a platform. The declined angle of ramp surface can be adjusted to 5°, 10° and 15°. Gait speeds was monitored by two sets of photocells (63501 IR, Lafayette Instrument Inc., IN, USA) and two electronic timers (54035A, Lafayette Instrument Inc., IN, USA). The photocells were placed 3 meters apart for level walking, and 1.5 meters apart at shoulder height for ramp walking.

A 16-channel surface EMG system (1200 Hz, Trigno™ Wireless EMG System, Delsys, INC, Natick MA, USA) was used to detect the muscle EMG activities of following muscles on both sides of the body: vastus medialis (VM), semitendinosus (ST) and medial gastrocnemius (MG). The skin of the electrode attachment sites was shaved and cleaned with alcohol swab before the application of the electrodes. The placement of the EMG electrodes on the selected muscles were based on the recommendations of SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) (40). Both GRF and EMG data were sampled simultaneously with the 3D kinematic data using the VICON system and Nexus software package (2.5, Vicon Motion Analysis Inc., Oxford, UK).

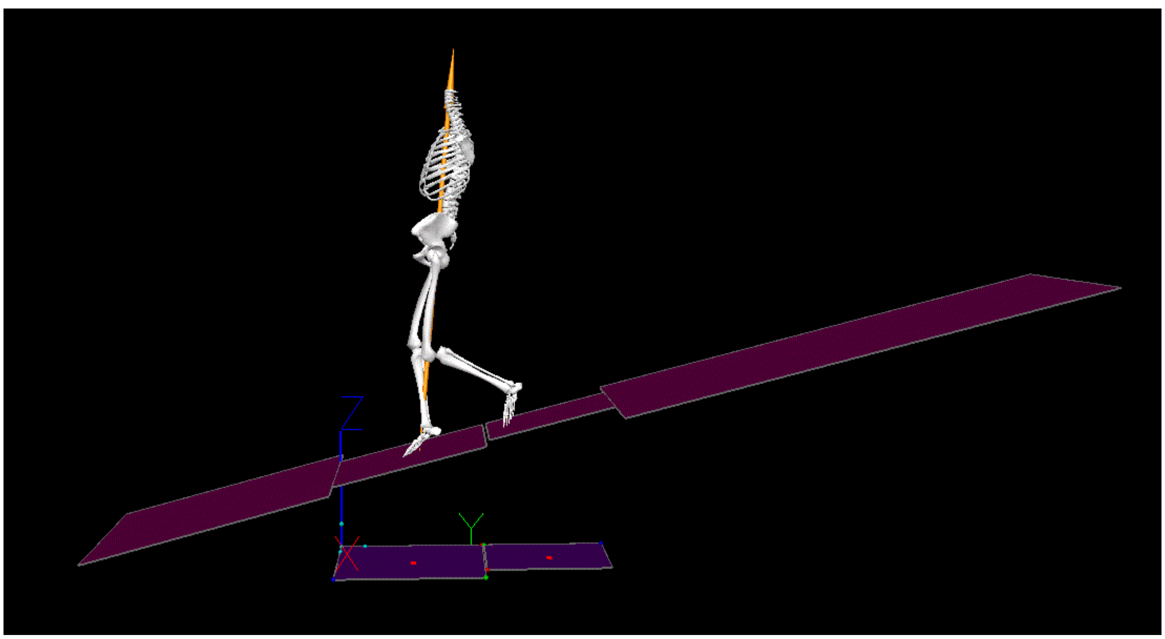

Figure 6 The setup of ramp at a 15° decline for experimental data collection.

Experimental Procedures

Both healthy controls and TKR patients completed an information sheet which collects demographic and injury history information, and the physical activity readiness survey (PAR-Q). Following completion of the surveys, participants performed a 3-minute walking on a treadmill at a self-selected speed as warm-up. For the purpose of EMG normalization (34), participants were asked to perform three trails in each of related functional tests to obtain baseline EMG values of the selected muscles. For VM, a half squat (bend knee to about 45°) was used. For ST, a leg curl (flex to 90°) from a standing position was performed for one leg at a time. For MG, a bilateral calf raise from a standing position was used. A rest period of one minute between testing movements was also provided.

All participants were asked to walk at four different slopes, 0° (level walking), and 5°, 10°, and 15° (downhill). The testing order of three decline ramp conditions (5°, 10°, 15°) was randomized first, and then followed by the randomization of right and left foot within each slope condition. Level walking was performed after ramp walking conditions. The testing order of right and left leg was randomized within each incline condition. The ramp conditions were tested first due to the need for its setup prior to participants coming to the lab to reduce the total testing time. Participants were asked to practice downhill and level walking trials at a self-selected speed for each ramp decline condition. Once participants were comfortable on downhill walking during the practice trials (about three trials each), the participants were asked to perform downhill and level walking at their self-selected speed range (mean ± 5%) obtained during the practice trials for each ramp condition. Participants was asked to repeat a trial if they did not make a full contact within the force platform with the targeted foot, and were not able to reach the pre-determined speed. A handrail was provided on the right side for balance purposes if needed, but participants were not encouraged to use it. A numerical visual analog pain scale (VAS) was used to assess pain in both knees for healthy and TKR patients prior to the warm-up, and at the end of each test condition.

Data Analyses

Visual3D biomechanical analysis software suite (version 2.6, C-Motion, Inc., Germantown, MD, USA) was used to compute the 3D kinematic and kinetic variables. An X-y-z Cardan rotational sequence was used in the 3D angular kinematics computations and a right-hand rule was used to determine the conventions of angular kinematic and kinetic variables. Joint moments were calculated as internal moments in the proximal segment and normalized to the participant's body mass yielding a unit of Nm/kg. Body segment masses were estimated based on Dempster's regression equations (23) and segment moment of inertias were estimated based on the Hanavan model (37). Positive values indicate knee extension ROM, knee adduction ROM and knee internal rotation ROM. For kinetic variables, positive values indicate knee extension, adduction moments, and internal rotation moments. Kinematic and GRF data were smoothed at cutoff frequency of 8 Hz using a fourth-order zero-lag Butterworth low-pass filter. Raw GRF were filtered alone using a fourth-order low-pass Butterworth filter with a cut-off frequency of 50 Hz for GRF data. Peak angles and moments were determined and organized for statistical analysis using customized programs (VB_V3D and VB_Table, MS Visual BASIC, Microsoft, Redmond, WA, USA). The GRFs were normalized to the participant's body weight (BW) and joint moments were normalized to the participant's body mass (Nm/kg).

The EMG data was analyzed using the Visual3D. Raw EMG signals were filtered with a band-pass filter with a high and low pass cutoff frequencies 10Hz and 450 Hz and fully rectified (1). A moving root-mean-square (RMS) filter was used to filter the rectified EMG signals using a

60-millisecond moving window. The maximum value of the RMS EMG signals of three functional test trails was used to normalize the filtered EMG signals of the testing movement trails. The mean RMS value was calculated for all muscles during the stance phase of movement trials (89).

Statistical Analyses

A one-way analysis of variance (ANOVA) was used to identify differences in demographic and survey data between TKR patients and healthy controls. A 2 × 4 (group: TKR and healthy controls x decline slope: 0°, 5°, 10° and 15°) ANOVA was used to examine the difference in walking speed between TKR patients and healthy controls. In addition, a 2 × 2 × 4 (limb: replaced and non-replaced limb × group × slope) mixed-design ANOVA was used to examine the interactions and main effects of VAS, knee flexion, adduction and internal rotation ROM, peak loading-response and push-off VGRF, KEM, KAbM and peak internal rotation moment, and mean RMS of normalized EMG of SM, MG and VM during downhill walking (24.0, IBM SPSS, Chicago, IL). The left and right limb of healthy controls were randomly selected as limb 1 and 2 to match with TKR replaced and non-replaced limb, respectively. An *a priori* alpha level was set to 0.05. When the ANOVA results revealed a significant three-way interaction, two-way ANOVAs were followed. When two-way ANOVA showed significant interaction or main effect, post-hoc comparisons with Bonferroni adjustments were used to detect differences between limb and angles (adjusted $p<0.0125$ for differences detected between slopes, $p<0.00625$ for interactions). In order to focus on effects on TKR patients and streamline result reporting, when there was a significant limb effect in 3-way or 2-way interaction, we only reported related TKR group results.

Results

The differences in age, height, and mass between TKR patients and healthy controls were not significant (Table 6). TKR patients had a significantly greater BMI than healthy controls ($p=0.014$). Participants walked significantly faster on level ground than on all three declined surfaces ($p<0.0001$ for all comparisons, Table 7). TKR patients showed higher VAS scores than healthy controls ($p<0.0001$ for all comparisons) in all walking conditions.

A significant decline slope main effect was found for all knee kinematic variables ($p<0.001$, Table 8). Knee flexion ROM significantly increased across all comparisons between 0° and 15° of decline angle ($p<0.001$ for all comparisons). Knee adduction ROM was significantly greater in 15° compared to level, 5° and 10° downhill walking ($p<0.001$ for all comparisons). It also in 10° downhill walking compared to level and 5° downhill walking ($p<0.029$). The knee internal rotation ROM was greater in 5° compared to 10° downhill walking ($p=0.008$). The replaced limb had greater knee internal rotation ROM than the non-replaced limb ($p=0.045$ for all comparisons).

The peak loading-response VGRF was lower in level walking compared to all downhill walking conditions, and lower in 5° compared to 10° and 15° downhill walking respectively ($p<0.001$ for all comparisons, Table 9). The non-replaced limb had greater peak loading-response VGRF than replaced-limb ($p=0.017$). A significant slope × group interaction was present for peak push-off VGRF ($p=0.009$, Table 9). For TKR patients, the peak push-off VGRF was greater in level walking compared to all downhill walking conditions ($P<0.012$ for all comparisons), and it was also greater in 5° compared to 15° downhill walking ($p=0.047$). For healthy controls, peak push-off VGRF was also greater in level walking compared to all downhill walking conditions ($p<0.001$ for all comparisons) and was greater in 5° compared to

10° and 15° downhill walking (p<0.007 for all comparisons). The non-replaced limb showed greater peak push-off VGRF than replaced limb (p<0.017 for all comparisons).

A significant limb x slope x group interaction was present in both peak loading-response (p=0.006) and push-off (p=0.035) KEM (Table 9). A limb x slope interaction was also found for peak loading-response (p=0.004) and push-off (p=0.011) KEM in TKR group. Both peak moments increased significantly across most slope comparisons in both replaced and non-replaced limbs (p<0.026 for all comparisons). The non-replaced limb had greater peak loading-response KEM than the replaced limb in all downhill walking conditions (p<0.048 for all comparisons), and it also had greater peak push-off KEM than the replaced limb in 10° and 15° downhill walking (p<0.003 for all comparisons). The replaced limb showed lower peak loading-response KEM than the matched limb of healthy controls in 10° downhill walking (p=0.03), and it also had lower peak push-off KEM than matched limb of healthy controls in 15° downhill walking (p=0.02). The non-replaced limb presented lower peak loading-response peak KEM than the matched limb of healthy controls in level and 5° downhill walking (p<0.047 for all comparisons).

The peak push-off KAbM was lower in level walking than that in 5°, 10° and 15° downhill walking (p<0.023 for all comparisons, Table 9). It was also lower in 5° compared to 15° downhill walking (p=0.023). The peak knee internal rotation moment was greater in 15° compared to 0°, 5° and 10° downhill walking, and was greater in 10 ° compared to 0° and 5 (p<0.001 for all comparisons). It was higher in the non-replaced limb than the replaced limb (p=0.004).

The ST EMG activity was higher in 5° downhill walking than level walking and also higher in 15° compared to 5° downhill walking (p<0.009 for all comparisons, Table 10). The

MG EMG activity was higher in level walking compared to 5° and 10° downhill walking conditions ($p<0.001$ for all comparisons). Healthy controls had higher MG EMG activity than TKR patients ($p=0.049$). A significant limb x group ($p=0.035$) was present in VM EMG, but the post-hoc comparisons did not show any differences. The VM EMG activity increased significantly across all comparisons between 0° and 15° of decline angle ($p<0.001$ for all comparisons).

Discussion

The purpose of this study was to compare knee biomechanics and knee muscles EMG activity of the replaced limb to the non-replaced limb of TKR patients and healthy control limb during walking on decline surfaces of the different slopes. The first hypothesis was TKR patients would exhibit lower peak KEM and similar peak KAbM in their replaced limb compared to matched limb of healthy controls. The results of this study support the hypothesis.

Compared to the matched healthy control limbs, the peak loading-response KEM was 28.4% lower in the replaced limb in 10° downhill walking and was 33.3% and 22% lower in the non-replaced limb in level and 5° downhill walking, respectively. The peak push-off KEM was also 18.3% lower in replaced limb compared to matched limbs of healthy controls in 15° downhill walking. These findings demonstrated that both replaced and non-replaced limb had reduction in sagittal plane knee kinetics compared to matched limb of healthy controls in both level and downhill walking. Similar discrepancies have been reported in a study by Reynolds (90) showing 36.3% lower peak loading-response KEM in replaced limb compared to matched limb of healthy controls in 7° downhill walking, but they did not compare with healthy controls. Previous studies also reported similar apparent deficits in knee loading-response KEM in replaced limbs compared to healthy controls in level walking (12, 62, 68, 85). Levinger et al.

(62) exhibited that TKR patients had 60.9% lower peak KEM in replaced limb at 12 month post-surgery while walking 17.5% slower compared to healthy controls. However, no group differences were detected in walking speed as well as peak VGRF and knee flexion ROM, across all comparisons between 0° and 15°, thus lower KEM in TKR patients may be due to the quadriceps strength deficit compared to healthy controls. VM EMG activity was lower in the replaced limb compared to matched limb of healthy controls in level, 5° and 10° downhill walking, which partially support the finding of reduced KEM in replaced and non-replaced limbs compared to healthy controls. Some studies reported a quadriceps strength loss after TKR surgery (78, 103, 104, 122), and also revealed that TKR patients had less quadriceps EMG activity than healthy controls in level walking (67), providing support for the findings of reduced KEM in TKR compared to healthy controls in level, 5° and 10° downhill walking.

Both peak loading-response and push-off KAbM were similar between TKR replaced and non-replaced limbs across all comparisons between 0° and 15° of decline angle, which supports our hypothesis. The loading-response KAbM is commonly used as a surrogate measure for medial compartment knee joint loading for knee OA patients in gait (125). Increased medial knee joint loading may increase wear and tear on the joint replacement (35). Similar peak loading-response KAbMs between replaced and matched limb of healthy controls in both level and downhill walking indicated that TKR surgeries may have successfully restored medial knee joint loading to the healthy level in not only level but also downhill walking.

The second hypothesis was that the replaced limb would have lower peak KEM and similar peak KAbM compared to the non-replaced limb. The results were in support of the hypothesis. Compared to non-replaced limb, the replaced limb had lower peak loading-response KEM across all comparisons between 0° and 15° of decline angle and lower peak push-off KEM in 10° and 15° downhill walking. In addition, interactions and post-hoc comparisons did not exhibit any differences between replaced and non-replaced limbs for both peak loading-responses and push-off KAbM. The peak loading-response KEM was 7.8%, 17.0%, 22.7% and 20.0% lower in replaced compared to non-replaced limb across all comparisons between 0° and 15° decline angle, respectively. The peak push-off KEM was 16.9% and 12.5% lower in replaced limb compared to non-replaced limb in 10° and 15° downhill walking respectively. Reynolds (90) also reported that the replaced limb was 22.7% and 22.4% lower in peak loading-response and push-off KEM respectively in 7° downhill walking.

The replaced limb had lower peak loading-response and push-off VGRF than the non-replaced in 10° and 15° downhill walking. Findings in VGRF provided partial support for the differences in peak KEMs between replaced and non-replaced limbs. These findings indicated that patients displayed unloading of the replaced limb, shifting the load to the non-replaced limb when performing downhill walking. The increased dependence on the non-replaced limb may be to compensate for the quadriceps strength deficits and/or residual pain in the replaced limb. However, greater knee joint loading in the non-replaced limb may accelerate development of knee OA in non-replaced limb. A previous study (74) reported that 40% of patients had to replace their contralateral knee within the 10 years after primary unilateral TKR surgery. Monitoring symmetry of patients during their recovery from primary unilateral TKR surgery may help to avoid or postpone contralateral TKR surgery in the future. However, no differences were found in peak KEM, VGRF and quadriceps muscle activity between replaced and non-replaced limb in level walking (77, 79). Downhill walking is more demanding than level walking, thus it may intensify the quadriceps strength deficit in the replaced limb compared to non-replaced limb.

Peak loading-response and push-off KAbM were not different between replaced and non-replaced limbs during level and downhill walking. Knee adduction ROM also did not show any difference between replaced and non-replaced limb in walking conditions. However, Alnadhdi et al. (5) reported that non-replaced limb had a greater knee adduction angle and KAbM compared to replaced limb in level walking. In the present study, we excluded patients who had severe OA on the contralateral knee, whereas Alnadhdi et al. did not specify if the patients with unilateral TKR had OA on contralateral knee. The KAbM is related to the severity of OA and provide prediction of OA progression (7). Greater KAbM in the non-replaced limb may subsequently expedite knee OA progression.

Our third hypothesis was that the peak KEM and the knee flexion ROM would increase across all slope comparisons between 0° and 15° in both replaced and non-replaced limb of TKR patients. The findings of this study supported the hypothesis that loading-response and push-off KEM and knee flexion ROM increased across all slope comparisons between 0° and 15° in replaced, non-replaced, and matched limb of healthy controls. The quadriceps muscle EMG activities also increased as the decline angle increased in replaced limb, providing support for the findings of KEM.

The slope effect was significant in both peak loading-response and push-off vertical GRFs. Peak loading-response VGRF increased significantly across all slope comparisons. The peak push-off VGRF was greater in level walking compared to all downhill walking conditions for both TKR patients and healthy controls. Previous studies also reported similar findings in VGRF in young healthy populations (56, 58, 94). As the decline angle increased during downhill walking, shock absorption increased in weight acceptance and propulsion decreased before toe-off. Greater peak loading-response VGRF may increase knee joint loading, and therefore downhill walking may not be appropriate to be included in rehabilitation protocols in early stage following TKR surgery, but it could be added to progressive rehabilitation scheme.

There was a significant slope effect for all kinetic variables except for peak loading–response KAbM. The finding in this study showed good agreement with previous studies on downhill walking (43, 56, 58, 94). Since the center of gravity of the body was continuously lowered during downhill walking, the knees had to maintain a more flexed position through the stance phase and therefore the knee sagittal-plane joint loading increased accordingly. No differences were present in peak loading-response KAbM across all slopes between 0° and 15° in replaced, non-replaced and matched limb of healthy controls, indicating the medial joint loading remained unchanged, even with increased sagittal-plane loading.

Several limitations in this study should be noted. First, three TKR patients could not perform 15° downhill walking. We excluded their data in all statistical analyses. Second, seven out of 25 TKR patients used handrail on our ramp system for balance purposes, which may influence their knee biomechanical results. We performed a 2×2×4 (limb × groups: handrail user and non-handrail user × decline slopes) ANOVA on peak loading-response and push-off VGRFs and KEM, and no group effects or interactions were detected in these key variables.

Conclusion

In summary, the replaced limb of TKR patients had lower peak loading-response and push-off KEM than healthy and non-replaced limb. No differences were found in loading-response and push-off KAbMs between replaced, non-replaced and matched limb of healthy controls. Greater peak KEM, loading-response VGRF, knee flexion ROM, quadriceps EMG activity were found in downhill walking compared to level walking. Finally, the push-off VGRF was lower in downhill walking compared to level walking. These results indicate that downhill walking may not be appropriate to be included in early stage rehabilitation protocols following TKR surgery.

Chapter V Appendix: Tables

Table 6 Descriptive Statistics (mean ± stdv)

	TKR	Healthy	P_value
Age (years)	68.8±4.9	69.1±4.6	0.869
Height (cm)	170.2±10.6	174.4±12.0	0.309
Mass (kg)	83.2±15.5	75.0±23.0	0.231
BMI (kg/m^2)	28.7±4.2	24.1±4.4	**0.014**

Table 7 Walking Speed and VAS (mean ± stdv)

			0°	5°	10°	15°
Walking Speed (m/s) $*^{\alpha\,\beta\,\gamma}$	TKR		1.08±0.14	0.94±0.14	0.89±0.15	0.92±0.18
	Healthy		1.17±0.20	1.02±0.19	0.99±0.22	0.94±0.18
VAS(mm)$^{@}$	TKR	Replaced	4±7	5.0±9.6	5.9±11.8	9.6±17
		Non-replaced	3.6±7.3	3.6±7.3	4.6±7	4.1±7.3
	Healthy	Limb1	0±0	0±0	0±0	0±0
		Limb2	0±0	0±0	0±0	0±0

*: Significant decline slope main effect

$^\alpha$: significantly different between 0° and 5°; $^\beta$: significantly different between 0° and 10°; $^\gamma$: significantly different between 0° and 15°

$^@$: Significant Group main effect

VAS: visual analogue pain scale

Table 8 Knee kinematics (°) during downhill walking (mean ± stdv).

Variable	Group	Limb	0°	5°	10°	15°
Knee flexion ROM $^{*\alpha\beta\gamma\delta\varepsilon\zeta}$	TKR	Replaced	-41.3±5.3	-51.2±5.8	-59.0±5.9	-65.8±6.0
		Non-replaced	-43.1±6.3	-53.5±5.7	-60.0±5.5	-66.7±6.3
	Healthy	Limb 1	-43.4±5.2	-53.6±8.3	-62.8±7.5	-71.0±6.5
		Limb 2	-44.9±8.4	-54.2±8.2	-62.9±6.9	-71.0±6.1
Knee Adduction ROM$^{*\beta\gamma\delta\varepsilon\zeta}$	TKR	Replaced	3.8±2.1	3.4±1.6	4.2±1.9	5.5±2.6
		Non-replaced	4.6±2.5	5.2±2.7	5.9±3.0	6.8±3.2
	Healthy	Limb 1	3.4±1.2	3.4±1.6	4.2±1.9	5.5±2.6
		Limb 2	3.1±1.5	3.7±1.2	4.6±1.3	6.1±2.1
Knee internal rotation ROM$^{*\#\delta}$	TKR	Replaced	9.0±4.9	8.2±4.6	6.8±4.2	7.1±3.8
		Non-replaced	5.9±4.8$^{\$}$	6.1±4.7$^{\$}$	5.7±4.8	5.5±5.7
	Healthy	Limb 1	7.9±4.5	8.7±4.7	7.2±3.1	7.6±3.6
		Limb 2	7.6±3.9	7.4±3.3	6.7±3.5	7.4±3.2

Positive values indicate knee extension, adduction and internal rotation ROM.
*: Significant slope main effect; #: Significant limb main effect; $^{\$}$: significantly different from replaced limb;
$^{\alpha}$: significantly different between 0° and 5°; $^{\beta}$: significantly different between 0° and 10°; $^{\gamma}$: significantly different between 0° and 15°; $^{\delta}$: significantly different between 5° and 10°; $^{\varepsilon}$: significantly different between 5° and 15°; $^{\zeta}$: significantly different between 10° and 15°;
ROM: range of motion

Table 9 GRF (BW) and knee moments (Nm/kg) during downhill walking (mean±stdv).

Variables	Group	Limb	0°	5°	10°	15°
peak Loading-response VGRF *$^{\# \alpha \beta \gamma \delta \varepsilon}$	TKR	Replaced	1.03±0.08	1.11±0.12	1.17±0.13	1.23±0.18
		Non-Replaced	1.05±0.07	1.14±0.10	1.23±0.13	1.30±0.17
	Healthy	Limb 1	1.07±0.07	1.13±0.09	1.19±0.09	1.20±0.11
		Limb 2	1.09±0.07	1.15±0.07	1.22±0.11	1.22±0.15
peak Push-off VGRF *$^{\#Y}$	TKR $^{\alpha \beta \gamma \varepsilon}$	Replaced	1.01±0.07	0.98±0.06	0.95±0.06	0.91±0.07
		Non-Replaced	1.03±0.06	1.00±0.04	0.98±0.06	0.94±0.09
	Healthy $^{\alpha \beta \gamma \delta \varepsilon}$	Limb 1	1.05±0.05	0.97±0.06	0.92±0.08	0.90±0.08
		Limb 2	1.06±0.04	0.98±0.04	0.93±0.06	0.90±0.08
Peak loading-response KEM ^^{X}*$^{\#}$	TKR	Replaced	0.35±0.21^{abc}	0.44±0.22^{bc}	0.58±0.24$^{c\&}$	0.75±0.27
		Non-Replaced	0.38±0.22$^{abc\&}$	0.53±0.24$^{bc\&\$}$	0.75±0.29$^{c\$}$	0.94±0.39$^{\$}$
	Healthy	Limb 1	0.49±0.29	0.57±0.30	0.81±0.40	1.00±0.41
		Limb 2	0.57±0.26	0.68±0.22	0.89±0.26	0.96±0.41
Peak push-of KEM^^{X}*	TKR	Replaced	0.15±0.11^{abc}	0.37±0.17^{bc}	0.69±0.23^{c}	0.98±0.23$^{\&}$
		Non-Replaced	0.16±0.17^{abc}	0.43±0.16^{bc}	0.83±0.27$^{c\,\$}$	1.12±0.31$^{\$}$
	Healthy	Limb 1	0.18±0.07	0.34±0.07	0.73±0.18	1.20±0.25
		Limb 2	0.21±0.07	0.38±0.08	0.74±0.13	1.12±0.25
Peak loading-response KAbM	TKR	Replaced	-0.36±0.12	0.35±0.14	-0.36±0.15	-0.38±0.14
		Non-Replaced	-0.41±0.20	-0.42±0.21	-0.44±0.22	-0.44±0.23
	Healthy	Limb 1	-0.43±0.14	-0.42±0.11	-0.45±0.12	-0.42±0.13
		Limb 2	-0.43±0.15	-0.41±0.15	-0.41±0.19	-0.42±0.20
Peak push-off KAbM* $^{\alpha \beta \gamma \varepsilon}$	TKR	Replaced	-0.29±0.12	-0.32±0.15	-0.35±0.14	-0.38±0.15
		Non-Replaced	-0.32±0.17	-0.36±0.19	-0.40±0.19	-0.40±0.20
	Healthy	Limb 1	-0.25±0.13	-0.28±0.14	-0.30±0.15	-0.33±0.15
		Limb 2	-0.27±0.18	-0.31±0.18	-0.32±0.20	-0.36±0.18
Peak knee internal rotation moment *$^{\# \beta \gamma \delta \varepsilon \zeta}$	TKR	Replaced	0.09±0.05	0.10±0.05	0.12±0.05	0.17±0.06
		Non-Replaced	0.12±0.05	0.13±0.06	0.17±0.07	0.21±0.08
	Healthy	Limb 1	0.1±0.07	0.11±0.07	0.15±0.07	0.18±0.08
		Limb 2	0.13±0.05	0.14±0.05	0.17±0.06	0.20±0.10

Positive moment values indicate knee extension, adduction and internal rotation moments. #: Significant limb main effect; *: Significant decline slope main effect, $^{\alpha}$: significantly different between 0° and 5°; $^{\beta}$: significantly different between 0° and 10°; $^{\gamma}$: significantly different between 0° and 15°; $^{\delta}$: significantly different between 5° and 10°; $^{\varepsilon}$: significantly different between 5° and 15°; $^{\zeta}$: significantly different between 10° and 15°; ^{X}: significant limb x group interaction Y: significant slope x group interaction ^: significant limb x slope x group interaction, ^{a}: significantly different from 5°, ^{b}: significantly different from 10°, ^{c}: significantly different from 15°. $^{\$}$: significantly different from replaced limb; $^{\&}$: significantly different from Healthy controls
VGRF: vertical ground reaction force KEM: knee extension moment KAbM: Knee abduction moment

Table 10 Mean root mean square (RMS) of normalized EMG (mean±stdv).

			0	5	10	15
Semitendinosus * $^{\alpha\,\varepsilon}$	TKR	Replaced	0.23±0.12	0.20±0.10	0.22±0.11	0.25±0.12
		Non-replaced	0.23±0.11	0.20±0.09	0.24±0.11	0.28±0.13
	Healthy	Limb 1	0.34±0.16	0.27±0.08	0.25±0.06	0.27±0.08
		Limb 2	0.25±0.10	0.22±0.08	0.23±0.08	0.26±0.09
Medial Gastrocnemius *$^{@\,\alpha\,\beta}$	TKR	Replaced	0.20±0.09	0.16±0.08	0.15±0.07	0.15±0.08
		Non-replaced	0.17±0.09	0.13±0.07	0.15±0.07	0.16±0.08
	Healthy	Limb 1	0.21±0.05	0.18±0.08	0.19±0.08	0.21±0.12
		Limb 2	0.24±0.08	0.20±0.06	0.20±0.07	0.21±0.07
Vastus Medialis *$^{X\,\alpha\,\beta\,\gamma\,\delta\,\varepsilon\,\zeta}$	TKR	Replaced	0.18±0.09	0.21±0.09	0.28±0.10	0.41±0.17
		Non-replaced	0.22±0.12	0.27±0.15	0.36±0.19	0.46±0.21
	Healthy	Limb1	0.27±0.08	0.30±0.08	0.37±0.10	0.43±0.14
		Limb2	0.23±0.06	0.26±0.07	0.32±0.12	0.37±0.14

*: Significant slope main effect $^{@}$: Significant Group main effect ^{X}: significant limb x group interaction

$^{\alpha}$: significantly different between 0° and 5°; $^{\beta}$: significantly different between 0° and 10°; $^{\gamma}$: significantly different between 0° and 15°; $^{\delta}$: significantly different between 5° and 10°; $^{\varepsilon}$: significantly different between 5° and 15°; $^{\zeta}$: significantly different between 10° and 15°;

CHAPTER VI

KNEE BIOMECHANICS OF OLDER ADULTS WITH DIFFERENT TYPES OF TOTAL KNEE REPLACEMENT DURING UPHILL AND DOWNHILL WALKING

Abstract

The purpose of this study was to compare knee biomechanics of patients with bi-cruciate stabilized (BCS), cruciate retaining (CR), posterior stabilized (PS), total knee replacement (TKR) implants and healthy controls during walking uphill and downhill on a 10° ramp. Five BCS, 10 CR, 10 PS TKR patients and 10 healthy controls performed five walking trials on 10° instrumented ramp. A 2 × 4 (limb × group) ANOVA was used to examine selected biomechanics variables. During uphill walking, peak KEMs were lower in BCS patients than healthy controls, and were lower in replaced limbs than their non-replaced limbs. Peak loading-response KAbMs were mostly similar between the replaced limbs of three TKR groups and healthy controls in both uphill and downhill walking. Moreover, he replaced limbs had lower peak loading-response and push-off KEMs than non-replaced limbs in downhill walking. Additionally, peak loading-response KAbMs were also greater in non-replaced limbs of BCS ans PS patients compared to that in their replaced limbs.

Keywords: total knee arthroplasty, posterior cruciate retaining prosthesis, posterior stabilized prosthesis, bi-cruciate stabilized prosthesis

Introduction

One of the controversies in total knee replacement (TKR) surgery is whether to retain or replicate the posterior cruciate ligament (PCL). If the PCL is healthy enough to maintain knee stability from extension to flexion, the cruciate-retaining (CR) knee implant is typically used (116). Posterior-stabilized (PS) prosthesis is one of most commonly used types of implants in TKR surgery when the PCL is removed, using a cam-post concept aiming to replicate the functions of the PCL. A recently developed TKR design, bi-cruciate stabilized implant (BCS), intends to reproduce normal knee functions by implementing a tibial post and two femoral cams, which substitutes for both anterior cruciate ligament (ACL) and PCL. The addition of the anterior femoral cam aims to prevent excessive posterior movement of femur on tibia.

Only a few studies have compared biomechanical parameters between the patients with different types of TKR implants during level walking (49, 111) and no differences were found between the PS and CR implants in major knee biomechanical parameters. A previous study (15) has reported there were no differences in knee kinematics and kinetics during stair ambulation between PS and CR implants. Catani et al. (17) performed gait analysis for 16 patients who received a unilateral BCS TKR. They reported that changing patterns of knee angle and moment in the sagittal plane were symmetrical between the replaced and non-replaced limb in level walking. However, they only analyzed the curve patterns of knee kinematics and kinetics in sagittal plane and did not provide detailed discrete peak values regarding knee biomechanical variables at critical gait events.

Both uphill and downhill walking require different gait adaptions compared to level walking (32, 56, 58, 73, 94, 110). Peak knee extension moment (KEM) increased significantly as the incline angle increased in both replaced and non-replaced limb of TKR patients during uphill walking (Chapter Four). The peak KEM and the knee flexion ROM increased across all slope comparisons between 0° and 15° in TKR replaced and non-replaced limbs during downhill walking (Chapter Five). The replaced limbs of TKR patients also had lower KEM than their non-replaced limb and matched limb of healthy controls in both uphill (Chapter Four) and downhill (Chapter Five) walking. In addition, the peak internal knee abduction moments (KAbM) were similar between replaced, non-replaced limb and matched limb of healthy controls in both uphill and downhill walking.

Walking on inclined (and decline) surfaces is an inevitable part of daily living and it has been integrated into rehabilitation protocols after TKR surgery (75). No studies have explored the effects of different types of TKR implants on gait dynamics during uphill and downhill walking. The purpose of this study was to compare knee biomechanics of patients with three TKR implants (PS, CR and BCS) to healthy controls during walking up and down on a 10° ramp. We hypothesized that TKR patients, no matter what type of implants they have, would have lower peak KEM and similar peak KAbM in replaced limb compared to their non-replaced limbs and the limbs of healthy controls during both uphill and downhill walking.

Methods

Participants

Five TKR patients with BCS (Journey II, Smith and Nephew, Memphis, TN), 10 patients with CR (Journey II, Smith and Nephew, Memphis, TN) and 10 patients with the PS (Persona, Zimmer, Warsaw, IN) were recruited from a local orthopedic clinic (Table 1). The inclusion criteria for TKR patients were having a unilateral total knee replacement (conducted by a single surgeon) between 6 months and 60 months and between the ages of 50 and 75 years. Potential participants were excluded if they had any additional lower extremity joint replacements, any additional diagnosed OA of the hip or ankle, more than 75% radiographic joint space narrowing and chronic pain at the contralateral knee of the TKR side, BMI greater than 38 kg/m^2, or neurological diseases. Ten older adults without any major lower extremity pathology participated in the study as healthy controls.

Instrumentation

A twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) were used to acquire three-dimensional (3D) kinematics of the trunk, pelvis, thigh, shank, and feet of the participants. Participants were asked to wear tight fitting workout clothing and a pair of standardized laboratory running shoes (Noveto, Adidas, USA) during the experiment. Reflective anatomical markers were placed bilaterally on the 2nd toe, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and acromion processes. A cluster of four reflective tracking markers on a semi-rigid thermoplastic shell was placed on the lateral aspect of shanks, thighs, pelvis and posterior trunk. Four discrete tracking markers were place on the lateral and posterior heel counter of the shoe.

A customized instrumented ramp system was used in the study to measure the ground reaction forces (GRF) and the moments of forces during ramp walking (Figure 7). The ramp consists of a walkway that is 1 m wide and 3 m long and with two separate walking surfaces/structures bolted on to two force platforms (BP600600 and OR-6-7, 1200Hz, American Mechanical Technology Inc., Watertown, MA, USA), and ends with a platform. The inclined angle of ramp surface was set up at 10°. Gait speeds were monitored by two sets of photocells (63501 IR, Lafayette Instrument Inc., IN, USA) and two electronic timers (54035A, Lafayette Instrument Inc., IN, USA). The photocells were placed 3 meters apart for level walking, and 1.5 meters apart at shoulder height for ramp walking.

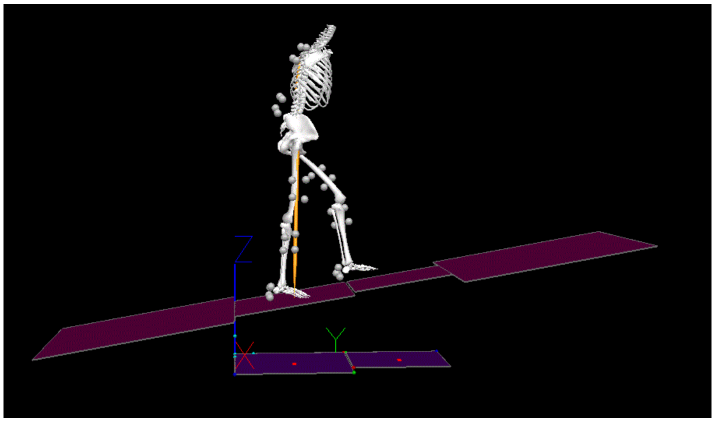

Figure 7 The setup of 10° incline ramp.

Experimental Procedures

TKR patients were asked to complete the 2011 Knee Society Scoring System (KSS) (99) and Knee injury and Osteoarthritis Outcome Score (KOOS) (93). KSS is a questionnaire aimed to assess patient satisfaction, expectations and functional abilities following TKR. KOOS is a self-reported questionnaire consisted of five subscales: knee related pain, other symptoms, function in daily living, function in sport and recreation, and knee related quality of life. Both healthy and TKR patients completed an information sheet which collects demographic and injury history information, and the physical activity readiness survey (PAR-Q). Following completion of the surveys, participants performed 3 minutes of walking on a treadmill at a self-selected speed as warm-up.

Participants were then fitted with markers as previously mentioned. All participants were asked to walk up and down on the 10° ramp (Figure 7). The testing order right and left limbs was randomized. Then participants were asked to practice uphill and downhill walking trials at a self-selected speed. Once participants were comfortable on ramp walking during the practice trials (about three trials each), the participants were asked to perform uphill and downhill walking at their self-selected speed range (mean ± 5%) obtained during the practice trials for each walking condition. Participants was asked to repeat a trial if they did not make full contact within the force platform with the targeted foot, and were not able to reach the pre-determined speed. A handrail was provided for balance purposes if needed, but participants were not encouraged to use it. A numerical visual analog pain scale (VAS) was used to assess pain in both knees for healthy and TKR patients prior to the warm-up, and at the end of each test condition.

Data Analyses

Visual3D biomechanical analysis software suite (version 2.6, C-Motion, Inc., Germantown, MD, USA) was used to compute the 3D kinematic and kinetic variables. An X-y-z Cardan rotational sequence was used in the 3D angular kinematics computations and a right-hand rule was used to determine the conventions of angular kinematic and kinetic variables. Positive values indicate knee extension ROM, knee adduction ROM and knee internal rotation ROM. For kinetic variables, positive values indicate internally applied knee extension, adduction, and internal rotation moments. Kinematic and GRF data were smoothed at cutoff frequency of 8 Hz using a fourth-order zero-lag Butterworth low-pass filter. Raw GRF were filtered alone using a fourth-order low-pass Butterworth filter with a cut-off frequency of 50 Hz for GRF data. Peak GRFs, peak angles, ROM, and peak moments were determined and organized for statistical analysis using customized programs (VB_V3D and VB_Table, MS Visual BASIC, Microsoft, Redmond, WA, USA). The GRFs were normalized to the participant's body weight (BW) and joint moments were normalized to the participant's body mass (Nm/kg).

Statistical Analyses

A one-way analysis of variance (ANOVA) was used to identify differences in demographic and survey data between TKR patients with three different implants and healthy controls (24.0, IBM SPSS, Chicago, IL). A 2 × 4 (limb: replaced and non-replaced limb × group:

BCS, CR, PS and healthy) ANOVA was used to examine the difference in VAS, knee extension, flexion and abduction ROM and peak vertical GRFs, KEMs and KAbMs during uphill and downhill walking respectively. The left and right limb of healthy controls were randomly selected to match with TKR replaced and non-replaced limbs, respectively. An *a priori* alpha level was set to 0.05. When ANOVA showed significant interaction or main effect, least significant difference (LSD) post-hoc comparisons were used to detect differences between limb and groups.

Results

The differences in age, height, mass and/or post-surgery time between different groups of TKR patients and healthy controls were not significant (Table 11). Healthy controls showed greater BMI than BCS ($p=0.012$) and PS ($p = 0.029$) patients. Sport/Recreation sub-scale of KOOS was significantly greater in healthy controls than the three groups of TKR patients ($p<0.001$ for all comparisons). TKR patients showed significantly higher VAS score than healthy controls in both uphill and downhill walking (Table 12).

Knee extension ROM was greater in healthy controls compared to three TKR groups in uphill walking ($p<0.041$ for all comparisons, Table 13). A significant limb effect was detected in peak loading-response VGRF in uphill walking ($p=0.028$, Table 14), however, post-hoc comparisons did not show significant difference between replaced and non-replaced limbs. Peak KEM was significantly greater in healthy controls compared to BCS ($p=0.005$). The non-replaced limbs showed greater peak KEM than replaced limbs (0=0.001).

Both peak loading-response ($p=0.002$) and push-off VGRF ($p=0.005$) was greater in non-replaced limbs compared to their replaced limb in downhill walking (Table 15). Both peak loading-response ($p=0.006$) and push-off ($p=0.015$) KEMs were greater in non-replaced limbs than replaced limbs. A significant limb × group was found in peak loading-response KAbM (P=0.041). Peak loading-response KAbMs were only greater for BCS (p=0.018) and PS (p=0.001) non-replaced limbs compared to their respective replaced limbs. In addition, push-off KAbMs were greater in non-replaced limbs compared to replaced limbs (p=0.002).

Discussion

The purpose of this study was to compare knee biomechanics of patients with three TKR implants (PS, CR and BCS) to healthy controls during walking up and down on a 10° ramp. We hypothesized that TKR patients, no matter what type of implants they have, would have lower peak KEM and similar peak KAbM in their replaced limbs compared to non-replaced limbs and the limbs of healthy controls during both uphill and downhill walking. The findings of this study partially supported the hypothesis.

BCS patients showed 63.5 % lower peak KEM than healthy controls in uphill walking, respectively. BCS, CR and PS patients showed 52%, 38.7% and 33.1% lower knee extension ROM than healthy controls, respectively. A previous study (46) has reported that the peak knee flexion angles during the stance phase of level walking was 45% and 20% lower in PS and CR patient compared to healthy controls respectively. Saari et al. (95) also reported that PS patients extended their replaced knee less than healthy controls, however, no significant differences were found in peak KEM between PS patient and healthy controls in level walking. Our results showed no differences in walking speeds and VGRFs between TKR patients and healthy controls, therefore the findings in knee sagittal plane kinetics and kinematics may indicate knee extensor muscle strength deficits of BCS patients compared to healthy controls. They also showed that the patients whose TKR implants adopted the two cam-post mechanism had altered sagittal plane knee kinematics and kinetics compared to their healthy peers in uphill walking approximately two years after the surgery.

Peak loading-response KAbMs were similar between three TKR groups and healthy controls in both uphill and downhill walking, which supports our hypothesis about KAbM. In addition, no differences were detected in knee abduction ROM between the three groups of TKR patients and healthy controls in both uphill and downhill walking. The KAbM plays an important role in prediction of medial compartment knee OA progression and severity (7). All three types of TKR implant successfully reduced the peak loading-response KAbM and subsequent frontal plane knee loading to the level of their healthy peers.

The replaced limbs were lower in peak KEM in uphill walking compared to non-replaced limbs. During downhill walking, the replaced limbs showed a significant lower in peak loading-response and push-off KEMs compared to replaced limb. The peak loading-response and push-off VGRF was greater in non-replaced limb compared to replaced limb. The replaced limb also showed lower peak push-off KEM compared to non-replaced in downhill walking. These results indicate that TKR patients may have shift the load to the non-replaced limb in order to compensate for knee extensor muscles strength deficits and/or residual pain in their replaced limb. Asymmetric knee loading may accelerate development of knee OA in their non-replaced limb. Rehabilitation strategies should focus on knee extensor muscle of replaced limb even though it has been two years after surgery.

The differences in peak loading-response KAbM between replaced and non-replaced limbs in the three groups of TKR patients were small and non-significant in uphill walking. However, the peak loading-response and push-off KAbMs of non-replaced limbs of PS patients were 24.4% and 22.2% greater than their replaced limbs in downhill walking, respectively. Peak loading-response KAbM was also 35.8% greater in non-replaced limb of BCS patients compared to that in their replaced limb. Greater peak loading-response KAbM may subsequently expedite knee OA progression in the non-replaced limbs of BCS and PS patients. They may have increased medial compartment loading and therefore increased risks of developing contralateral knee OA in the future. The patients with BCS and PS implants using the cam-post mechanism had greater peak loading-response KAbMs in downhill walking in non-replaced limbs than their replaced limbs. Future studies should investigate rehabilitation strategies to improve the symmetrical knee loading of BCS and PS patients, therefore postponing or avoiding another TKR surgery.

Certain limitations in this study should be noted. The sample size of BCS patients in this study is small due to the difficulties in recruiting qualified patients. Therefore, the significant results with this group of TKR patients may be considered as minimum differences. Due to the small sample size of BCS group, we did not perform Bonferronni adjustments in the post-hoc comparisons when a significant main effects or interactions were present. Caution should be taken when comparint other BCS gait analyses to this study due to the small sample size. However, a strength of this study is that all three groups of patients had their TKR surgeries performed by the same surgeon. No studies have compared BCS, CR and PS TKR implants on gait dynamics during uphill and downhill walking. This study provides novel data in knee biomechanics for uphill and downhill walking in TKR population.

Conclusion

In summary, peak KEM was lower in BCS patients than healthy controls in uphill walking and it was lower in replaced limbs than non-replaced limbs. Peak loading-response KAbMs were mostly similar between three TKR groups and healthy controls in both uphill and downhill walking. Moreover, the replaced limbs had lower peak loading-response and push-off KEMs than non-replaced limbs in downhill walking. Additionally, peak loading-response KAbM was also greater in non-replaced limbs of BCS and PS patients compared to that in their replaced limb. The patients with BCS and PS implants using the cam-post mechanism had greater peak loading-response KAbMs in non-replaced limbs than their replaced limbs during downhill walking. They may have increased risks of developing contralateral knee OA in future.

Chapter VI Appendix: Tables

Table 11 Descriptive statistics and survey data (mean ± stdv).

	Healthy	BCS	CR	PS	P_value
Number of patients	10	5	10	10	
Age (years)	69.1±4.6	68.4±6.8	67.9±5.3	69.9±3.7	0.824
Height (cm)	174.4±12.0	168.7±11.6	172.1±10.8	169.1±10.8	0.688
Mass (kg)	75.0±23.0	86.2±16.7	82.5±13.2	82.4±18.4	0.667
BMI (kg/m^2)	24.1±4.4 [ac]	30.4±6.2	27.8±3.2	28.5±4.1	**0.044**
Post-surgery Time (Months)	-	23.8±9.8	20.8±11.2	22.5±13.9	0.895
KOOS					
Symptom	92.5±13.1	79.3±12.2	77.1±23.9	80.0±18.8	0.265
Pain	96.1±4.0	83.3±16.1	81.9±19.8	82.8±17.1	0.157
Activity of daily life	98.7±1.8	85.3±11.0	85.3±19.6	84.9±18.4	0.146
Sport/Recreation	87.5±14.2[abc]	52.0±17.5	44.5±26.2	54.5±23.0	**0.001**
Quality of life	90.6±10.3	71.3±27.5	68.8±23.6	75.6±23.8	0.154
KSS					
Symptoms	-	6.0±1.0	6.4±3.7	5.7±2.8	0.873
Patient Satisfaction	-	34.4±5.9	30.6±9.7	33.2±8.1	0.669
Patient Expectation	-	7.8±1.6	9.9±3.7	11.7±7.5	0.154
Functional Activities	-	80.8±15.8	74.7±19.8	77.6±12.2	0.787
Walking and Standing	-	28.2±2.7	22.6±8.0	24.9±5.1	0.270
Standard Activates	-	23.8±5.1	24.7±5.6	22.7±5.1	0.703
Advanced Activities	-	16.2±6.7	14.8±5.1	17.6±4.2	0.484
Discretionary Knee Activities	-	12.6±1.9	12.6±2.7	12.4±2.5	0.981

[a]: significantly different from BCS°, [b]: significantly different from CR°, [c]: significantly different from PS°.

-: no comparable values

KOOS: Knee Injury and Osteoarthritis Outcome Score, KSS: Knee Society Scoring System

Table 12 Walking speed and VAS data (mean ± stdv).

			Healthy	BCS	CR	PS
Walking Speed (m/s)	10° uphill		1.02±0.17	1.01±0.21	0.92±0.12	1.02±0.17
	10° downhill		0.99±0.22	0.94±0.21	0.80±0.11	0.88±0.17
VAS(mm)	10° uphill*	Replaced limb	0.0±0.0	6.0±8.9	9.0±17.3	5.0±7.5
		Non-replaced limb	0.0±0.0	6.0±8.9	7.0±9.5	5.0±9.7
	10° downhill*	Replaced limb	0.0±0.0	6.0±8.9	9.0±17.3	5.0±7.1
		Non-replaced limb	0.0±0.0	6.0±8.9	7.0±9.5	5.0±9.7

*: Significant group main effect
VAS: visual analogue pain Scale

Table 13 Mean selected knee kinematic variables (°) during 10° uphill and downhill walking (mean ± stdv).

Condition	Variables	Limb	Healthy	BCS	CR	PS
10° uphill walking	Knee extension ROM* abc	Replaced limb	28.4±5.4	13.6±9.7	17.4±6.4	19.0±8.3
		Non-replaced limb	26.5±6.7	14.2±8.1	21.2±7.0	21.3±8.3
	Knee flexion ROM	Replaced limb	-38.2±6.1	-31.6±4.6	-29.6±4.1	-32.3±4.2
		Non-replaced limb	-37.0±5.5	-32.1±7.4	-34.2±5.8	-33.7±5.6
	Knee Abduction ROM	Replaced limb	7.4±2.6	4.2±2.4	5.9±4.7	4.8±2.3
		Non-replaced limb	7.1±4.1	6.3±2.7	5.7±3.2	5.0±2.4
10° downhill walking	Knee flexion ROM	Replaced limb	-62.8±7.5	-63.5±9.2	-56.1±4.6	-57.6±6.5
		Non-replaced limb	-62.9±6.9	-61.2±4.5	-59.2±6.2	-59.6±4.8
	Knee Abduction ROM	Replaced limb	4.2±1.9	6.1±1.9	6.0±2.9	5.2±3.8
		Non-replaced limb	4.6±1.3	6.8±3.3	5.3±2.9	4.6±1.3

*: Significant group main effect
[a]: significantly different between healthy controls and BCS patients, [b]: significantly different between healthy controls and CR patients, [c]: significantly different between healthy controls and PS patients.
ROM: range of motion

Table 14 Mean VGRF (BW) and selected peak knee moments (Nm/kg) during 10° uphill walking (mean ± stdv).

Variables	Limb	Healthy	BCS	CR	PS
Peak loading-response VGRF[#]	Replaced limb	1.04±0.06	0.93±0.02	1.00±0.06	0.98±0.11
	Non-replaced limb	1.04±0.06	0.99±0.05	1.01±0.05	1.01±0.12
Peak push-off VGRF	Replaced limb	1.09±0.07	1.02±0.05	1.06±0.06	1.02±0.09
	Non-replaced limb	1.08±0.08	0.99±0.05	1.07±0.06	1.05±0.12
Peak KEM[#* a]	Replaced limb	0.67±0.39	0.18±0.31	0.49±0.25	0.39±0.23
	Non-replaced limb	0.76±0.30	0.35±0.33	0.58±0.28	0.54±0.34
Peak KFM	Replaced limb	-0.53±0.14	-0.38±0.14	-0.34±0.17	-0.39±0.14
	Non-replaced limb	-0.43±0.23	-0.46±0.05	-0.44±0.21	-0.48±0.20
Peak loading-response KAbM	Replaced limb	-0.39±0.11	-0.33±0.04	-0.34±0.10	-0.30±0.12
	Non-replaced limb	-0.38±0.18	-0.42±0.13	-0.32±0.22	-0.41±0.16
Peak push-off KAbM	Replaced limb	-0.19±0.16	-0.26±0.11	-0.21±0.12	-0.22±-0.11
	Non-replaced limb	-0.19±0.18	-0.31±0.16	-0.23±0.18	-0.29±0.12

*: Significant group main effect #: significant limb effect

[a]: significantly different between healthy controls and BCS patients

VGRF: vertical ground reaction force, KEM: Knee extension moment, KFM: knee flexion moment, KAbM: Knee Abduction moment

Table 15 Mean VGRF (BW) and selected peak knee moments (Nm/kg) during 10° downhill walking (mean ± stdv)

Variables	Limb	Healthy	BCS	CR	PS
Peak loading-response VGRF#	Replaced limb	1.19±0.09	1.15±0.07	1.13±0.11	1.18±0.19
	Non-replaced limb	1.22±0.06	1.23±0.10	1.17±0.09	1.21±0.21
Peak push-off VGRF#	Replaced limb	0.92±0.08	0.91±0.06	0.97±0.04	0.93±0.09
	Non-replaced limb	0.93±0.06	0.97±0.08	0.98±0.05	0.97±0.09
Peak loading-response KEM#	Replaced limb	0.92±0.07	0.91±0.06	0.97±0.04	0.94±0.09
	Non-replaced limb	0.93±0.06	0.97±0.08	0.98±0.05	0.97±0.09
Peak push-off KEM#	Replaced limb	0.73±0.18	0.70±0.20	0.74±0.28	0.61±0.18
	Non-replaced limb	0.74±0.13	0.77±0.16	0.91±0.34	0.71±0.19
Peak loading-response KAbM^#	Replaced limb	-0.45±0.12	-0.34±0.12	-0.34±0.19	-0.37±0.15
	Non-replaced limb	-0.43±0.20	-0.53±0.15$	-0.33±0.23	-0.49±0.18$
Peak push-off KAbM#	Replaced limb	-0.30±0.15	-0.28±0.14	-0.35±0.15	-0.35±-0.12
	Non-replaced limb	-0.32±0.20	-0.48±0.11	-0.32±0.21	-0.45±0.15

#: significant limb effect, ^ significant limb x group effect

$: significantly different from replaced limb

VGRF: vertical ground reaction force, KEM: knee extension moment, KAbM: knee abduction moment

CHAPTER VII

CONCLUSION

The purpose of this dissertation was to examine the effects of different types of TKR implants on gait dynamics during level, uphill and downhill walking. In study one, the analysis of uphill walking found TKR patients had lower peak KEM and smaller knee extension ROM than healthy controls in all uphill walking conditions. The replaced limbs showed lower peak KEM in 10° and 15° uphill walking than non-replaced limbs. The peak loading-response KAbM was greater in level walking compared to 10° and 15° uphill walking. In study two, the analysis of downhill walking showed that replaced limbs of TKR patients had lower peak loading-response and push-off KEM activity than non-replaced and matched limb of healthy controls in downhill walking. Greater peak KEM, quadriceps EMG activity were found in downhill walking compared to level walking. In study three, peak KEM was lower BCS patients than healthy controls and it was lower in replaced limbs than non-replaced limbs during the 10° uphill walking. Peak loading-response KAbMs were similar between three TKR groups and healthy controls in both uphill and downhill walking. Moreover, the replaced limbs had lower peak loading-response and push-off KEMs than non-replaced limbs in downhill walking. Additionally, peak loading-response KAbM was greater in non-replaced limbs of BCS and PS patients compared to that in their replaced limb.

This dissertation provides novel data in knee biomechanics for uphill and downhill walking in TKR population. The findings also suggest that uphill walking may have the potential to become a safe exercise for unilateral TKR patients, but it should be avoided walking on a 10° or steeper slope in rehabilitation exercises. Downhill walking may not be appropriate to be included in the early-stage rehabilitation exercise protocols for TKR patients, whereas it could be added to progressive rehabilitation scheme. The patients with BCS and PS implants using the cam-post mechanism had greater peak loading-response KAbMs in downhill walking in non-replaced limbs than their replaced limbs. They may have increased risks of developing contralateral knee OA in the future. Therefore, future studies should investigate rehabilitation strategies to improve the symmetrical knee loading of BCS and PS patients, therefore postponing or avoiding another TKR surgery.

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APPENDICES

Appendix A: Knee injury and Osteoarthritis Outcome Score (KOOS)

KOOS KNEE SURVEY

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

Name: ____

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

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

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

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

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

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

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

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

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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Pain

P1. How often do you experience knee pain?

Never	Monthly	Weekly	Daily	Always
☐	☐	☐	☐	☐

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

P2. Twisting/pivoting on your knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P3. Straightening knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P4. Bending knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, daily living

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

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A4. Standing

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A14. Sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

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

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2. Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4. Twisting/pivoting on your injured knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Quality of Life

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

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

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

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

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

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

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

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

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

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Appendix B: 2011 Knee Society Scoring System

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

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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)

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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) [ ]

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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 (-8 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)

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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)		

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Appendix C: Physical Activity Readiness Questionnaire

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	1.	**Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	2.	**Do you feel pain in your chest when you do physical activity?**
☐	☐	3.	**In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	4.	**Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	5.	**Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	6.	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	7.	**Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ______________________________

SIGNATURE ______________________________ DATE ______________________________

SIGNATURE OF PARENT ______________________________ WITNESS ______________________________
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

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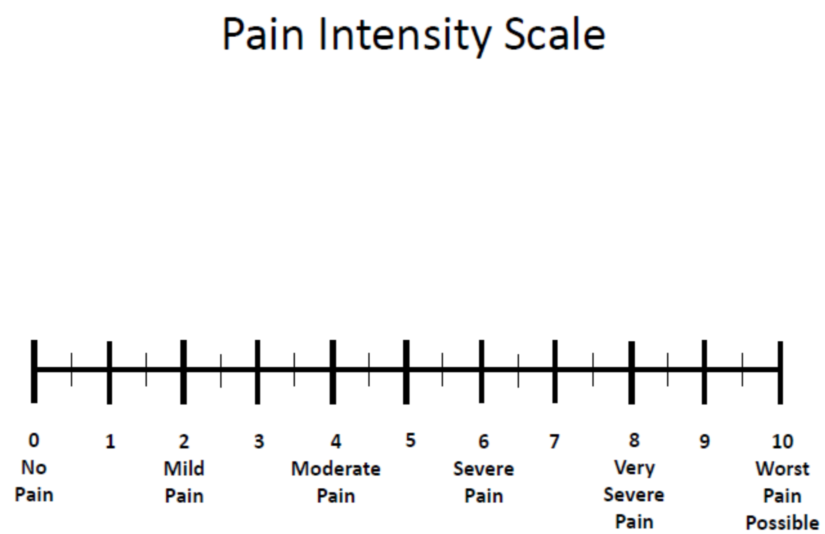
Appendix D: Visual Analogue Pain Scale

Visual Analogue Pain Scale



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Appendix E: Informed Consents

Informed consent form for TKR patients

Informed Consent Form

Investigator: Chen Wen, MS and Songning Zhang (Faculty Advisor), Ph.D.
Address: Biomechanics/Sports Medicine Lab
The University of Tennessee Knoxville
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: 865-974-2091

Introduction

You are invited to participate in a research study entitled, "Influence of Cruciate Retaining, Posterior Stabilizing and Bi-Cruciate Posterior Stabilizing Total Knee Arthroplasty Designs on Gait Mechanics During Incline and Level Walking". The primary purpose of this study is to learn the differences in how the knee works during incline and level walking in people with one of three total knee replacement (TKR) designs (cruciate retaining, posterior stabilizing and bi-cruciate posterior stabilizing) and those whose knees are healthy. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol

If you agree to participate in one laboratory testing session which will take about 2.5-3 hours to complete. Parking on campus will be free to you. You will complete the Knee Society Scoring system, Knee Injury And Osteoarthritis Outcome Score and the Western Ontario and McMaster Universities Osteoarthritis Index questionnaire, demographic and injury history information sheet, and Physical Activity Readiness Survey (PAR-Q). The information related to your type of implant will be used to classify TKR participants. The information collected during the phone screening will be used for the study.

Following completion of the surveys, you will change into appropriate testing attire and footwear. Height and weight will be recorded. You will then complete a 3-minute walking on the treadmill at a self-selected speed as warm-up. Both before and after the warm-up, you will be asked to rate your knee pain.

EMG electrodes will be placed on you and 2-3 sub-maximal strength testing and 2-3 maximal strength testing will be performed on each of the hip, knee and ankle muscles/groups on a dynamometer, a machine estimating muscle force, torque and power. The electrodes are used to record the electrical signals of the muscles and will not discharge any electrical shock to you. A minimum rest period of 2 minutes after testing of each muscle group will be provided.

After completion of the aforementioned tests, you will do a knee muscle strenth test on a strength testing machine. You will perform this test in a seated position and a waist strap and a thigh strap will be used to fasten to the seat of the strength testing machine. You will bend and extend the knee against a testing arm of the machine at a given speed. A rest period of one minute was provided between the tests.

__________ (Place initials here)

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After completion of strength tests, you will be asked to complete level and ramp walking test. Reflective markers will be placed on your body using double-sided tapes. You will then perform 3-5 successful tests for each of seven movement test conditions: level walking, uphill walking at 5°, 10° and 15° inclines and downhill at 5°, 10° and 15° inclines. Tests need to be completed at your own speed for both right and left sides. You will be asked to rate your knee pain after each of the level and ramp walking conditions. None of the instruments will interfere with your ability to do the test. The cameras used for motion capture will not record images of you. If you have any further questions, interests or concerns about any equipment to be used in this test, please feel free to ask the investigators or other research personnel.

Potential Risks

Risks for participating in the study are minimal so they are no greater than your daily activities. You can practice all of the exercises before the testing and hold on to the hand rail during the exercises. In order to prevent potential falls and trips, the ramp includes a handrail on the right side on the uphill (left side during downhill) for support and balance if needed. The top platform of the ramp is surrounded by a guardrail. You may experience minor skin irritation where the adhesive electrodes were placed. You man also experience muscle soreness and tightness which are common when participating in physical activities, especially when those activities a new to you.

If any injury should occur during the course of testing, standard first aid procedures will be administered if needed. At least one researcher with a basic knowledge of first aid procedures will be present. In the unlikely event a physical injury is suffered as a result of participation in this study, the University of Tennessee does not "automatically" reimburse subjects for medical claims or other compensation. If physical injury is suffered in the course of research, please contact Chen Wen (974-2091) or Dr. Songning Zhang (974-4716).

Breach of confidentiality is a potential risk, however, we have taken measures to prevent this.

Benefits

You may not benefit from your participation in this study directly. If you want, you can receive your individual study information to share with your personal physician in case it might be helpful to your future health care.

Identifying the gait abnormalities following total knee replacement (TKR) with different TKR designs may be also beneficial in improving future TKR designs, and surgical and rehabilitation methods in order to achieve higher levels of patient functions after their knee joint replacements.

Confidentiality

Only the principal investigator, faculty advisor, study personnel, will have access to the respective subject information and data. Data will be stored on hard drives of password protected computers in the Biomechanics/Sports Medicine Lab and will be backed up onto DVDs and/or portable hard drives, and erased from the hard drives after

_________ (Place initials here)

the completion of the study. All subject data will be coded numerically and referred to only by the code and not by subject name.

The results will be shared in the form of presentations, and/or publications. Subject information sheets, informed consent, and backup data DVDs and/or portable hard drives will be stored in a locked file cabinet in Biomechanics/Sports Medicine Laboratory. The information sheets including the consent forms and other forms containing subject's identity information will be destroyed six years after the completion of the study. If subject decide to withdraw from the study, their information sheet, consent form and data with the identity will be destroyed. The cameras used in the study do not capture images of the subjects.

Under federal privacy regulations, you have the right to determine who has access to your personal health information (called "protected health information" or PHI). PHI collected in this study may include weight, age, gender, side of implant, type of implant, date of knee replacement surgery, range of motion for knee joint, amount of instability, joint alignment of the implanted lower limb, pain levels before and after the knee replacement, overall satisfaction with the knee replacement, and questions regarding the activities after having knee replacement surgery, as well as basic demographic information. By signing this consent form, you are authorizing the research team at the University of Tennessee to access and use your PHI from Tennessee Orthopedic Clinics in this study. The Institutional Review Board (IRB) at the University of Tennessee may review your PHI as part of its responsibility to protect the rights and welfare of research subjects. Your PHI will not be used or disclosed to any other person or entity, except as required by law, or for authorized oversight of this research study by other regulatory agencies, or for other research for which the use and disclosure of your PHI has been approved by the IRB. You PHI will be used only for the research purposes described in this consent form. Your PHI will be used until the study is completed.

You may cancel this authorization in writing at any time by contacting the principal investigator listed on the first page of the consent form. If you cancel the authorization, continued use of your PHI is permitted if it was obtained before the cancellation and its use is necessary in completing the research. However, PHI collected after your cancellation may not be used in the study. If you refuse to provide this authorization, you will not be able to participate in the research study. If you cancel the authorization, then you will be withdrawn from the study. Finally, the federal regulations allow you to obtain access to your PHI collected or used in this study. However, in order to complete the research, your access to this PHI may be temporarily suspended while the research is in progress. When the study is completed, your right of access to this information will be reinstated.

Contact Information

If you have questions at any time about the study or the procedures or if you experience adverse effects as a result of participating in this study, you may contact the

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researcher, Chen Wen or Dr. Songning Zhang at 865-974-2091 or at the address shown above. If you have questions about your rights as a participant, contact the Office of Research Compliance Officer at (865) 974-7697.

Participation

Your participation in this study is voluntary; you may decline to participate without penalty or loss of benefits to which you are otherwise entitled. You may be withdrawn from the study by the investigator if it is determined that you do not meet the eligibility criteria or you answer yes to any of the questions on the PAR-Q.

If you decide to participate, you may withdraw from the study at anytime without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed.

CONSENT

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

Participant's name _____________ Participant's signature ______________ Date _____

Investigator's signature ______________________ Date _________ Subject # _____

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Informed Consent Forms for Healthy Controls

Informed Consent Form

Investigator: Chen Wen, MS and Songning Zhang (Faculty Advisor), Ph.D.
Address: Biomechanics/Sports Medicine Lab
The University of Tennessee Knoxville
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: 865-974-2091

Introduction

You are invited to participate in a research study entitled, "Influence of Cruciate Retaining, Posterior Stabilizing and Bi-Cruciate Posterior Stabilizing Total Knee Arthroplasty Designs on Gait Mechanics During Incline and Level Walking" because you are a healthy adult and are between 50 and 75 years old. The primary purpose of this study is to learn the differences in how the knee works during incline and level walking in people with one of three total knee replacement designs (cruciate retaining, posterior stabilizing and bi-cruciate posterior stabilizing) and those whose knees are healthy. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol

If you agree to participate in one laboratory testing session which will take about 2.5-3 hours to complete. Parking on campus will be free to you. You will complete Western Ontario and McMaster Universities Osteoarthritis Index questionnaire and demographic and injury history information sheet, and Physical Activity Readiness Survey (PAR-Q).

Following completion of the surveys, you will change into appropriate testing attire and footwear. Height and weight will be recorded. You will then complete a 3-minute walking on the treadmill at a self-selected speed as warm-up. Both before and after the warm-up, you will be asked to rate your knee pain.

EMG electrodes will be placed on you and 2-3 sub-maximal strength testing and 2-3 maximal strength testing will be performed on each of the hip, knee and ankle muscles/groups on a dynamometer, a machine estimating muscle force, torque and power. The electrodes are used to record the electrical signals of the muscles and will not discharge any electrical shock to you. A minimum rest period of 2 minutes after testing of each muscle group will be provided.

After completion of the aforementioned tests, you will do a knee muscle strength test on a strength testing machine. You will perform this test in a seated position and a waist strap and a thigh strap will be used to fasten to the seat of the strength testing machine. You will bend and extend the knee against a testing arm of the machine at a given speed. A rest period of one minute will be provided between the test sets.

After completion of strength tests, you will be asked to complete level and ramp walking tests. Reflective markers will be placed on your body using double-sided tapes. You will then perform 3-5 successful tests for each of seven movement test conditions:

_________ (Place initials here)

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level walking, uphill walking at 5°, 10° and 15° inclines and downhill at 5°, 10° and 15° inclines. Tests need to be completed at your own speed for both right and left sides. You will be asked to rate your knee pain after each of the level and ramp walking conditions. None of the instruments will interfere with your ability to do the test. The cameras used for motion capture will not record images of you. If you have any further questions, interests or concerns about any equipment to be used in this test, please feel free to ask the investigators or other research personnel.

Potential Risks

Risks for participating in the study are minimal, so they are no greater than your daily activities. You can practice all of the exercises before the testing and hold on to the hand rail during the exercise. In order to prevent potential falls and trips, the ramp includes a handrail on the right side on the uphill (left side during downhill) for support and balance if needed. The top platform of the ramp is surrounded by a guardrail. You may experience minor skin irritation where the adhesive electrodes are placed. You may experience muscle soreness, tightness, and fatigue which are common when participating in physical activity, especially when those activities a new to you.

If any injury should occur during the course of testing, standard first aid procedures will be administered if needed. In the unlikely event a physical injury is suffered as a result of participation in this study, the University of Tennessee does not "automatically" reimburse subjects for medical claims or other compensation. If physical injury is suffered in the course of research, please contact Chen Wen (974-2091) or Dr. Songning Zhang (974-4716).

Breach of confidentiality is a potential risk, however, we have taken measures to prevent this.

Benefits

You may not benefit from your participation in this study directly. If you want you can receive your individual study information to share with your personal physician in case it might be helpful to your future health care.

Identifying the gait abnormalities following total knee replacement (TKR) with different TKR designs may be also beneficial in improving future TKR designs, and surgical and rehabilitation methods in order to achieve higher levels of patient functions after their knee joint replacements.

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The results will be shared in the form of presentations, and/or publications. Subject information sheets, informed consent, and backup data DVDs and/or portable hard drives will be stored in a locked file cabinet in Biomechanics/Sports Medicine Laboratory. The information sheets including the consent forms and other forms containing subject's identity information will be destroyed six years after the completion of the study. If subject decide to withdraw from the study, their information sheet, consent form and data with the identity will be destroyed. The cameras used in the study do not capture images of the subjects.

Contact Information

If you have questions at any time about the study or the procedures or if you experience adverse effects as a result of participating in this study, you may contact the researcher, Chen Wen or Dr. Songning Zhang at 865-974-2091 or at the address shown above. If you have questions about your rights as a participant, contact the Office of Research Compliance Officer at (865) 974-7697.

Participation

Your participation in this study is voluntary; you may decline to participate without penalty or loss of benefits to which you are otherwise entitled. You may be withdrawn from the study by the investigator if it is determined that you do not meet the eligibility criteria or you answer yes to any of the questions on the PAR-Q.

If you decide to participate, you may withdraw from the study at anytime without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed.

CONSENT

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

Participant's name ____________ Participant's signature ______________ Date _____

Investigator's signature ____________________ Date _____________ Subject # _____

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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 Cruciate Retaining Bi-Cruciate Posterior Stabilized

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): _____/_______

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Appendix G: Recruitment Flyers

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 Sport Studies at UT are conducting research to study the affects of TKR on various activities of daily living.

Test and Control participants will be asked to attend one 2.5-3 hour testing sessions at the UT biomechanics laboratory.

If you'd like to participate, or would like more information, call **Chen Wen** at the UT Biomechanics/Sports Medicine Lab.

- **Office: (865) 974-2091**
- **E-mail: cwen@vols.utk.edu**

You may be able to participate if

- You are between the ages of 50-75
- A TKR in one knee (Test)
- No TKR in one knee(Control)
- No other joint replacements
- Able to walk uphill and downhill

Contact: Chen Wen
P: 865-974-2091
E: cwen@vols.utk.edu

Contact: Chen Wen
P: 865-974-2091
E: cwen@vols.utk.edu

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E: cwen@vols.utk.edu

Contact: Chen Wen
P: 865-974-2091
E: cwen@vols.utk.edu

Appendix H: Subject Demographics

Table 16 TKR patients' characteristics

Subject	Gender	Height (cm)	Weight (kg)	BMI (kg/m^2)	Age (years)	Replaced limb	Time from surgery (months)	Type of knee replacement implant
S1	Male	188	88.5	25.0	69	Right	22	BCS
S2	Female	162	68	25.9	74	Right	24	CR
S3	Male	175	72.6	23.7	68	Left	17	CR
S4	Male	175	81.6	26.6	62	Left	16	PS
S5	Male	170	104.3	36.1	72	Right	23	PS
S6	Female	170	99.8	34.5	70	Right	16	PS
S7	Female	160	69.4	27.1	67	Left	46	PS
S8	Male	190.5	106.6	29.4	73	Left	30	PS
S9	Female	167.6	92.3	32.8	62	Right	35	BCS
S10	Female	160	71.2	27.8	74	Left	7	PS
S11	Female	165.1	79.38	29.1	75	Right	30	CR
S12	Female	162.5	61.2	23.2	61	Right	33	BCS
S13	Male	190.4	89.34	24.6	65	Left	36	CR
S14	Female	154.9	69.4	28.9	71	Left	37	CR
S15	Female	160	59.87	23.4	67	Left	24	PS
S16	Male	180.3	110.6	34.0	62	Right	25	CR
S18	Male	167.64	107.01	38.1	75	Right	16	BCS
S19	Female	172.7	72.57	24.3	73	Right	8	CR
S20	Female	157.48	82.2	33.1	75	Right	13	BCS
S21	Female	162.5	65.2	24.7	72	Left	7	PS
S22	Male	177.8	91.74	29.0	65	Left	8	CR
S23	Female	160	65.77	25.7	73	Left	44	PS
S24	Male	180	93.22	28.8	67	Left	13	CR
S28	Female	162.6	81.2	30.7	59	Left	10	CR
S31	Male	182.9	99.93	29.9	69	Right	12	PS
Mean	-	170.2	83.32	28.7	68.8	-	22.1	-

Table 17 Healthy control participant characteristics

Subject	Gender	Height (cm)	Weight (kg)	BMI (kg/m^2)	Age (years)
S17	Female	172.7	76.5	25.6	72
S25	Male	190.5	117.66	32.4	66
S26	Female	160	61.2	23.9	63
S27	Male	190	102.1	28.3	62
S29	Female	172.8	68.19	22.8	73
S30	Male	167.6	66.5	23.7	69
S32	Male	187.9	93.6	26.5	71
S33	Male	168	54	19.2	75
S34	Female	157.5	43.3	17.5	67
S35	Female	177.8	66.22	20.9	73
Mean	-	174.4	74.9	24.09	69.1

Appendix I: Individual Results for Select Variables

Table 18 KOOS subscales for TKR patients.

Subject	Symptom	Pain	Activity of Daily Life	Sport/Recreation	Quality of Life
S1	60.7	66.7	80.9	30.0	31.3
S2	89.3	77.8	82.4	25.0	68.8
S3	78.6	83.3	100.0	40.0	68.8
S4	78.6	86.1	94.1	75.0	81.3
S5	96.4	97.2	98.5	50.0	93.8
S6	96.4	97.2	98.5	45.0	93.8
S7	60.7	75.0	67.6	15.0	56.3
S8	82.1	77.8	80.9	55.0	68.8
S9	82.1	80.6	80.9	40.0	87.5
S10	75.0	75.0	73.5	60.0	56.3
S11	35.7	38.9	50.0	0.0	25.0
S12	92.9	100.0	100.0	60.0	100.0
S13	96.4	100.0	100.0	95.0	93.8
S14	96.4	100.0	98.5	35.0	87.5
S15	39.3	41.7	44.1	25.0	18.8
S16	35.7	58.3	51.5	25.0	37.5
S18	85.7	100.0	92.6	75.0	81.3
S19	89.3	91.7	97.1	55.0	87.5
S20	75.0	69.4	72.1	55.0	56.3
S21	78.6	88.9	91.2	65.0	93.8
S22	92.9	100.0	100.0	65.0	93.8
S23	100.0	88.9	100.0	60.0	93.8
S24	92.9	86.1	94.1	60.0	68.8
S28	64.3	83.3	79.4	45.0	56.3
S31	92.9	100.0	100.0	95.0	100.0
Mean	78.7	82.6	85.1	50.0	72.0

Table 19 KOOS subscales for healthy control participants.

Subject	Symptom	Pain	Activity of Daily Life	Sport/Recreation	Quality of Life
S17	100.0	100.0	100.0	100.0	100.0
S25	82.1	83.3	86.8	65.0	81.3
S26	92.9	94.4	98.5	100.0	93.8
S27	92.9	91.7	98.5	85.0	75.0
S29	60.7	97.2	95.6	70.0	75.0
S30	100.0	100.0	100.0	100.0	100.0
S32	100.0	94.4	95.6	85.0	81.3
S33	100.0	100.0	100.0	100.0	100.0
S34	100.0	100.0	100.0	95.0	100.0
S35	78.6	94.4	98.5	80.0	87.5
Mean	90.7	95.6	97.4	88.0	89.4

Table 20 KSS subscales for TKR patients

Subject	Symptoms	Patients Satisfaction	Patients Expectation	Functional Activities	Walking and Standing	Standard Activities	Advanced Activities	Discretionary Knee Activity
S1	6	34	6	59	24	18	7	10
S2	4	20	12	69	24	24	9	12
S3	3	30	9	88	27	30	16	15
S4	4	34	15	85	27	25	21	12
S5	7	40	15	87	27	27	19	14
S6	5	38	14	89	30	27	17	15
S7	6	34	9	58	21	14	11	12
S8	1	28	9	74	21	21	20	12
S9	7	32	9	84	30	25	17	12
S10	7	24	9	63	15	20	18	10
S11	9	10	3	35	9	13	4	9
S12	5	40	9	92	30	29	19	14
S13	5	40	14	93	30	30	19	14
S14	5	34	9	82	21	27	19	15
S15	12	16	3	64	27	17	13	7
S16	16	26	6	48	10	18	13	7
S18	5	40	9	98	30	28	25	15
S19	6	40	9	86	27	27	18	14
S20	7	26	6	71	27	19	13	12
S21	5	38	13	78	21	26	19	12
S22	5	40	15	94	30	30	19	15
S23	5	40	15	90	30	20	25	15
S24	5	34	13	84	30	23	18	13
S28	6	32	9	68	18	25	13	12
S31	5	40	15	88	30	30	13	15
Mean	6.04	32.4	10.2	77.08	24.64	23.72	16.2	12.52

Table 21 Walking Speed (m/s)

Subject	Group	Level Walking	Uphill Walking			Downhill walking		
			5°	10°	15°	5°	10°	15°
S1	TKR	1.13	1.08	1.08	1.04	1.08	1.20	1.26
S2	TKR	1.03	1.08	1.04	0.86	1.01	0.88	0.88
S3	TKR	0.81	0.83	0.80	0.79	0.73	0.77	0.74
S4	TKR	0.93	0.86	0.87	0.92	0.95	0.72	0.80
S5	TKR	1.14	1.20	1.19	1.22	0.97	1.10	1.25
S6	TKR	0.92	0.94	0.96	0.98	0.86	0.90	1.06
S7	TKR	1.03	1.07	0.97	0.94	1.01	0.67	-
S8	TKR	1.29	1.20	1.30	1.11	1.08	1.00	1.02
S9	TKR	0.98	1.12	1.09	0.96	0.80	0.90	0.80
S10	TKR	0.90	1.03	0.89	0.90	1.03	0.77	0.95
S11	TKR	0.81	0.82	0.82	0.77	0.62	0.58	-
S12	TKR	1.21	1.20	1.30	1.31	1.06	1.07	1.07
S13	TKR	1.20	1.20	1.14	1.01	0.91	0.91	0.89
S14	TKR	1.17	0.96	1.04	1.06	1.03	0.93	1.03
S15	TKR	1.22	1.01	1.14	0.92	1.10	1.10	1.01
S16	TKR	1.04	0.85	0.86	0.86	0.71	0.69	0.65
S18	TKR	0.82	0.69	0.76	0.82	0.51	0.64	-
S19	TKR	1.09	0.90	0.87	0.86	0.83	0.79	0.75
S20	TKR	1.10	0.88	0.84	0.80	0.75	0.87	0.91
S21	TKR	1.23	1.32	1.08	0.99	1.22	0.98	0.92
S22	TKR	1.18	1.08	0.97	0.98	1.11	0.74	0.88
S23	TKR	0.89	0.92	0.72	0.79	0.86	0.65	0.86
S24	TKR	0.98	0.84	0.76	0.71	0.78	0.74	0.73
S28	TKR	1.04	1.03	0.94	0.88	0.84	0.92	0.90
S31	TKR	1.29	1.02	1.10	1.03	0.94	0.97	0.95
S17	Healthy	1.16	1.14	1.12	1.11	1.13	1.08	1.05
S25	Healthy	1.44	1.23	1.24	1.12	1.19	1.27	1.15
S26	Healthy	0.93	0.76	0.79	0.70	0.75	0.71	0.68
S27	Healthy	1.30	1.15	0.92	0.89	1.06	0.84	0.79
S29	Healthy	1.04	0.85	0.90	0.90	0.84	0.80	0.82
S30	Healthy	1.20	1.03	1.18	1.03	0.92	1.06	0.95
S32	Healthy	1.50	1.36	1.17	1.14	1.27	1.23	1.08
S33	Healthy	1.14	1.15	1.14	1.14	1.25	1.21	1.21
S34	Healthy	0.89	0.93	0.76	0.71	0.90	0.69	0.73
S35	Healthy	1.10	0.92	0.98	0.87	0.86	1.00	0.96
Mean	TKR	1.06	1.01	0.98	0.94	0.91	0.86	0.92
Mean	Healthy	1.17	1.05	1.02	0.96	1.02	0.99	0.94

Table 22 VAS (mm) during level and uphill walking for TKR patients

Subject	**Replaced limb**				**Non-replaced limb**			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	20	30	20	30	0	0	0	0
S2	20	20	10	20	20	10	10	10
S3	0	0	0	0	0	0	0	0
S4	10	10	10	10	10	10	10	10
S5	0	0	0	0	0	0	0	0
S6	0	0	0	0	0	0	0	0
S7	0	0	10	0	10	30	30	30
S8	0	0	0	10	0	0	0	0
S9	0	0	0	0	0	0	0	0
S10	0	0	10	0	0	0	10	0
S11	10	10	30	40	0	0	0	0
S12	0	0	0	0	0	0	0	0
S13	0	0	0	0	0	0	20	20
S14	0	0	0	0	20	20	20	20
S15	10	10	20	30	0	0	0	0
S16	20	30	50	60	0	0	0	0
S18	0	0	0	0	20	20	20	20
S19	0	0	0	0	20	20	20	20
S20	10	20	10	30	10	20	10	10
S21	0	0	0	0	0	0	0	0
S22	0	0	0	0	0	0	0	0
S23	0	0	0	0	0	0	0	0
S24	0	0	0	0	0	0	0	0
S28	0	0	0	10	0	0	0	10
S31	0	0	0	0	0	0	0	0
Mean	4	5.2	6.8	9.6	4.4	5.2	6	6

Table 23 VAS (mm) during level and uphill walking for healthy control participants.

Subject	**Limb 1**				**Limb 2**			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0	0	0	0	0	0	0	0
S25	0	0	0	0	0	0	0	0
S26	0	0	0	0	0	0	0	0
S27	0	0	0	0	0	0	0	0
S29	0	0	0	0	0	0	0	0
S30	0	0	0	0	0	0	0	0
S32	0	0	0	0	0	0	0	0
S33	0	0	0	0	0	0	0	0
S34	0	0	0	0	0	0	0	0
S35	0	0	0	0	0	0	0	0
Mean	0	0	0	0	0	0	0	0

Table 24 VAS (mm) during downhill walking for TKR patients

Subject	Replaced limb			Non-replaced limb		
	5°	**10°**	**15°**	**5°**	**10°**	**15°**
S1	30	20	20	0	0	0
S2	10	10	20	10	10	10
S3	0	0	0	0	0	0
S4	10	10	10	10	10	10
S5	0	0	0	0	0	0
S6	0	0	0	0	0	0
S7	0	10	-	30	30	-
S8	0	0	10	0	0	0
S9	0	0	0	0	0	0
S10	0	10	0	0	10	0
S11	10	30	-	0	0	-
S12	0	0	0	0	0	0
S13	0	0	0	0	20	20
S14	0	0	0	20	20	20
S15	10	20	50	0	0	0
S16	30	50	60	0	0	0
S18	0	0	-	20	20	-
S19	0	0	0	20	20	20
S20	20	10	30	20	10	10
S21	0	0	0	0	0	0
S22	0	0	0	0	0	0
S23	0	0	0	0	0	0
S24	0	0	0	0	0	0
S28	0	0	10	0	0	0
S31	0	0	0	0	0	0
Mean	4.8	6.8	9.5	5.2	6	4.1

Table 25 VAS (mm) during downhill walking for healthy control participants

Subject	Limb 1			Limb 2		
	5°	10°	15°	5°	10°	15°
S17	0	0	0	0	0	0
S25	0	0	0	0	0	0
S26	0	0	0	0	0	0
S27	0	0	0	0	0	0
S29	0	0	0	0	0	0
S30	0	0	0	0	0	0
S32	0	0	0	0	0	0
S33	0	0	0	0	0	0
S34	0	0	0	0	0	0
S35	0	0	0	0	0	0
Mean	0	0	0	0	0	0

Table 26 Peak loading-response vertical GRF (BW) during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.928±0.032	0.956±0.026	0.933±0.018	0.930±0.015	1.010±0.031	1.061±0.045	1.046±0.063	1.025±0.018
S2	1.072±0.038	1.126±0.052	1.084±0.036	1.019±0.016	1.025±0.008	1.146±0.080	1.068±0.047	1.016±0.018
S3	1.090±0.025	1.083±0.024	1.092±0.029	1.102±0.048	1.113±0.022	1.025±0.031	1.066±0.043	1.058±0.018
S4	1.043±0.023	0.999±0.032	0.993±0.036	1.000±0.021	1.055±0.019	1.002±0.016	1.006±0.017	1.030±0.033
S5	1.150±0.026	1.159±0.029	1.037±0.025	0.996±0.024	1.227±0.068	1.098±0.033	1.102±0.050	1.079±0.016
S6	1.032±0.021	1.006±0.034	1.014±0.055	1.000±0.020	1.068±0.025	1.018±0.024	1.044±0.020	1.063±0.047
S7	0.752±0.010	0.712±0.028	0.667±0.008	0.682±0.025	0.748±0.018	0.701±0.013	0.674±0.018	0.708±0.020
S8	1.062±0.032	1.030±0.025	1.021±0.025	0.990±0.031	1.181±0.069	1.169±0.029	1.119±0.041	1.062±0.022
S9	1.060±0.031	1.003±0.063	0.940±0.038	0.977±0.041	1.064±0.071	0.986±0.028	0.978±0.037	0.965±0.028
S10	1.043±0.026	1.037±0.017	1.008±0.032	1.020±0.038	1.030±0.041	1.013±0.049	1.011±0.016	1.097±0.040
S11	1.032±0.021	1.050±0.043	0.987±0.026	1.008±0.022	1.050±0.014	1.049±0.011	1.032±0.022	0.979±0.034
S12	0.940±0.030	0.953±0.050	0.916±0.036	0.807±0.020	1.022±0.017	0.980±0.038	1.039±0.049	0.949±0.027
S13	1.031±0.036	1.025±0.048	0.982±0.051	0.927±0.042	1.059±0.014	1.019±0.033	0.986±0.051	0.947±0.036
S14	1.119±0.045	1.085±0.042	1.030±0.019	1.076±0.025	1.115±0.015	1.012±0.027	0.980±0.029	1.028±0.037
S15	1.243±0.088	1.043±0.055	1.098±0.028	0.962±0.059	1.073±0.041	1.034±0.131	1.016±0.060	0.963±0.041
S16	1.086±0.061	0.976±0.047	0.967±0.020	1.012±0.041	1.027±0.021	0.951±0.015	0.994±0.055	1.001±0.047
S18	1.047±0.068	0.981±0.016	0.955±0.025	0.989±0.058	0.997±0.027	0.957±0.011	0.943±0.025	0.951±0.015
S19	1.072±0.019	1.037±0.021	1.040±0.031	1.002±0.045	1.033±0.025	1.017±0.017	1.034±0.032	1.006±0.013
S20	0.907±0.050	0.937±0.012	0.918±0.028	0.928±0.035	0.899±0.046	0.925±0.015	0.927±0.026	0.958±0.007
S21	0.989±0.014	1.015±0.017	1.025±0.034	0.966±0.009	1.025±0.024	1.036±0.022	1.042±0.013	1.015±0.039
S22	0.981±0.037	0.892±0.022	0.940±0.011	0.950±0.038	0.992±0.024	0.930±0.028	0.932±0.019	0.863±0.020
S23	0.983±0.015	1.001±0.024	0.974±0.020	0.950±0.015	1.020±0.009	0.996±0.017	0.995±0.030	1.029±0.018
S24	0.940±0.008	0.923±0.016	0.950±0.030	0.968±0.025	1.025±0.022	0.980±0.019	1.013±0.021	0.957±0.038
S28	1.000±0.019	0.971±0.015	0.937±0.012	0.933±0.029	0.987±0.035	0.918±0.021	0.952±0.006	0.953±0.025
S31	1.104±0.039	1.039±0.035	1.011±0.025	0.974±0.034	1.083±0.057	1.076±0.018	1.073±0.043	1.066±0.049
Mean	1.028±0.094	1.001±0.086	0.981±0.084	0.967±0.081	1.037±0.088	1.004±0.088	1.003±0.085	0.991±0.080

Table 27 Peak loading-response vertical GRF (BW) during level and uphill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	1.030±0.040	1.058±0.036	1.023±0.043	1.039±0.021	1.007±0.022	1.013±0.018	0.986±0.057	0.963±0.019
S25	1.132±0.039	1.126±0.030	1.111±0.059	1.117±0.031	1.089±0.031	1.073±0.041	1.063±0.023	1.049±0.036
S26	1.082±0.027	1.053±0.036	1.048±0.024	1.051±0.013	1.098±0.028	1.054±0.017	0.970±0.022	1.048±0.026
S27	1.112±0.006	1.070±0.055	1.078±0.043	1.089±0.034	1.145±0.020	1.114±0.043	1.116±0.028	1.095±0.032
S29	1.036±0.020	1.014±0.020	1.001±0.021	1.003±0.018	1.014±0.029	0.977±0.010	0.958±0.009	0.944±0.017
S30	1.113±0.033	1.047±0.014	0.993±0.020	0.976±0.020	1.103±0.014	1.078±0.016	1.047±0.030	1.031±0.027
S32	1.087±0.022	1.092±0.034	1.051±0.060	1.028±0.033	1.157±0.020	1.107±0.073	1.000±0.064	1.062±0.052
S33	1.172±0.029	1.106±0.062	1.108±0.033	1.137±0.025	1.230±0.041	1.116±0.032	1.149±0.051	1.219±0.039
S34	0.940±0.030	0.953±0.050	0.916±0.036	0.807±0.020	1.022±0.017	0.980±0.038	1.039±0.049	0.949±0.027
S35	1.033±0.025	1.017±0.017	1.034±0.032	1.006±0.013	1.072±0.019	1.037±0.021	1.040±0.031	1.002±0.045
Mean	1.074±0.066	1.054±0.050	1.036±0.058	1.025±0.092	1.094±0.071	1.055±0.052	1.037±0.062	1.036±0.082

Table 28 Peak push-off vertical GRF during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.801±0.014	1.016±0.008	1.011±0.013	1.016±0.023	0.821±0.015	0.990±0.034	0.997±0.014	1.059±0.009
S2	1.093±0.050	1.112±0.024	1.088±0.023	1.027±0.090	1.083±0.025	1.040±0.052	1.006±0.048	0.981±0.089
S3	1.098±0.019	1.128±0.025	1.141±0.032	1.178±0.043	1.083±0.020	1.008±0.008	1.110±0.050	1.129±0.024
S4	1.056±0.009	1.064±0.014	1.091±0.032	1.076±0.024	1.061±0.009	1.063±0.009	1.115±0.017	1.082±0.015
S5	1.015±0.024	1.005±0.027	1.040±0.012	0.993±0.042	1.005±0.008	0.995±0.012	0.989±0.037	0.967±0.043
S6	0.989±0.018	0.979±0.027	0.987±0.034	0.963±0.035	0.994±0.035	1.012±0.030	1.019±0.026	1.001±0.042
S7	0.779±0.008	0.804±0.022	0.782±0.010	0.735±0.023	0.792±0.014	0.785±0.015	0.770±0.012	0.783±0.099
S8	0.984±0.017	1.024±0.029	1.045±0.018	1.034±0.011	1.040±0.053	1.070±0.019	1.095±0.021	1.102±0.073
S9	1.080±0.014	1.097±0.016	1.101±0.041	1.035±0.034	1.069±0.040	1.079±0.026	1.066±0.030	1.038±0.059
S10	1.059±0.014	1.092±0.022	1.045±0.023	1.005±0.037	1.092±0.026	1.137±0.019	1.083±0.018	1.077±0.031
S11	1.032±0.018	1.042±0.020	1.019±0.028	0.968±0.039	0.988±0.022	1.030±0.026	1.082±0.043	1.059±0.024
S12	0.973±0.029	1.000±0.027	1.039±0.055	1.007±0.012	1.035±0.027	1.044±0.029	0.996±0.021	1.005±0.030
S13	1.032±0.018	1.078±0.054	1.131±0.035	1.097±0.073	1.072±0.020	1.123±0.038	1.156±0.039	1.143±0.036
S14	1.103±0.025	1.167±0.017	1.134±0.018	1.079±0.018	1.095±0.015	1.159±0.019	1.138±0.020	1.122±0.037
S15	1.010±0.034	1.057±0.020	1.049±0.065	1.035±0.028	0.993±0.028	1.100±0.041	1.123±0.025	1.011±0.063
S16	0.959±0.024	0.973±0.019	0.981±0.019	0.967±0.028	1.002±0.032	0.990±0.021	1.016±0.018	0.978±0.047
S18	0.965±0.005	0.968±0.020	0.981±0.035	0.963±0.054	0.986±0.021	0.946±0.014	0.960±0.006	0.999±0.026
S19	1.027±0.038	1.050±0.048	1.054±0.024	1.036±0.042	1.037±0.031	1.045±0.025	1.051±0.023	0.990±0.006
S20	0.994±0.011	0.997±0.006	0.974±0.017	0.937±0.019	0.998±0.025	1.003±0.013	0.949±0.012	0.983±0.024
S21	1.010±0.025	1.040±0.007	1.049±0.025	1.049±0.022	1.017±0.025	1.083±0.024	1.098±0.025	1.101±0.024
S22	0.899±0.022	0.968±0.012	1.016±0.026	1.079±0.042	1.023±0.021	1.027±0.035	1.076±0.012	1.123±0.026
S23	0.998±0.013	1.018±0.016	1.022±0.009	0.967±0.010	1.016±0.005	1.036±0.012	1.034±0.011	1.016±0.008
S24	0.990±0.015	1.019±0.019	1.001±0.022	1.058±0.040	0.981±0.013	0.987±0.014	0.986±0.022	1.006±0.017
S28	1.046±0.024	1.025±0.007	1.025±0.022	0.953±0.020	1.029±0.032	1.088±0.012	1.085±0.017	1.069±0.024
S31	1.049±0.036	1.067±0.028	1.093±0.035	1.126±0.057	1.100±0.033	1.114±0.039	1.200±0.027	1.215±0.024
Mean	1.002±0.080	1.032±0.070	1.036±0.072	1.015±0.083	1.016±0.074	1.038±0.075	1.048±0.086	1.042±0.083

Table 29 Peak push-off vertical GRF (BW) during level and uphill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	1.093±0.019	1.121±0.031	1.146±0.024	1.110±0.030	1.090±0.010	1.113±0.040	1.122±0.024	1.096±0.014
S25	1.042±0.024	1.063±0.027	1.029±0.071	1.110±0.063	0.982±0.020	1.025±0.025	0.975±0.029	1.019±0.015
S26	1.020±0.006	1.051±0.008	1.071±0.010	1.079±0.016	1.049±0.014	1.033±0.010	1.037±0.009	1.051±0.020
S27	1.032±0.019	1.024±0.021	1.059±0.041	1.089±0.042	1.055±0.014	1.051±0.026	1.078±0.024	1.083±0.013
S29	1.051±0.014	1.082±0.022	1.094±0.021	1.077±0.011	1.071±0.017	1.059±0.018	1.066±0.010	1.043±0.016
S30	1.104±0.031	1.084±0.023	1.135±0.029	1.114±0.039	1.051±0.029	1.061±0.036	1.197±0.028	1.164±0.033
S32	1.023±0.054	1.098±0.030	0.986±0.027	1.015±0.051	1.084±0.019	1.138±0.024	1.011±0.022	0.989±0.054
S33	1.129±0.043	1.134±0.037	1.244±0.039	1.216±0.038	1.127±0.031	1.137±0.017	1.234±0.017	1.376±0.074
S34	0.973±0.029	1.000±0.027	1.039±0.055	1.007±0.012	1.035±0.027	1.044±0.029	0.996±0.021	1.005±0.030
S35	1.037±0.031	1.045±0.025	1.051±0.023	0.990±0.006	1.027±0.038	1.050±0.048	1.054±0.024	1.036±0.042
Mean	1.050±0.046	1.070±0.042	1.085±0.073	1.081±0.066	1.057±0.039	1.071±0.042	1.077±0.085	1.086±0.114

Table 30 Knee extension ROM (°) during uphill walking for TKR patients

Subject	Replaced limb			Non-replaced limb		
	5°	10°	15°	5°	10°	15°
S1	2.145±1.897	18.751±1.128	31.660±0.673	-0.411±1.253	13.383±6.485	28.427±5.421
S2	7.573±3.301	18.257±4.376	25.977±4.367	3.436±10.725	12.030±5.664	19.175±9.274
S3	2.766±1.550	10.244±2.866	27.611±7.776	-2.510±4.490	9.304±6.350	33.566±2.768
S4	10.696±1.091	23.265±1.466	32.867±3.433	3.865±2.661	22.085±2.527	31.543±0.695
S5	2.703±3.453	9.666±2.671	24.713±2.133	-3.503±1.516	10.944±5.050	29.076±2.224
S6	1.946±1.718	21.548±3.356	33.561±2.523	-5.004±0.000	10.169±3.008	20.255±14.382
S7	1.935±2.742	9.537±2.161	19.157±2.433	1.176±0.758	14.113±2.081	26.257±1.903
S8	2.192±0.000	9.453±1.594	24.998±3.440	3.536±1.659	18.466±2.642	28.697±2.754
S9	-4.709±1.173	5.351±2.600	17.757±5.475	-3.542±0.000	4.557±2.169	15.481±2.188
S10	9.546±4.923	20.094±2.481	34.890±5.092	12.537±2.486	26.030±2.979	36.779±3.126
S11	4.835±2.633	17.806±0.937	27.582±2.929	-3.221±0.000	18.048±2.942	27.684±2.804
S12	0.577±0.796	4.132±0.799	20.441±2.560	-0.154±2.853	12.523±3.200	25.548±3.019
S13	14.355±3.823	30.423±2.902	42.473±2.567	17.218±1.713	30.786±2.487	41.299±2.761
S14	0.265±2.386	12.106±3.243	27.686±1.256	6.783±2.008	16.809±2.813	29.395±6.742
S15	5.678±1.769	22.865±2.894	28.825±2.994	5.985±2.593	26.953±1.802	28.429±5.101
S16	6.616±1.758	21.042±0.593	31.449±4.052	2.795±3.307	27.594±2.680	29.378±3.391
S18	-4.447±0.921	12.441±2.995	19.134±5.568	0.000±0.000	13.514±1.240	26.506±1.955
S19	2.899±4.052	22.256±5.410	36.661±2.265	6.829±1.194	24.849±2.343	39.986±1.374
S20	10.384±3.821	27.295±1.698	38.188±3.246	4.210±2.649	27.138±2.381	30.204±2.463
S21	6.830±2.939	20.306±1.991	33.852±1.683	15.352±3.001	33.804±3.652	45.629±1.619
S22	7.373±1.248	16.657±5.521	27.391±4.244	11.865±1.999	27.138±3.114	41.281±1.845
S23	0.710±2.748	17.236±2.883	28.612±3.280	3.703±3.913	18.727±3.402	35.522±0.502
S24	0.557±1.697	17.375±4.965	33.808±1.902	2.448±1.272	22.866±4.610	38.056±1.442
S28	-8.485±1.876	8.129±2.007	32.481±3.884	-0.049±2.349	22.795±1.384	41.179±2.069
S31	24.560±1.880	36.439±4.060	44.047±2.497	13.732±1.300	31.563±0.820	39.001±1.543
Mean	4.380±6.634	17.307±7.807	29.833±6.837	3.926±6.141	19.848±7.952	31.534±7.597

Table 31 Knee extension ROM (°) during uphill walking for healthy control participants

Subject	Limb 1			Limb 2		
	5°	**10°**	**15°**	**5°**	**10°**	**15°**
S17	13.839±0.874	33.557±4.251	44.204±3.648	14.311±1.081	29.824±2.538	43.381±3.329
S25	7.436±4.038	24.786±1.645	41.657±2.889	9.016±2.634	19.718±1.478	34.811±2.074
S26	11.578±2.936	28.329±1.939	38.362±1.873	16.893±0.919	30.340±0.442	38.216±1.452
S27	11.840±3.165	30.455±1.339	45.137±1.617	16.314±1.864	33.147±1.964	45.698±1.638
S29	14.315±2.705	31.767±0.740	41.392±1.316	11.145±1.335	27.260±3.663	37.788±2.331
S30	23.797±2.788	36.821±1.710	48.274±1.610	15.533±3.839	28.883±0.897	42.897±2.212
S32	2.791±3.324	26.942±3.593	40.385±3.293	10.327±4.645	26.242±2.958	37.745±3.330
S33	15.940±2.180	29.034±2.992	41.442±1.778	16.788±1.872	34.728±3.001	51.131±2.254
S34	0.577±0.796	17.510±2.412	20.441±2.560	-0.154±2.853	12.523±3.200	25.548±3.019
S35	6.829±1.194	24.849±2.343	39.986±1.374	2.899±4.052	22.256±5.410	36.661±2.265
Mean	10.894±6.785	28.405±5.373	40.128±7.487	11.307±5.977	26.492±6.695	39.388±6.932

Table 32 Knee flexion ROM (°) during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	-30.568±0.943	-36.661±2.008	-35.336±0.713	-34.828±2.023	-28.645±0.584	-41.255±2.976	-37.966±0.232	-30.202±0.174
S2	-34.470±3.359	-30.609±1.024	-24.226±1.523	-18.274±1.090	-42.814±1.909	-30.332±1.234	-27.045±1.078	-20.594±1.490
S3	-40.080±3.377	-35.248±0.725	-27.524±2.032	-29.514±1.243	-42.085±1.194	-34.226±0.664	-33.930±1.195	-33.683±1.063
S4	-38.505±1.268	-38.054±2.014	-34.266±1.232	-31.122±1.024	-40.186±1.446	-39.132±2.030	-33.866±0.570	-30.788±2.214
S5	-43.306±1.755	-34.960±0.427	-33.837±2.012	-28.654±1.642	-44.004±1.480	-34.459±3.680	-34.125±0.718	-29.455±2.514
S6	-40.048±1.005	-30.204±3.027	-31.902±1.934	-29.761±0.435	-45.259±1.890	-35.849±0.564	-29.185±0.480	-26.758±1.473
S7	-35.189±1.008	-30.017±2.122	-26.083±0.810	-24.189±0.823	-40.607±2.786	-33.564±2.862	-24.686±1.122	-18.489±1.751
S8	-44.442±0.617	-36.106±1.529	-30.217±2.018	-26.846±2.011	-41.851±2.726	-35.621±0.515	-30.818±0.573	-22.131±0.846
S9	-48.292±2.014	-34.684±2.016	-32.284±2.141	-28.046±1.034	-41.982±3.337	-34.845±2.658	-31.617±0.760	-26.217±0.650
S10	-35.367±0.714	-35.950±1.022	-29.804±0.923	-29.778±0.637	-32.918±2.169	-33.990±0.828	-30.606±1.545	-29.496±0.804
S11	-39.376±2.018	-28.714±0.920	-26.838±1.028	-22.202±0.839	-48.520±0.165	-33.796±0.841	-31.387±0.648	-24.733±0.598
S12	-53.413±3.029	-48.506±1.327	-35.621±2.055	-38.274±1.012	-53.625±0.740	-41.026±0.780	-33.892±0.374	-28.161±0.892
S13	-46.759±1.018	-41.832±2.054	-39.667±1.035	-33.946±0.773	-45.936±1.987	-45.516±0.761	-40.327±0.944	-33.247±1.835
S14	-44.026±2.025	-37.100±3.017	-31.358±0.918	-26.232±2.018	-39.386±2.252	-37.487±0.840	-27.579±2.144	-21.454±2.707
S15	-43.517±1.034	-37.402±2.420	-29.610±1.065	-29.049±1.028	-43.502±0.973	-43.823±0.686	-41.430±0.557	-34.482±1.265
S16	-42.163±0.824	-22.430±1.419	-29.501±0.719	-30.574±1.828	-37.241±1.907	-26.595±1.440	-26.907±1.490	-15.084±1.262
S18	-36.968±3.005	-26.304±1.920	-24.217±2.035	-25.291±0.654	-38.078±0.041	-23.399±1.446	-19.773±0.745	-17.147±2.857
S19	-39.510±2.038	-31.806±0.848	-28.432±1.024	-28.508±0.942	-39.293±2.463	-35.549±1.782	-36.0020.174	-35.927±2.641
S20	-33.861±1.011	-31.762±1.206	-30.513±0.817	-25.158±2.019	-47.286±2.169	-37.075±1.187	-37.482±1.150	-26.460±3.843
S21	-42.915±2.025	-37.289±1.707	-35.141±1.025	-33.087±0.822	-41.945±2.538	-39.624±1.146	-36.546±1.110	-33.546±2.582
S22	-35.510±1.022	-32.684±0.812	-30.420±2.326	-22.830±0.742	-37.130±1.478	-40.510±1.159	-38.328±2.895	-34.152±1.831
S23	-46.728±3.013	-34.420±0.416	-30.870±0.759	-31.262±1.510	-48.843±0.442	-34.767±0.743	-32.202±0.288	-28.796±1.214
S24	-42.883±0.815	-35.966±0.519	-28.227±1.022	-28.677±2.040	-50.182±1.964	-44.582±0.599	-42.514±1.763	-40.838±1.924
S28	-40.364±2.124	-32.031±0.707	-29.319±2.022	-29.331±1.720	-52.831±2.958	-40.766±0.939	-38.000±0.744	-33.368±0.438
S31	-40.922±3.036	-42.749±1.028	-41.380±0.935	-37.934±1.257	-52.335±3.200	-43.398±0.666	-43.289±0.999	-40.500±3.574
Mean	-40.767±5.167	-34.539±5.362	-31.064±4.237	-28.935±4.651	-43.059±6.091	-36.847±5.351	-33.580±5.818	-28.628±6.819

Table 33 Knee flexion ROM (°) during level and uphill walking for healthy control participants.

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	-52.075±1.227	-44.040±1.027	-42.300±2.582	-36.429±1.695	-49.926±1.362	-49.547±2.707	-44.003±0.438	-40.473±1.041
S25	-46.745±2.371	-47.894±1.054	-45.953±1.410	-44.620±1.427	-56.195±1.034	-46.765±1.083	-41.138±1.185	-39.512±1.032
S26	-35.919±1.023	-35.357±1.975	-30.285±1.695	-27.759±1.436	-40.767±3.843	-37.405±1.128	-33.328±1.244	-32.253±0.650
S27	-45.870±1.038	-43.700±1.814	-38.615±1.869	-36.230±1.013	-45.463±2.231	-42.529±1.869	-39.289±1.217	-36.765±0.884
S29	-31.988±1.022	-32.951±1.109	-29.086±1.149	-21.164±1.032	-35.364±2.017	-33.611±2.121	-30.964±1.427	-29.942±0.871
S30	-42.411±1.047	-43.663±1.751	-42.244±1.018	-35.503±1.013	-45.079±1.183	-36.322±1.149	-34.706±1.436	-28.700±1.835
S32	-52.556±0.724	-41.999±1.063	-42.034±3.776	-39.486±2.128	-46.066±0.933	-38.915±2.018	-39.871±1.013	-34.795±2.121
S33	-33.435±1.853	-39.734±1.316	-43.578±2.136	-41.677±0.906	-34.647±1.501	-45.865±1.869	-44.109±2.032	-45.281±0.768
S34	-53.414±1.142	-48.506±0.846	-31.607±1.047	-38.274±1.145	-53.625±0.742	-41.026±1.006	-33.892±2.013	-28.161±2.105
S35	-39.292±2.371	-35.549±1.179	-36.002±1.185	-35.927±0.847	-39.510±1.424	-31.706±1.343	-28.432±1.263	-28.508±1.482
Mean	-43.370±8.028	-41.339±5.326	-38.170±6.065	-35.707±6.762	-44.664±7.244	-40.369±5.854	-36.973±5.461	-34.439±5.942

Table 34 Knee Abduction ROM (°) during level and uphill walking for TKR patients.

Subject	Replaced limb			Non-replaced limb		
	5°	10°	15°	5°	10°	15°
S1	-4.068±0.683	-7.126±1.275	-11.502±1.011	-3.848±1.447	-7.288±1.235	-9.330±2.477
S2	-0.912±0.746	-2.770±0.964	-3.364±0.314	-7.359±0.000	-3.792±1.243	-5.571±3.674
S3	-4.527±0.834	-4.859±0.601	-13.128±1.225	-2.890±0.995	-5.417±1.196	-9.421±0.901
S4	-3.705±0.263	-7.402±0.813	-12.139±0.877	-5.240±1.051	-5.097±0.828	-9.863±0.814
S5	-5.667±0.931	-8.768±0.471	-10.780±1.174	-4.634±1.066	-5.419±2.595	-7.675±1.068
S6	-4.377±1.559	-5.182±1.896	-7.274±1.541	-4.134±0.494	-4.983±1.469	-8.682±2.417
S7	-4.203±0.716	-4.709±1.003	-3.892±1.398	-1.600±0.512	-2.390±1.027	-4.697±1.639
S8	-5.154±0.847	-3.096±1.233	-7.169±1.254	-2.760±0.762	-3.321±1.030	-7.663±0.842
S9	-1.512±0.894	-2.378±0.273	-4.625±2.087	-3.007±0.354	-4.775±1.099	-11.282±1.550
S10	-3.101±0.413	-1.968±0.546	-5.150±1.867	-4.486±0.352	-5.414±1.296	-4.186±1.737
S11	-3.441±0.618	-3.701±0.653	-6.090±0.395	-2.224±0.464	-2.805±0.368	-2.613±0.275
S12	-2.441±1.083	-3.068±0.789	-1.776±0.225	-3.505±0.755	-2.346±0.643	-6.845±2.966
S13	-7.611±1.643	-18.547±0.459	-24.086±0.512	-4.853±1.312	-12.844±1.574	-19.313±1.510
S14	-4.122±0.440	-7.014±1.187	-11.753±3.158	-2.648±0.582	-6.414±0.909	-14.465±3.575
S15	-2.591±0.251	-2.208±0.342	-3.053±0.631	-1.703±0.497	-1.295±0.517	-3.314±1.807
S16	-2.747±0.161	-4.541±0.905	-9.014±0.966	-1.851±0.483	-4.468±0.949	-11.828±0.920
S18	-2.439±0.000	-2.154±0.708	-5.829±1.084	-2.479±0.741	-8.525±0.873	-11.000±0.344
S19	-1.577±0.423	-3.142±0.760	-3.830±0.936	-1.561±0.021	-4.069±0.917	-4.074±1.187
S20	-1.874±0.258	-6.335±0.808	-11.312±0.967	-2.780±1.297	-8.495±0.714	-11.762±0.991
S21	-3.956±0.566	-2.966±0.610	-4.038±0.380	-5.600±0.737	-9.193±0.000	-3.585±0.467
S22	-3.699±0.815	-4.135±0.784	-8.798±0.703	-6.021±0.238	-3.779±0.447	-3.244±0.697
S23	-2.515±1.341	-4.745±1.402	-5.812±1.136	-3.477±1.395	-8.015±0.949	-9.067±1.134
S24	-1.654±0.625	-3.323±0.386	-7.475±1.553	-4.230±1.995	-9.492±1.066	-13.225±1.273
S28	-5.871±0.400	-6.463±0.924	-8.774±1.021	-4.651±0.815	-3.802±0.720	-2.340±0.516
S31	-3.748±0.665	-6.604±1.513	-10.386±1.199	-1.918±0.610	-5.071±0.929	-8.151±0.982
Mean	-3.473±1.551	-5.092±3.391	-8.069±4.640	-3.579±1.526	-5.540±2.695	-8.128±4.221

Table 35 Knee Abduction ROM (°) during uphill walking for healthy control participants

Subject	**Limb 1**			**Limb 2**		
	5°	**10°**	**15°**	**5°**	**10°**	**15°**
S17	-4.198±0.396	-6.932±1.499	-9.873±1.534	-2.278±0.329	-4.051±0.900	-4.455±0.454
S25	-6.190±0.699	-9.550±1.302	-13.212±0.479	-6.584±0.534	-10.277±0.694	-13.811±1.285
S26	-5.950±1.052	-6.201±0.693	-7.369±0.594	-4.687±0.114	-6.813±0.000	-10.505±1.148
S27	-3.451±0.369	-7.467±0.968	-11.229±0.850	-6.120±0.867	-5.298±2.152	-6.989±0.678
S29	-3.133±2.223	-6.241±1.277	-5.133±0.697	-2.705±1.164	-3.404±1.160	-3.827±0.955
S30	-6.298±1.192	-10.904±1.118	-13.815±0.660	-4.369±0.320	-9.013±0.702	-15.503±0.656
S32	-4.211±0.446	-9.940±1.491	-16.403±1.769	-4.372±1.573	-12.691±1.317	-17.024±1.781
S33	-5.810±1.051	-9.933±1.287	-13.327±0.365	-5.346±1.050	-13.808±1.563	-17.850±0.587
S34	-2.441±1.083	-3.038±0.789	-1.776±0.225	-3.505±0.755	-2.346±0.643	-6.845±2.966
S35	-1.561±0.021	-4.069±0.917	-4.074±1.187	-1.577±0.423	-3.142±0.760	-3.830±0.936
Mean	-4.325±1.687	-7.427±2.643	-9.621±4.835	-4.154±1.641	-7.084±4.144	-10.064±5.597

Table 36 Peak knee extension moment (Nm/kg) during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	5°	10°	15°	0°	5°	10°	15°
S1	0.722±0.050	0.512±0.134	0.580±0.032	0.525±0.055	0.710±0.088	0.595±0.087	0.858±0.203	0.835±0.047
S2	0.252±0.093	0.654±0.049	0.839±0.065	0.779±0.031	0.315±0.044	0.719±0.204	0.846±0.097	0.912±0.068
S3	0.277±0.111	0.279±0.159	0.325±0.098	0.719±0.107	0.241±0.073	0.092±0.053	0.340±0.100	0.719±0.072
S4	0.366±0.031	0.363±0.039	0.408±0.169	0.629±0.079	0.332±0.034	0.367±0.057	0.553±0.042	0.834±0.081
S5	0.492±0.037	0.509±0.103	0.509±0.084	0.528±0.120	0.754±0.168	0.539±0.059	0.827±0.192	0.908±0.070
S6	0.132±0.037	0.200±0.098	0.433±0.090	0.420±0.062	0.159±0.074	0.068±0.045	0.373±0.155	0.506±0.033
S7	0.093±0.030	0.054±0.066	-0.033±0.029	-0.023±0.014	0.172±0.041	0.087±0.039	0.150±0.039	0.197±0.064
S8	0.712±0.041	0.478±0.104	0.567±0.086	0.793±0.105	0.833±0.190	0.812±0.090	1.046±0.084	1.155±0.047
S9	0.315±0.100	0.146±0.086	0.180±0.124	0.291±0.185	0.414±0.134	0.138±0.036	0.234±0.097	0.412±0.075
S10	0.360±0.064	0.297±0.067	0.267±0.109	0.290±0.040	0.238±0.073	0.302±0.116	0.374±0.048	0.427±0.071
S11	0.362±0.033	0.284±0.049	0.375±0.019	0.271±0.104	0.260±0.037	0.091±0.049	0.409±0.027	0.488±0.064
S12	-0.066±0.031	-0.181±0.029	-0.235±0.004	-0.202±0.020	0.104±0.080	0.021±0.058	0.263±0.062	0.373±0.049
S13	0.526±0.051	0.472±0.063	0.682±0.094	0.823±0.105	0.592±0.060	0.522±0.077	0.747±0.081	0.964±0.152
S14	0.368±0.026	0.252±0.026	0.212±0.025	0.261±0.059	0.306±0.031	0.144±0.054	0.166±0.057	0.227±0.071
S15	0.289±0.140	0.025±0.060	0.129±0.058	0.049±0.044	0.121±0.069	-0.144±0.091	-0.035±0.118	-0.038±0.033
S16	0.595±0.110	0.312±0.124	0.441±0.113	0.597±0.107	0.586±0.081	0.546±0.086	0.912±0.208	1.060±0.142
S18	0.074±0.112	-0.101±0.024	0.020±0.046	0.233±0.122	-0.210±0.029	-0.222±0.025	-0.049±0.080	0.019±0.069
S19	0.434±0.071	0.503±0.123	0.592±0.130	0.591±0.044	0.290±0.048	0.313±0.073	0.451±0.064	0.529±0.047
S20	0.035±0.053	0.147±0.085	0.337±0.053	0.316±0.087	0.069±0.056	0.147±0.108	0.452±0.101	0.590±0.060
S21	0.349±0.022	0.522±0.046	0.667±0.057	0.671±0.026	0.532±0.068	0.780±0.113	0.946±0.045	0.924±0.052
S22	0.109±0.035	0.134±0.083	0.255±0.104	0.285±0.076	0.242±0.065	0.370±0.062	0.323±0.050	0.275±0.074
S23	0.225±0.066	0.448±0.193	0.307±0.086	0.358±0.073	0.335±0.048	0.231±0.112	0.525±0.064	0.546±0.104
S24	0.636±0.042	0.619±0.077	0.872±0.084	0.940±0.084	0.603±0.089	0.553±0.028	0.957±0.105	0.884±0.106
S28	0.141±0.042	0.049±0.036	0.260±0.132	0.469±0.022	0.230±0.036	0.339±0.089	0.657±0.038	0.900±0.090
S31	0.390±0.101	0.493±0.133	0.666±0.088	0.596±0.080	0.427±0.057	0.482±0.077	0.681±0.118	0.623±0.032
Mean	0.327±0.210	0.299±0.225	0.386±0.267	0.448±0.279	0.346±0.240	0.316±0.276	0.520±0.316	0.611±0.325

Table 37 Peak knee extension moment (Nm/kg) during level and uphill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0.254±0.067	0.440±0.029	0.663±0.058	0.778±0.054	0.257±0.106	0.413±0.061	0.679±0.091	0.838±0.046
S25	0.829±0.127	0.985±0.039	1.295±0.094	1.437±0.121	0.892±0.060	1.085±0.136	1.228±0.076	1.257±0.125
S26	0.527±0.042	0.518±0.065	0.634±0.027	0.520±0.050	0.447±0.035	0.438±0.061	0.584±0.008	0.432±0.093
S27	0.457±0.035	0.474±0.087	0.760±0.086	1.009±0.072	0.855±0.052	0.967±0.100	1.208±0.058	1.246±0.064
S29	0.496±0.045	0.680±0.085	0.793±0.039	0.581±0.027	0.570±0.058	0.528±0.041	0.584±0.091	0.580±0.038
S30	0.461±0.100	0.625±0.110	0.729±0.062	1.002±0.107	0.645±0.069	0.777±0.095	0.920±0.091	1.205±0.016
S32	0.650±0.070	0.522±0.129	0.769±0.138	0.827±0.036	0.646±0.059	0.460±0.140	0.643±0.121	0.798±0.097
S33	0.961±0.073	0.807±0.065	0.874±0.095	0.851±0.050	0.802±0.044	0.594±0.126	0.925±0.091	1.034±0.075
S34	-0.066±0.031	-0.181±0.029	-0.235±0.004	-0.202±0.020	0.104±0.080	0.021±0.058	0.263±0.062	0.373±0.049
S35	0.290±0.048	0.313±0.073	0.451±0.064	0.529±0.047	0.434±0.071	0.513±0.123	0.592±0.130	0.591±0.044
Mean	0.486±0.292	0.518±0.312	0.673±0.385	0.733±0.429	0.565±0.258	0.580±0.303	0.763±0.303	0.836±0.338

Table 38 Peak knee flexion moment (Nm/kg) during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	-0.147±0.000	-0.124±0.039	-0.283±0.036	-0.390±0.058	0.069±0.026	-0.449±0.075	-0.520±0.053	-0.498±0.062
S2	-0.188±0.078	-0.146±0.034	-0.245±0.072	-0.068±0.122	0.063±0.135	0.016±0.133	0.016±0.075	0.001±0.042
S3	-0.146±0.026	-0.497±0.033	-0.596±0.088	-0.676±0.081	-0.116±0.006	-0.335±0.044	-0.611±0.086	-0.659±0.031
S4	-0.399±0.037	-0.509±0.050	-0.665±0.050	-0.729±0.062	-0.401±0.026	-0.542±0.068	-0.669±0.031	-0.698±0.028
S5	-0.047±0.008	-0.233±0.035	-0.284±0.070	-0.309±0.057	-0.118±0.046	-0.225±0.032	-0.331±0.050	-0.397±0.054
S6	-0.155±0.043	-0.248±0.034	-0.441±0.014	-0.483±0.045	-0.329±0.037	-0.462±0.031	-0.506±0.045	-0.559±0.094
S7	-0.090±0.029	-0.228±0.018	-0.401±0.028	-0.472±0.019	-0.064±0.026	-0.110±0.018	-0.229±0.009	-0.344±0.054
S8	0.065±0.103	-0.072±0.052	-0.195±0.040	-0.239±0.050	-0.006±0.057	-0.184±0.061	-0.232±0.074	-0.238±0.024
S9	0.068±0.017	-0.127±0.007	-0.340±0.032	-0.415±0.031	-0.050±0.020	-0.218±0.017	-0.415±0.039	-0.425±0.051
S10	-0.216±0.033	-0.459±0.053	-0.449±0.064	-0.578±0.085	-0.407±0.027	-0.654±0.031	-0.649±0.041	-0.778±0.064
S11	0.065±0.065	-0.099±0.044	-0.188±0.037	-0.241±0.038	-0.184±0.008	-0.370±0.044	-0.481±0.048	-0.485±0.049
S12	-0.299±0.039	-0.415±0.027	-0.579±0.053	-0.724±0.016	-0.280±0.072	-0.429±0.053	-0.396±0.057	-0.506±0.035
S13	-0.074±0.087	-0.373±0.049	-0.466±0.059	-0.459±0.144	-0.035±0.067	-0.316±0.007	-0.330±0.036	-0.257±0.071
S14	-0.243±0.066	-0.340±0.064	-0.417±0.048	-0.535±0.061	-0.294±0.030	-0.408±0.035	-0.519±0.025	-0.543±0.041
S15	-0.340±0.038	-0.477±0.045	-0.471±0.049	-0.684±0.049	-0.323±0.112	-0.626±0.118	-0.859±0.100	-0.912±0.103
S16	-0.028±0.044	-0.171±0.083	-0.357±0.031	-0.466±0.056	-0.293±0.063	-0.315±0.057	-0.522±0.072	-0.305±0.072
S18	-0.126±0.137	-0.432±0.049	-0.472±0.032	-0.476±0.074	-0.462±0.077	-0.487±0.089	-0.501±0.064	-0.677±0.059
S19	-0.103±0.040	-0.162±0.056	-0.256±0.028	-0.332±0.055	-0.193±0.052	-0.297±0.030	-0.478±0.042	-0.487±0.071
S20	-0.115±0.036	-0.178±0.028	-0.242±0.044	-0.177±0.159	-0.165±0.060	-0.318±0.078	-0.474±0.048	-0.330±0.104
S21	-0.068±0.051	-0.190±0.044	-0.202±0.057	-0.275±0.070	-0.032±0.022	-0.259±0.035	-0.374±0.076	-0.481±0.056
S22	-0.280±0.044	-0.407±0.054	-0.402±0.070	-0.465±0.093	-0.455±0.023	-0.599±0.050	-0.685±0.021	-0.737±0.050
S23	-0.135±0.024	-0.451±0.052	-0.373±0.088	-0.443±0.045	-0.178±0.013	-0.407±0.065	-0.412±0.044	-0.533±0.033
S24	0.166±0.042	0.023±0.030	0.005±0.016	-0.021±0.038	0.000±0.035	-0.174±0.024	-0.205±0.039	-0.319±0.037
S28	-0.233±0.051	-0.373±0.040	-0.430±0.057	-0.542±0.080	-0.118±0.076	-0.319±0.066	-0.575±0.038	-0.577±0.055
S31	-0.301±0.082	-0.392±0.048	-0.410±0.054	-0.491±0.035	-0.298±0.012	-0.426±0.035	-0.508±0.049	-0.605±0.082
Mean	-0.143±0.138	-0.293±0.153	-0.366±0.148	-0.428±0.188	-0.204±0.154	-0.356±0.161	-0.459±0.181	-0.494±0.198

Table 39 Peak knee flexion moment (Nm/kg) during level and uphill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	-0.444±0.016	-0.677±0.013	-0.802±0.036	-0.844±0.063	-0.304±0.084	-0.576±0.082	-0.655±0.012	-0.678±0.078
S25	-0.182±0.064	-0.368±0.093	-0.347±0.109	-0.402±0.105	-0.075±0.050	-0.312±0.055	-0.276±0.027	-0.388±0.059
S26	-0.132±0.019	-0.221±0.036	-0.342±0.036	-0.450±0.009	-0.273±0.028	-0.419±0.015	-0.501±0.028	-0.664±0.029
S27	-0.397±0.039	-0.460±0.071	-0.625±0.085	-0.770±0.041	-0.179±0.013	-0.283±0.057	-0.413±0.036	-0.487±0.041
S29	-0.173±0.055	-0.316±0.045	-0.481±0.031	-0.510±0.054	-0.024±0.031	-0.151±0.018	-0.229±0.030	-0.315±0.029
S30	-0.446±0.024	-0.485±0.071	-0.483±0.023	-0.527±0.075	0.001±0.053	-0.083±0.080	-0.150±0.027	-0.219±0.079
S32	-0.220±0.017	-0.455±0.081	-0.587±0.098	-0.498±0.093	-0.249±0.051	-0.489±0.056	-0.548±0.051	-0.518±0.050
S33	-0.328±0.039	-0.443±0.112	-0.568±0.085	-0.628±0.084	-0.567±0.018	-0.560±0.102	-0.918±0.075	-1.008±0.132
S34	-0.299±0.039	-0.415±0.027	-0.579±0.053	-0.724±0.016	-0.280±0.072	-0.429±0.053	-0.396±0.057	-0.506±0.035
S35	-0.193±0.052	-0.297±0.030	-0.478±0.042	-0.487±0.071	-0.103±0.040	-0.172±0.056	-0.256±0.028	-0.332±0.055
Mean	-0.281±0.118	-0.414±0.125	-0.529±0.136	-0.584±0.149	-0.205±0.169	-0.347±0.174	-0.434±0.232	-0.512±0.228

Table 40 Peak loading-response KAbM (Nm/kg) during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	-0.340±0.047	-0.394±0.026	-0.367±0.036	-0.355±0.022	-0.510±0.023	-0.626±0.038	-0.598±0.034	-0.584±0.052
S2	-0.243±0.052	-0.199±0.109	-0.105±0.052	-0.079±0.095	-0.012±0.041	-0.123±0.153	-0.101±0.041	-0.041±0.056
S3	-0.464±0.039	-0.483±0.036	-0.432±0.062	-0.475±0.039	-0.727±0.071	-0.672±0.038	-0.760±0.051	-0.505±0.309
S4	-0.393±0.037	-0.391±0.015	-0.419±0.035	-0.397±0.023	-0.775±0.016	-0.731±0.026	-0.684±0.025	-0.721±0.020
S5	-0.531±0.024	-0.519±0.058	-0.518±0.048	-0.488±0.052	-0.442±0.063	-0.492±0.015	-0.512±0.034	-0.584±0.029
S6	-0.416±0.014	-0.269±0.084	-0.288±0.050	-0.333±0.054	-0.353±0.032	-0.365±0.024	-0.332±0.040	-0.321±0.032
S7	-0.272±0.021	-0.317±0.025	-0.275±0.033	-0.292±0.026	-0.381±0.023	-0.332±0.007	-0.292±0.033	-0.286±0.020
S8	-0.491±0.034	-0.502±0.036	-0.453±0.027	-0.424±0.047	-0.760±0.035	-0.668±0.045	-0.650±0.034	-0.641±0.038
S9	-0.496±0.022	-0.402±0.042	-0.348±0.035	-0.388±0.043	-0.510±0.061	-0.502±0.017	-0.458±0.018	-0.557±0.056
S10	-0.121±0.033	-0.207±0.051	-0.199±0.031	-0.143±0.058	-0.382±0.036	-0.345±0.026	-0.230±0.055	-0.381±0.044
S11	-0.401±0.046	-0.409±0.023	-0.351±0.039	-0.394±0.012	-0.318±0.026	-0.364±0.030	-0.340±0.023	-0.265±0.028
S12	-0.390±0.011	-0.334±0.027	-0.282±0.028	-0.198±0.018	-0.352±0.041	-0.278±0.039	-0.235±0.034	-0.250±0.029
S13	-0.266±0.025	-0.280±0.065	-0.359±0.047	-0.424±0.060	-0.148±0.052	-0.057±0.031	-0.082±0.036	-0.094±0.034
S14	-0.372±0.040	-0.358±0.056	-0.361±0.072	-0.405±0.042	-0.152±0.018	-0.082±0.025	-0.157±0.032	-0.258±0.045
S15	-0.225±0.050	-0.249±0.020	-0.168±0.043	-0.187±0.017	-0.429±0.039	-0.349±0.077	-0.303±0.043	-0.189±0.054
S16	-0.292±0.035	-0.325±0.021	-0.306±0.035	-0.330±0.044	-0.294±0.019	-0.338±0.021	-0.315±0.024	-0.363±0.012
S18	-0.224±0.028	-0.282±0.074	-0.289±0.023	-0.195±0.064	-0.218±0.021	-0.322±0.017	-0.367±0.036	-0.404±0.026
S19	-0.444±0.035	-0.367±0.019	-0.334±0.036	-0.260±0.028	-0.331±0.020	-0.350±0.071	-0.344±0.050	-0.359±0.061
S20	-0.457±0.035	-0.339±0.047	-0.369±0.053	-0.310±0.061	-0.269±0.033	-0.330±0.045	-0.420±0.020	-0.371±0.024
S21	-0.292±0.012	-0.260±0.028	-0.269±0.039	-0.201±0.015	-0.378±0.027	-0.300±0.023	-0.276±0.046	-0.228±0.029
S22	-0.280±0.039	-0.265±0.029	-0.275±0.050	-0.297±0.018	-0.400±0.032	-0.260±0.022	-0.158±0.025	-0.165±0.007
S23	-0.101±0.017	-0.162±0.052	-0.151±0.062	-0.127±0.028	-0.320±0.011	-0.326±0.039	-0.396±0.047	-0.319±0.022
S24	-0.512±0.011	-0.484±0.023	-0.478±0.033	-0.417±0.004	-0.711±0.019	-0.658±0.028	-0.637±0.041	-0.582±0.025
S28	-0.528±0.038	-0.396±0.037	-0.385±0.045	-0.327±0.038	-0.458±0.053	-0.263±0.034	-0.306±0.015	-0.191±0.026
S31	-0.378±0.046	-0.244±0.021	-0.247±0.043	-0.202±0.047	-0.414±0.062	-0.376±0.037	-0.416±0.018	-0.355±0.057
Mean	-0.357±0.122	-0.338±0.098	-0.321±0.101	-0.306±0.114	-0.402±0.190	-0.380±0.180	-0.375±0.182	-0.361±0.176

Table 41 Peak loading-response KAbM (Nm/kg) during level and uphill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	-0.454±0.023	-0.487±0.021	-0.464±0.042	-0.439±0.038	-0.482±0.028	-0.417±0.054	-0.453±0.025	-0.361±0.029
S25	-0.570±0.053	-0.476±0.033	-0.472±0.033	-0.406±0.075	-0.607±0.055	-0.584±0.031	-0.621±0.006	-0.589±0.034
S26	-0.510±0.019	-0.434±0.090	-0.432±0.062	-0.411±0.058	-0.210±0.043	-0.306±0.012	-0.214±0.037	-0.271±0.058
S27	-0.569±0.015	-0.588±0.040	-0.526±0.032	-0.509±0.041	-0.624±0.015	-0.556±0.017	-0.478±0.013	-0.404±0.025
S29	-0.187±0.018	-0.261±0.016	-0.192±0.024	-0.201±0.021	-0.189±0.026	-0.116±0.033	-0.045±0.041	-0.028±0.036
S30	-0.224±0.028	-0.240±0.011	-0.194±0.017	-0.180±0.026	-0.442±0.044	-0.438±0.022	-0.481±0.021	-0.539±0.024
S32	-0.449±0.032	-0.513±0.042	-0.477±0.034	-0.503±0.080	-0.379±0.059	-0.329±0.066	-0.393±0.065	-0.367±0.080
S33	-0.598±0.030	-0.481±0.030	-0.554±0.039	-0.532±0.025	-0.573±0.025	-0.377±0.222	-0.589±0.109	-0.550±0.036
S34	-0.390±0.011	-0.354±0.025	-0.282±0.028	-0.198±0.018	-0.352±0.041	-0.278±0.039	-0.235±0.034	-0.250±0.029
S35	-0.331±0.020	-0.350±0.071	-0.344±0.050	-0.359±0.061	-0.444±0.035	-0.370±0.019	-0.334±0.036	-0.260±0.028
Mean	-0.428±0.144	-0.419±0.113	-0.394±0.133	-0.374±0.135	-0.430±0.152	-0.377±0.136	-0.384±0.179	-0.362±0.171

Table 42 Peak push-off KAbM (Nm/kg) during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	5°	10°	15°	0°	5°	10°	15°
S1	-0.254±0.044	-0.296±0.014	-0.281±0.067	-0.323±0.013	-0.429±0.018	-0.546±0.027	-0.521±0.015	-0.502±0.026
S2	-0.241±0.036	-0.074±0.023	-0.065±0.048	-0.076±0.063	-0.055±0.016	0.011±0.000	-0.124±0.030	-0.073±0.059
S3	-0.346±0.026	-0.256±0.012	-0.276±0.037	-0.234±0.044	-0.575±0.042	-0.461±0.076	-0.481±0.078	-0.452±0.114
S4	-0.422±0.024	-0.365±0.029	-0.343±0.035	-0.318±0.024	-0.714±0.019	-0.576±0.065	-0.573±0.018	-0.582±0.023
S5	-0.299±0.015	-0.337±0.172	-0.382±0.106	-0.219±0.033	-0.355±0.037	-0.379±0.015	-0.354±0.042	-0.366±0.056
S6	-0.371±0.017	-0.327±0.040	-0.159±0.035	-0.144±0.033	-0.194±0.037	-0.178±0.027	-0.141±0.037	-0.128±0.055
S7	-0.210±0.023	-0.222±0.021	-0.271±0.032	-0.264±0.017	-0.366±0.018	-0.300±0.018	-0.328±0.011	-0.341±0.054
S8	-0.411±0.017	-0.334±0.027	-0.362±0.100	-0.313±0.038	-0.387±0.046	-0.307±0.048	-0.297±0.044	-0.333±0.108
S9	-0.500±0.018	-0.408±0.036	-0.321±0.045	-0.305±0.048	-0.460±0.046	-0.442±0.006	-0.394±0.036	-0.374±0.028
S10	-0.173±0.065	-0.184±0.029	-0.131±0.032	-0.087±0.049	-0.357±0.021	-0.311±0.013	-0.288±0.061	-0.274±0.041
S11	-0.342±0.025	-0.341±0.065	-0.264±0.065	-0.268±0.041	-0.227±0.024	-0.263±0.030	-0.254±0.010	-0.250±0.025
S12	-0.197±0.031	-0.127±0.032	-0.078±0.024	-0.032±0.040	-0.218±0.040	-0.134±0.029	-0.105±0.060	-0.079±0.033
S13	-0.182±0.038	-0.146±0.058	-0.147±0.014	-0.163±0.028	-0.101±0.047	-0.037±0.031	-0.050±0.009	-0.039±0.024
S14	-0.259±0.025	-0.219±0.015	-0.166±0.020	-0.180±0.050	-0.109±0.027	-0.052±0.029	0.027±0.040	-0.077±0.045
S15	-0.132±0.022	-0.047±0.055	-0.134±0.062	-0.123±0.065	-0.294±0.054	-0.214±0.036	-0.229±0.033	-0.154±0.063
S16	-0.172±0.029	-0.134±0.019	-0.118±0.049	-0.201±0.048	-0.241±0.033	-0.227±0.040	-0.199±0.022	-0.263±0.037
S18	-0.257±0.042	-0.257±0.042	-0.264±0.034	-0.326±0.044	-0.399±0.078	-0.235±0.034	-0.240±0.059	-0.220±0.040
S19	-0.235±0.028	-0.206±0.051	-0.155±0.017	-0.089±0.010	-0.272±0.031	-0.297±0.047	-0.235±0.025	-0.191±0.014
S20	-0.444±0.057	-0.329±0.056	-0.348±0.050	-0.229±0.026	-0.238±0.013	-0.291±0.014	-0.295±0.069	-0.237±0.110
S21	-0.241±0.013	-0.232±0.015	-0.213±0.031	-0.231±0.007	-0.312±0.015	-0.275±0.018	-0.229±0.026	-0.159±0.013
S22	-0.159±0.033	-0.172±0.049	-0.161±0.044	-0.085±0.057	-0.217±0.016	-0.234±0.018	-0.176±0.032	-0.263±0.039
S23	-0.094±0.004	-0.167±0.028	-0.123±0.056	-0.074±0.016	-0.265±0.022	-0.229±0.044	-0.238±0.036	-0.193±0.029
S24	-0.480±0.037	-0.509±0.031	-0.489±0.036	-0.429±0.022	-0.698±0.024	-0.592±0.019	-0.569±0.030	-0.539±0.019
S28	-0.375±0.028	-0.201±0.033	-0.259±0.028	-0.242±0.013	-0.279±0.047	-0.135±0.044	-0.262±0.026	-0.244±0.029
S31	-0.289±0.035	-0.172±0.019	-0.117±0.036	-0.092±0.043	-0.307±0.011	-0.234±0.022	-0.243±0.036	-0.354±0.035
Mean	-0.283±0.112	-0.243±0.109	-0.225±0.109	-0.202±0.103	-0.323±0.163	-0.277±0.157	-0.272±0.150	-0.268±0.147

Table 43 Peak push-off KAbM (Nm/kg) during level and uphill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	-0.322±0.024	-0.325±0.024	-0.284±0.027	-0.264±0.054	-0.421±0.024	-0.288±0.037	-0.305±0.029	-0.241±0.022
S25	-0.319±0.041	-0.250±0.024	-0.165±0.074	-0.192±0.021	-0.372±0.019	-0.335±0.013	-0.225±0.050	-0.195±0.028
S26	-0.328±0.026	-0.299±0.042	-0.237±0.020	-0.227±0.019	-0.144±0.025	-0.093±0.016	-0.115±0.027	-0.091±0.037
S27	-0.476±0.027	-0.520±0.031	-0.499±0.032	-0.501±0.052	-0.591±0.024	-0.582±0.033	-0.557±0.021	-0.561±0.007
S29	-0.101±0.024	-0.141±0.014	-0.118±0.019	-0.082±0.023	-0.047±0.026	-0.097±0.030	-0.028±0.024	0.111±0.047
S30	-0.025±0.025	-0.026±0.043	0.076±0.029	-0.162±0.059	-0.138±0.034	-0.112±0.052	-0.075±0.025	-0.109±0.113
S32	-0.146±0.017	-0.189±0.037	-0.090±0.082	-0.069±0.049	-0.065±0.025	-0.040±0.026	0.067±0.081	0.043±0.038
S33	-0.339±0.017	-0.273±0.053	-0.302±0.048	-0.368±0.039	-0.448±0.033	-0.273±0.098	-0.385±0.031	-0.377±0.082
S34	-0.197±0.031	-0.127±0.036	-0.078±0.024	-0.032±0.040	-0.218±0.040	-0.134±0.029	-0.105±0.060	-0.079±0.033
S35	-0.272±0.031	-0.297±0.047	-0.235±0.025	-0.191±0.014	-0.235±0.028	-0.212±0.051	-0.155±0.017	-0.089±0.010
Mean	-0.253±0.134	-0.245±0.135	-0.193±0.156	-0.209±0.143	-0.268±0.182	-0.217±0.161	-0.188±0.185	-0.159±0.197

Table 44 Root mean square of normalized EMG for long head of bicpes frmoris during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.214±0.032	0.257±0.030	0.284±0.004	0.367±0.006	0.163±0.045	0.145±0.045	0.142±0.013	0.166±0.020
S2	0.229±0.041	0.271±0.030	0.261±0.007	0.235±0.015	0.170±0.025	0.269±0.010	0.277±0.011	0.337±0.009
S3	0.168±0.029	0.286±0.028	0.341±0.016	0.344±0.017	0.199±0.055	0.241±0.032	0.256±0.009	0.282±0.018
S4	0.112±0.055	0.213±0.032	0.222±0.002	0.254±0.016	0.135±0.038	0.241±0.018	0.375±0.009	0.412±0.018
S5	0.448±0.027	0.289±0.019	0.779±0.017	0.823±0.013	0.325±0.045	0.194±0.024	0.261±0.012	0.295±0.018
S6	0.086±0.090	0.110±0.015	0.123±0.007	0.141±0.010	0.709±0.028	0.880±0.015	0.757±0.006	0.812±0.031
S7	0.187±0.042	0.353±0.035	0.329±0.016	0.438±0.014	0.269±0.071	0.611±0.050	0.398±0.011	0.788±0.022
S8	0.341±0.014	0.314±0.024	0.457±0.005	0.433±0.007	0.393±0.016	0.556±0.011	0.612±0.014	0.664±0.013
S9	0.108±0.024	0.175±0.017	0.272±0.033	0.281±0.024	0.194±0.041	0.186±0.021	0.160±0.020	0.178±0.028
S10	0.286±0.037	0.545±0.017	0.737±0.014	0.706±0.033	0.179±0.041	0.398±0.045	0.380±0.009	0.478±0.021
S11	0.198±0.105	0.335±0.057	0.402±0.022	0.442±0.045	0.385±0.069	0.479±0.051	0.653±0.048	0.617±0.291
S12	0.279±0.074	0.206±0.037	0.238±0.019	0.278±0.012	0.088±0.054	0.136±0.047	0.188±0.004	0.198±0.014
S13	0.074±0.039	0.152±0.008	0.175±0.024	0.162±0.012	0.065±0.028	0.069±0.041	0.102±0.012	0.090±0.007
S14	0.120±0.020	0.276±0.031	0.306±0.022	0.404±0.017	0.300±0.053	0.511±0.019	0.610±0.009	0.634±0.012
S15	0.141±0.050	0.178±0.022	0.321±0.022	0.317±0.012	0.088±0.060	0.244±0.018	0.294±0.036	0.320±0.012
S16	0.096±0.063	0.159±0.010	0.251±0.014	0.626±0.016	0.142±0.050	0.229±0.075	0.238±0.021	0.295±0.021
S18	0.478±0.067	0.661±0.030	0.752±0.014	0.758±0.027	0.535±0.061	0.545±0.032	0.703±0.025	0.907±0.008
S19	0.081±0.063	0.117±0.015	0.157±0.015	0.171±0.009	0.099±0.083	0.160±0.013	0.180±0.031	0.189±0.018
S20	0.377±0.029	0.221±0.043	0.453±0.016	0.301±0.031	0.223±0.044	0.315±0.021	0.272±0.006	0.280±0.030
S21	0.309±0.064	0.360±0.002	0.402±0.010	0.377±0.078	0.159±0.023	0.256±0.030	0.337±0.015	0.371±0.012
S22	0.557±0.066	0.714±0.029	0.567±0.020	0.691±0.052	0.070±0.040	0.147±0.036	0.218±0.042	0.280±0.036
S23	0.060±0.035	0.084±0.011	0.126±0.034	0.165±0.014	0.027±0.060	0.019±0.011	0.066±0.056	0.134±0.010
S24	0.145±0.040	0.231±0.058	0.189±0.033	0.251±0.047	0.087±0.048	0.095±0.030	0.100±0.060	0.124±0.016
S28	0.234±0.059	0.219±0.010	0.242±0.021	0.211±0.018	0.128±0.090	0.161±0.041	0.168±0.006	0.167±0.070
S31	0.317±0.097	0.331±0.027	0.362±0.022	0.460±0.070	0.147±0.036	0.181±0.045	0.190±0.026	0.293±0.020
Mean	0.226±0.136	0.282±0.157	0.350±0.107	0.386±0.197	0.211±0.159	0.291±0.203	0.318±0.200	0.340±0.226

Table 45 Root mean square of normalized EMG for bicpes frmoris during level and uphill walking for healthy control participants

Subject	**Limb 1**				**Limb 2**			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0.217±0.039	0.245±0.033	0.268±0.091	0.284±0.028	0.084±0.076	0.138±0.099	0.250±0.055	0.214±0.054
S25	0.050±0.089	0.073±0.041	0.089±0.076	0.102±0.036	0.431±0.054	0.181±0.082	0.227±0.057	0.300±0.066
S26	0.149±0.038	0.242±0.023	0.438±0.049	0.554±0.068	0.225±0.054	0.559±0.042	0.823±0.074	1.102±0.031
S27	0.291±0.085	0.339±0.021	0.350±0.014	0.366±0.098	0.219±0.057	0.302±0.009	0.380±0.092	0.414±0.056
S29	0.128±0.029	0.129±0.039	0.152±0.055	0.171±0.050	0.219±0.008	0.373±0.033	0.327±0.031	0.367±0.017
S30	0.245±0.051	0.250±0.076	0.279±0.049	0.231±0.038	0.169±0.035	0.195±0.044	0.242±0.026	0.296±0.056
S32	0.185±0.047	0.230±0.056	0.121±0.075	0.162±0.016	0.235±0.057	0.263±0.034	0.179±0.023	0.257±0.038
S33	0.176±0.032	0.251±0.068	0.256±0.066	0.222±0.003	0.109±0.026	0.233±0.031	0.329±0.041	0.333±0.044
S34	0.120±0.019	0.170±0.085	0.226±0.013	0.216±0.046	0.101±0.074	0.131±0.090	0.280±0.013	0.432±0.009
S35	0.144±0.032	0.151±0.069	0.190±0.035	0.165±0.097	0.083±0.047	0.097±0.083	0.132±0.045	0.136±0.022
Mean	0.171±0.069	0.209±0.077	0.237±0.106	0.248±0.130	0.188±0.106	0.248±0.138	0.317±0.193	0.386±0.267

Table 46 Root mean square of normalized EMG for medial gastrocnemius during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.023±0.019	0.039±0.011	0.053±0.008	0.068±0.030	0.127±0.023	0.155±0.020	0.216±0.018	0.284±0.022
S2	0.402±0.003	0.379±0.034	0.399±0.016	0.507±0.014	0.199±0.020	0.241±0.004	0.262±0.060	0.305±0.022
S3	0.168±0.006	0.252±0.021	0.250±0.013	0.363±0.030	0.140±0.044	0.169±0.015	0.272±0.007	0.329±0.016
S4	0.176±0.042	0.192±0.050	0.230±0.022	0.251±0.032	0.136±0.016	0.215±0.019	0.266±0.031	0.341±0.021
S5	0.145±0.021	0.209±0.005	0.261±0.027	0.337±0.008	0.102±0.014	0.169±0.041	0.297±0.019	0.313±0.027
S6	0.183±0.078	0.278±0.020	0.353±0.020	0.431±0.019	0.182±0.034	0.262±0.007	0.313±0.048	0.386±0.028
S7	0.179±0.032	0.384±0.007	0.300±0.071	0.417±0.012	0.127±0.019	0.336±0.042	0.301±0.005	0.450±0.037
S8	0.122±0.027	0.191±0.018	0.281±0.037	0.334±0.009	0.111±0.016	0.166±0.029	0.248±0.060	0.385±0.049
S9	0.139±0.021	0.227±0.001	0.283±0.025	0.326±0.053	0.209±0.017	0.275±0.015	0.384±0.013	0.407±0.038
S10	0.280±0.020	0.414±0.033	0.391±0.026	0.459±0.024	0.206±0.004	0.320±0.019	0.504±0.034	0.389±0.040
S11	0.127±0.033	0.202±0.012	0.324±0.011	0.299±0.036	0.078±0.008	0.145±0.030	0.208±0.008	0.241±0.017
S12	0.194±0.016	0.135±0.010	0.152±0.004	0.133±0.012	0.090±0.013	0.087±0.021	0.110±0.061	0.126±0.014
S13	0.327±0.019	0.455±0.016	0.527±0.023	0.519±0.042	0.080±0.017	0.171±0.020	0.240±0.008	0.228±0.012
S14	0.321±0.031	0.440±0.028	0.438±0.016	0.462±0.018	0.312±0.014	0.439±0.034	0.617±0.016	0.571±0.052
S15	0.326±0.045	0.356±0.013	0.378±0.016	0.358±0.043	0.152±0.007	0.234±0.024	0.276±0.030	0.264±0.037
S16	0.159±0.061	0.178±0.099	0.197±0.042	0.253±0.015	0.347±0.021	0.347±0.024	0.472±0.057	0.633±0.033
S18	0.150±0.037	0.165±0.089	0.193±0.014	0.257±0.044	0.190±0.019	0.184±0.022	0.187±0.025	0.366±0.026
S19	0.230±0.051	0.249±0.014	0.301±0.030	0.273±0.017	0.381±0.094	0.424±0.074	0.445±0.026	0.426±0.050
S20	0.195±0.049	0.251±0.031	0.355±0.023	0.379±0.019	0.298±0.033	0.355±0.016	0.367±0.040	0.458±0.028
S21	0.138±0.011	0.196±0.024	0.222±0.011	0.237±0.021	0.047±0.009	0.099±0.073	0.119±0.055	0.132±0.032
S22	0.110±0.024	0.182±0.079	0.263±0.019	0.306±0.023	0.155±0.006	0.189±0.024	0.266±0.013	0.396±0.062
S23	0.180±0.035	0.258±0.032	0.324±0.029	0.363±0.008	0.093±0.016	0.145±0.008	0.272±0.031	0.220±0.032
S24	0.087±0.044	0.146±0.132	0.182±0.017	0.210±0.038	0.117±0.008	0.175±0.003	0.222±0.055	0.241±0.049
S28	0.345±0.012	0.327±0.104	0.348±0.014	0.318±0.038	0.084±0.047	0.211±0.032	0.335±0.045	0.383±0.037
S31	0.176±0.019	0.216±0.053	0.250±0.032	0.292±0.043	0.167±0.014	0.221±0.013	0.289±0.025	0.307±0.069
Mean	0.195±0.091	0.253±0.104	0.290±0.100	0.326±0.108	0.165±0.088	0.229±0.094	0.299±0.116	0.343±0.118

Table 47 Root mean square of normalized EMG for medial gastrocnemius during level and uphill walking for healthy control participants

Subject	**Limb 1**				**Limb 2**			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0.201±0.096	0.251±0.066	0.305±0.026	0.360±0.049	0.221±0.038	0.241±0.023	0.370±0.053	0.372±0.047
S25	0.293±0.045	0.398±0.026	0.391±0.048	0.422±0.093	0.230±0.054	0.146±0.061	0.295±0.056	0.337±0.037
S26	0.278±0.062	0.342±0.078	0.434±0.065	0.506±0.018	0.268±0.022	0.288±0.064	0.321±0.071	0.361±0.046
S27	0.199±0.087	0.206±0.078	0.243±0.049	0.247±0.023	0.260±0.045	0.277±0.065	0.356±0.045	0.420±0.023
S29	0.162±0.096	0.214±0.024	0.271±0.018	0.280±0.018	0.154±0.049	0.295±0.056	0.285±0.025	0.318±0.028
S30	0.132±0.089	0.140±0.016	0.198±0.095	0.181±0.052	0.128±0.023	0.172±0.013	0.224±0.041	0.275±0.009
S32	0.149±0.041	0.177±0.030	0.255±0.045	0.217±0.015	0.208±0.045	0.206±0.073	0.198±0.079	0.181±0.017
S33	0.232±0.042	0.258±0.057	0.291±0.099	0.311±0.060	0.359±0.071	0.356±0.071	0.365±0.094	0.555±0.082
S34	0.290±0.066	0.325±0.050	0.410±0.019	0.550±0.021	0.347±0.049	0.421±0.095	0.436±0.047	0.419±0.043
S35	0.183±0.093	0.222±0.085	0.233±0.041	0.255±0.031	0.184±0.036	0.223±0.038	0.288±0.078	0.302±0.022
Mean	0.213±0.059	0.254±0.080	0.304±0.081	0.333±0.124	0.236±0.075	0.263±0.083	0.314±0.071	0.354±0.100

Table 48 Root mean square of normalized EMG for vastus lateralis during level and uphill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.293±0.031	0.331±0.023	0.364±0.015	0.431±0.078	0.196±0.025	0.207±0.024	0.279±0.028	0.273±0.029
S2	0.126±0.019	0.304±0.013	0.350±0.017	0.453±0.014	0.121±0.024	0.211±0.009	0.117±0.008	0.145±0.067
S3	0.299±0.042	0.356±0.018	0.348±0.026	0.419±0.031	0.141±0.015	0.196±0.011	0.343±0.004	0.465±0.024
S4	0.109±0.025	0.138±0.029	0.170±0.048	0.285±0.021	0.186±0.013	0.242±0.018	0.283±0.038	0.388±0.026
S5	0.206±0.035	0.252±0.028	0.358±0.019	0.397±0.013	0.271±0.007	0.287±0.013	0.486±0.007	0.538±0.008
S6	0.063±0.037	0.085±0.024	0.123±0.032	0.167±0.021	0.066±0.018	0.079±0.016	0.122±0.006	0.226±0.024
S7	0.419±0.027	0.541±0.029	0.403±0.033	0.545±0.034	0.235±0.013	0.382±0.027	0.397±0.037	0.436±0.013
S8	0.473±0.029	0.452±0.017	0.387±0.023	0.441±0.011	0.176±0.016	0.245±0.023	0.255±0.009	0.399±0.027
S9	0.058±0.010	0.048±0.029	0.038±0.006	0.169±0.023	0.081±0.058	0.077±0.019	0.063±0.025	0.090±0.008
S10	0.349±0.009	0.427±0.018	0.459±0.007	0.636±0.019	0.221±0.009	0.365±0.027	0.444±0.035	0.707±0.015
S11	0.424±0.023	0.387±0.026	0.567±0.024	0.724±0.028	0.519±0.026	0.461±0.029	0.635±0.015	0.830±0.008
S12	0.062±0.022	0.098±0.025	0.187±0.018	0.271±0.023	0.071±0.017	0.127±0.014	0.237±0.022	0.390±0.007
S13	0.235±0.035	0.323±0.019	0.168±0.028	0.291±0.007	0.104±0.009	0.183±0.038	0.166±0.019	0.239±0.026
S14	0.259±0.013	0.292±0.006	0.438±0.014	0.317±0.016	0.181±0.033	0.279±0.014	0.226±0.016	0.795±0.014
S15	0.167±0.017	0.244±0.005	0.349±0.037	0.233±0.011	0.135±0.019	0.125±0.019	0.216±0.006	0.184±0.029
S16	0.127±0.026	0.125±0.017	0.123±0.004	0.194±0.017	0.142±0.029	0.137±0.025	0.224±0.009	0.305±0.013
S18	0.335±0.026	0.170±0.022	0.305±0.022	0.324±0.030	0.154±0.013	0.128±0.012	0.120±0.012	0.254±0.009
S19	0.249±0.028	0.247±0.018	0.358±0.017	0.423±0.023	0.168±0.016	0.203±0.018	0.265±0.015	0.308±0.016
S20	0.104±0.016	0.157±0.024	0.206±0.007	0.270±0.025	0.118±0.016	0.149±0.025	0.257±0.029	0.340±0.024
S21	0.205±0.026	0.314±0.019	0.506±0.012	0.588±0.023	0.195±0.017	0.290±0.019	0.384±0.009	0.438±0.016
S22	0.176±0.029	0.185±0.026	0.311±0.007	0.334±0.032	0.226±0.018	0.268±0.016	0.243±0.011	0.314±0.018
S23	0.020±0.024	0.020±0.019	0.036±0.008	0.037±0.025	0.183±0.005	0.175±0.023	0.256±0.017	0.419±0.038
S24	0.145±0.027	0.181±0.028	0.272±0.011	0.335±0.021	0.102±0.019	0.126±0.048	0.242±0.034	0.304±0.019
S28	0.163±0.011	0.145±0.004	0.268±0.019	0.358±0.014	0.124±0.039	0.127±0.019	0.189±0.027	0.326±0.015
S31	0.194±0.018	0.157±0.010	0.170±0.013	0.214±0.009	0.178±0.014	0.232±0.014	0.236±0.014	0.308±0.024
Mean	0.211±0.123	0.240±0.132	0.291±0.140	0.355±0.158	0.172±0.089	0.212±0.096	0.268±0.127	0.377±0.183

Table 49 Root mean square of normalized EMG for vastus lateralis during level and uphill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0.206±0.021	0.221±0.055	0.293±0.016	0.280±0.027	0.272±0.023	0.357±0.019	0.408±0.019	0.490±0.025
S25	0.227±0.024	0.214±0.025	0.243±0.017	0.261±0.013	0.236±0.025	0.265±0.028	0.320±0.029	0.336±0.027
S26	0.318±0.012	0.325±0.021	0.492±0.012	0.560±0.026	0.384±0.028	0.403±0.025	0.512±0.014	0.594±0.019
S27	0.262±0.007	0.281±0.028	0.323±0.029	0.368±0.016	0.259±0.018	0.268±0.017	0.299±0.014	0.343±0.028
S29	0.203±0.009	0.268±0.009	0.292±0.015	0.288±0.026	0.212±0.024	0.289±0.025	0.231±0.013	0.289±0.022
S30	0.156±0.017	0.185±0.011	0.223±0.012	0.246±0.019	0.204±0.013	0.192±0.024	0.254±0.017	0.280±0.027
S32	0.288±0.015	0.267±0.028	0.301±0.006	0.384±0.013	0.283±0.037	0.285±0.028	0.372±0.024	0.451±0.017
S33	0.211±0.014	0.255±0.019	0.345±0.019	0.444±0.027	0.187±0.006	0.236±0.018	0.285±0.036	0.354±0.017
S34	0.188±0.016	0.254±0.014	0.341±0.036	0.393±0.018	0.233±0.029	0.339±0.016	0.433±0.012	0.538±0.013
S35	0.192±0.017	0.213±0.017	0.325±0.012	0.383±0.018	0.213±0.024	0.254±0.019	0.342±0.016	0.397±0.027
Mean	0.226±0.050	0.249±0.041	0.318±0.073	0.361±0.096	0.249±0.057	0.289±0.062	0.346±0.087	0.408±0.104

Table 50 Peak loading-response vertical GRF (BW) during downhill walking for TKR patients

Subject	Replaced limb			Non-replaced limb		
	5°	**10°**	**15°**	**5°**	**10°**	**15°**
S1	1.183±0.023	1.260±0.032	1.355±0.078	1.213±0.072	1.365±0.035	1.597±0.059
S2	1.316±0.079	1.258±0.040	1.311±0.039	1.249±0.122	1.314±0.079	1.455±0.111
S3	1.212±0.018	1.205±0.057	1.156±0.047	1.078±0.018	1.136±0.047	1.203±0.049
S4	1.119±0.048	1.183±0.026	1.258±0.043	1.129±0.033	1.134±0.012	1.170±0.033
S5	1.175±0.032	1.278±0.076	1.480±0.038	1.261±0.038	1.485±0.056	1.622±0.034
S6	1.063±0.032	1.151±0.034	1.276±0.071	1.121±0.055	1.132±0.034	1.250±0.055
S7	0.812±0.072	0.846±0.047	-	0.792±0.035	0.828±0.068	-
S8	1.124±0.026	1.171±0.057	1.260±0.034	1.231±0.014	1.302±0.050	1.340±0.026
S9	1.075±0.021	1.175±0.053	1.196±0.032	1.112±0.023	1.228±0.042	1.251±0.080
S10	1.094±0.056	1.138±0.063	1.222±0.092	1.088±0.026	1.112±0.040	1.194±0.070
S11	1.110±0.029	1.093±0.084	-	1.098±0.031	1.119±0.065	-
S12	0.973±0.052	1.113±0.053	0.957±0.055	1.185±0.072	1.233±0.101	1.001±0.097
S13	1.064±0.014	1.143±0.127	1.120±0.057	1.132±0.030	1.140±0.056	1.191±0.074
S14	1.155±0.052	1.358±0.111	1.633±0.165	1.146±0.030	1.350±0.031	1.445±0.152
S15	1.459±0.060	1.583±0.209	1.618±0.134	1.433±0.112	1.530±0.178	1.518±0.129
S16	0.946±0.030	0.923±0.040	0.929±0.091	1.077±0.071	1.133±0.083	1.127±0.080
S18	1.034±0.029	1.111±0.070	-	0.972±0.024	1.092±0.009	-
S19	1.077±0.022	1.098±0.079	1.103±0.041	1.029±0.029	1.109±0.075	1.137±0.089
S20	0.992±0.026	1.078±0.058	1.150±0.102	1.027±0.047	1.241±0.031	1.358±0.022
S21	1.145±0.021	1.184±0.029	1.217±0.031	1.182±0.031	1.311±0.029	1.344±0.032
S22	1.067±0.018	1.084±0.059	1.353±0.028	1.061±0.025	1.182±0.080	1.477±0.064
S23	1.008±0.015	1.002±0.014	1.031±0.033	1.028±0.025	1.065±0.052	1.120±0.080
S24	1.011±0.026	1.044±0.035	1.148±0.047	1.117±0.010	1.082±0.044	1.193±0.028
S28	1.054±0.013	1.114±0.051	1.063±0.045	1.020±0.017	1.147±0.048	1.103±0.077
S31	1.209±0.049	1.266±0.040	1.301±0.065	1.211±0.061	1.268±0.064	1.301±0.028
Mean	1.114±0.117	1.173±0.134	1.233±0.182	1.120±0.120	1.202±0.146	1.233±0.183

Table 51 Peak loading-response vertical GRF (BW) during downhill walking for healthy control participants

Subject	Limb 1			Limb 2		
	5°	**10°**	**15°**	**5°**	**10°**	**15°**
S17	1.093±0.022	1.128±0.046	1.168±0.061	1.090±0.019	1.123±0.038	1.061±0.053
S25	1.156±0.028	1.254±0.023	1.236±0.049	1.098±0.042	1.193±0.058	1.227±0.086
S26	1.128±0.017	1.186±0.044	1.178±0.058	1.135±0.013	1.195±0.054	1.283±0.033
S27	1.211±0.058	1.226±0.050	1.280±0.031	1.254±0.021	1.279±0.026	1.361±0.033
S29	1.076±0.012	1.061±0.034	1.200±0.062	1.043±0.031	1.093±0.053	1.067±0.041
S30	1.155±0.047	1.298±0.070	1.327±0.080	1.120±0.026	1.291±0.033	1.356±0.107
S32	1.193±0.060	1.226±0.056	1.244±0.039	1.236±0.106	1.431±0.060	1.399±0.075
S33	1.268±0.035	1.322±0.048	1.299±0.045	1.242±0.062	1.296±0.085	1.322±0.124
S34	0.973±0.052	1.113±0.053	0.957±0.055	1.185±0.072	1.233±0.101	1.001±0.097
S35	1.029±0.029	1.109±0.075	1.137±0.089	1.077±0.022	1.098±0.079	1.103±0.041
Mean	1.128±0.088	1.192±0.087	1.203±0.106	1.148±0.076	1.223±0.106	1.218±0.147

Table 52 Peak push-off vertical GRF (BW) during downhill walking for TKR patients

Subject	Replaced limb			Non-replaced limb		
	5°	10°	15°	5°	10°	15°
S1	0.899±0.027	0.878±0.027	0.751±0.037	0.912±0.024	0.862±0.029	0.788±0.025
S2	1.001±0.033	0.995±0.047	0.823±0.047	1.066±0.076	0.920±0.051	0.807±0.054
S3	1.045±0.012	1.052±0.031	1.063±0.049	0.983±0.008	1.096±0.035	1.094±0.096
S4	1.001±0.005	1.000±0.009	0.966±0.021	1.006±0.016	0.991±0.010	1.026±0.027
S5	0.986±0.024	0.852±0.034	0.765±0.062	1.005±0.025	0.859±0.073	0.789±0.023
S6	1.031±0.036	0.972±0.031	0.827±0.054	1.003±0.055	1.027±0.044	0.963±0.059
S7	0.730±0.011	0.715±0.020	-	0.812±0.002	0.758±0.024	-
S8	0.934±0.018	0.882±0.019	0.834±0.034	0.944±0.013	0.950±0.023	0.889±0.038
S9	1.045±0.011	0.966±0.031	0.999±0.035	1.061±0.008	1.052±0.046	0.986±0.028
S10	1.000±0.048	0.999±0.022	0.933±0.031	1.008±0.030	1.019±0.028	0.978±0.018
S11	1.029±0.010	1.010±0.020	-	1.003±0.014	1.003±0.021	-
S12	0.872±0.036	0.823±0.045	0.793±0.020	1.021±0.030	1.022±0.026	0.746±0.034
S13	0.960±0.014	0.942±0.026	0.919±0.027	1.009±0.028	0.973±0.034	0.902±0.050
S14	1.055±0.033	0.954±0.058	0.960±0.049	1.027±0.017	0.946±0.012	0.879±0.036
S15	0.948±0.027	0.888±0.029	0.898±0.019	0.977±0.022	0.967±0.057	0.953±0.027
S16	0.919±0.015	0.918±0.013	0.943±0.033	0.954±0.015	0.958±0.031	1.000±0.041
S18	0.953±0.024	0.954±0.037	-	0.897±0.009	0.925±0.057	-
S19	1.009±0.034	0.945±0.048	0.994±0.046	0.991±0.030	0.947±0.032	0.942±0.004
S20	0.955±0.018	0.920±0.029	0.922±0.029	0.994±0.029	0.975±0.022	0.950±0.034
S21	0.978±0.010	0.986±0.021	0.983±0.040	0.980±0.020	1.070±0.042	1.033±0.048
S22	0.924±0.013	0.957±0.021	0.848±0.071	0.985±0.014	0.970±0.027	0.879±0.040
S23	1.000±0.010	0.982±0.016	0.980±0.019	1.003±0.020	1.000±0.024	0.967±0.034
S24	0.983±0.024	0.958±0.020	0.970±0.018	0.956±0.016	0.933±0.019	0.937±0.009
S28	0.988±0.010	0.981±0.023	0.936±0.041	0.985±0.036	1.024±0.034	1.015±0.021
S31	1.033±0.018	0.987±0.029	0.880±0.033	1.078±0.026	1.043±0.041	1.046±0.047
Mean	0.980±0.049	0.947±0.055	0.908±0.083	0.986±0.055	0.972±0.073	0.935±0.092

Table 53 Peak push-off vertical GRF during downhill walking for healthy control participants

Subject	Limb 1			Limb 2		
	5°	10°	15°	5°	10°	15°
S17	1.034±0.007	0.968±0.028	0.908±0.035	1.017±0.019	0.985±0.043	0.918±0.057
S25	0.907±0.019	0.817±0.041	0.822±0.070	0.898±0.028	0.806±0.033	0.794±0.051
S26	1.017±0.020	0.993±0.014	0.902±0.024	0.969±0.020	0.940±0.011	0.949±0.031
S27	0.971±0.022	0.934±0.028	0.982±0.032	0.986±0.014	0.923±0.018	0.947±0.029
S29	0.987±0.016	1.029±0.039	1.031±0.026	0.982±0.010	0.947±0.011	0.917±0.021
S30	0.938±0.016	0.904±0.036	0.895±0.065	0.938±0.013	0.916±0.014	0.860±0.058
S32	0.916±0.016	0.816±0.044	0.860±0.023	0.972±0.028	0.876±0.013	0.865±0.029
S33	1.060±0.032	0.927±0.060	0.882±0.123	1.000±0.059	0.973±0.055	1.003±0.073
S34	0.872±0.036	0.823±0.045	0.793±0.020	1.021±0.030	1.022±0.026	0.746±0.034
S35	0.991±0.030	0.947±0.032	0.942±0.004	1.009±0.034	0.945±0.048	0.994±0.046
Mean	0.969±0.060	0.916±0.076	0.902±0.071	0.979±0.038	0.933±0.060	0.899±0.083

Table 54 Knee flexion ROM (°) during level and downhill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	-30.568±0.862	-49.677±2.737	-58.910±0.928	-63.823±1.998	-28.645±6.339	-55.212±1.855	-59.963±1.979	-65.303±1.669
S2	-34.470±1.710	-50.232±4.881	-55.393±1.885	-65.499±1.950	-42.814±4.613	-57.560±2.835	-61.757±2.809	-65.560±2.415
S3	-40.080±2.958	-55.526±3.336	-61.461±2.907	-72.648±2.116	-42.085±4.871	-53.535±2.634	-64.533±2.801	-71.634±1.846
S4	-38.505±0.696	-49.276±2.735	-56.181±1.548	-64.865±1.715	-40.186±0.604	-48.669±2.192	-57.149±1.419	-67.767±1.297
S5	-43.306±1.400	-57.926±1.779	-63.219±0.994	-68.843±1.236	-44.004±1.614	-56.397±1.182	-62.541±2.466	-68.548±1.434
S6	-40.048±0.769	-53.457±2.987	-62.185±5.745	-68.342±7.971	-45.259±1.248	-57.752±4.430	-59.867±1.729	-68.697±0.587
S7	-35.189±0.497	-37.063±2.166	-42.284±1.296	-	-40.607±1.304	-50.102±1.377	-57.403±2.174	-
S8	-44.442±1.303	-52.235±3.379	-60.668±2.466	-67.513±0.968	-41.851±0.879	-51.448±0.563	-61.389±2.605	-66.652±0.907
S9	-48.292±1.658	-59.396±1.896	-67.573±2.160	-72.855±3.224	-41.982±2.399	-50.990±2.295	-59.118±2.048	-65.553±0.978
S10	-35.367±2.261	-43.650±3.292	-53.741±1.841	-60.112±1.129	-32.918±2.340	-40.650±1.621	-50.109±5.758	-58.619±1.389
S11	-39.376±2.140	-43.218±2.367	-49.515±3.285	-	-48.520±0.780	-49.202±0.952	-59.312±0.810	-
S12	-53.413±1.133	-65.721±1.904	-75.823±0.398	-83.168±1.220	-53.625±1.203	-60.118±3.624	-69.098±2.025	-79.752±1.927
S13	-46.759±2.044	-53.335±1.985	-60.636±2.233	-67.793±1.330	-45.936±0.730	-55.498±1.425	-62.359±1.446	-67.325±2.230
S14	-44.026±2.893	-40.832±3.843	-49.762±2.361	-59.126±1.994	-39.386±2.165	-46.039±3.982	-50.807±3.934	-54.831±1.826
S15	-43.517±2.572	-52.853±3.722	-54.589±1.986	-60.269±3.729	-43.502±2.482	-55.428±4.364	-61.004±3.756	-70.897±3.399
S16	-42.163±1.364	-47.810±2.381	-57.267±3.302	-65.066±3.015	-37.241±1.490	-45.537±3.512	-52.628±3.684	-60.895±3.455
S18	-36.968±3.192	-54.085±1.801	-63.798±2.050	-	-38.078±1.037	-47.807±1.384	-57.885±1.395	-
S19	-39.510±3.528	-49.888±1.850	-50.173±1.205	-55.091±1.643	-39.293±2.790	-46.827±1.390	-50.133±2.957	-58.938±2.077
S20	-33.861±1.503	-40.628±1.182	-51.288±3.205	-57.036±3.702	-47.286±1.635	-55.684±2.185	-59.754±0.988	-62.620±0.734
S21	-42.915±2.459	-51.602±1.353	-58.665±1.360	-64.729±1.255	-41.945±1.572	-51.117±0.970	-56.051±1.531	-61.958±1.748
S22	-35.510±1.995	-45.389±2.848	-58.930±2.540	-64.555±0.959	-37.130±1.711	-48.731±1.805	-57.165±3.690	-59.102±2.334
S23	-46.728±1.384	-55.529±1.320	-64.130±1.302	-69.275±0.687	-48.843±1.224	-56.547±1.368	-62.854±1.312	-68.429±1.535
S24	-42.883±0.387	-50.853±1.455	-59.363±1.898	-66.004±1.238	-50.182±1.368	-58.698±1.415	-66.572±1.582	-73.075±1.415
S28	-40.364±2.261	-49.818±1.770	-58.304±2.505	-63.396±3.529	-52.831±3.252	-62.353±1.766	-66.315±1.791	-74.895±1.856
S31	-40.922±1.629	-51.466±2.912	-60.646±2.100	-68.506±2.512	-52.335±0.868	-62.445±2.223	-68.057±1.676	-76.925±1.032
Mean	-40.767±5.167	-51.232±5.800	-59.041±5.800	-65.842±5.989	-43.059±6.091	-52.974±5.565	-59.753±5.221	-66.726±6.317

Table 55 Knee flexion ROM (°) during level and downhill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	5°	10°	15°	0°	5°	10°	15°
S17	-52.074±1.354	-59.942±1.790	-67.626±2.341	-75.842±3.419	-49.926±2.964	-59.405±2.353	-67.801±2.134	-72.741±3.646
S25	-46.744±1.793	-58.500±1.947	-67.442±1.171	-71.174±2.246	-56.195±1.441	-65.434±2.085	-71.694±2.806	-74.787±3.092
S26	-35.919±0.597	-45.253±1.045	-57.423±2.745	-67.848±2.756	-40.767±0.422	-52.260±2.269	-62.098±0.676	-69.590±1.828
S27	-45.870±1.659	-55.910±0.894	-63.759±1.056	-72.294±2.077	-45.463±2.118	-54.631±0.866	-62.312±1.080	-68.189±1.341
S29	-31.988±2.807	-45.264±0.857	-56.117±2.864	-64.985±1.917	-35.364±2.196	-42.738±1.668	-54.228±1.233	-60.494±1.911
S30	-42.411±7.424	-53.723±2.300	-63.346±2.462	-72.139±1.181	-45.079±1.497	-55.062±1.241	-65.427±1.830	-68.719±1.969
S32	-52.556±1.772	-62.642±0.969	-68.846±2.103	-74.664±2.021	-46.066±3.085	-58.057±1.678	-62.122±2.884	-70.349±1.997
S33	-33.434±1.528	-42.035±1.817	-57.891±2.167	-68.932±3.554	-34.647±1.238	-39.875±4.316	-56.086±1.155	-66.968±3.245
S34	-53.413±1.133	-65.721±1.904	-75.823±0.398	-83.168±1.220	-53.625±1.203	-60.118±3.624	-69.098±2.025	-79.752±1.927
S35	-39.293±2.790	-46.827±1.390	-50.133±2.957	-58.938±2.077	-39.510±3.528	-49.888±1.850	-50.173±1.205	-55.091±1.643
Mean	-43.370±8.028	-53.582±8.280	-62.841±7.530	-70.998±6.530	-44.664±7.244	-53.747±7.895	-62.104±6.872	-68.668±6.951

Table 56 Knee adduction ROM (°) during level and downhill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	5°	10°	15°	0°	5°	10°	15°
S1	3.759±0.375	3.510±2.405	9.199±0.421	11.493±0.983	4.853±0.447	5.678±1.898	4.853±1.494	5.575±1.951
S2	4.944±1.500	5.889±1.676	5.269±1.475	8.968±1.130	9.086±0.817	12.601±1.222	9.086±1.352	12.993±1.266
S3	1.069±0.038	4.351±0.743	7.262±0.467	8.926±0.000	2.417±0.349	4.720±1.206	7.294±3.899	5.391±1.266
S4	1.300±0.066	2.414±0.363	2.729±0.260	3.816±0.650	0.825±0.578	6.584±0.444	7.397±1.469	6.672±1.469
S5	1.999±0.195	0.000±0.322	10.997±0.186	10.726±1.061	4.971±0.603	3.890±0.470	5.985±0.133	5.563±1.267
S6	7.115±0.552	8.011±0.915	9.981±0.610	16.194±0.000	11.067±0.000	11.196±1.834	13.708±0.606	13.995±1.327
S7	2.806±0.605	1.946±0.521	1.816±1.114	-	4.226±0.911	4.987±0.580	4.226±1.017	-
S8	6.961±0.000	7.644±1.868	10.305±0.538	10.335±1.158	6.340±0.294	7.254±0.266	9.353±0.747	10.803±1.169
S9	4.631±0.373	4.224±0.000	4.881±0.444	8.727±0.481	3.838±0.657	2.840±0.492	3.976±1.076	5.596±1.041
S10	5.830±0.665	6.065±1.527	5.171±0.652	4.844±1.120	4.430±0.649	4.671±1.034	5.129±0.775	4.927±1.035
S11	3.364±0.826	3.997±0.516	3.699±0.904	-	3.763±0.194	3.789±0.587	4.614±1.141	-
S12	5.552±0.680	3.499±0.000	4.600±1.325	4.337±1.239	4.337±0.488	4.491±0.000	6.540±0.507	5.770±1.655
S13	7.803±0.000	7.164±1.588	13.077±1.564	15.699±2.215	3.238±0.550	5.092±0.559	10.034±1.116	11.662±0.723
S14	5.886±0.519	6.530±0.556	6.331±1.037	5.463±0.955	4.181±0.516	4.925±0.564	5.419±0.254	5.423±1.103
S15	2.841±0.000	2.154±0.126	2.361±0.115	4.646±1.846	3.840±0.148	3.755±0.702	2.684±0.977	3.592±1.483
S16	3.266±0.211	1.845±0.397	2.560±0.743	3.893±0.879	3.893±0.285	4.323±0.579	4.063±0.291	6.884±1.042
S18	2.618±1.613	4.067±0.246	5.198±0.561	-	9.232±0.000	8.563±0.481	12.344±0.720	-
S19	2.824±0.636	3.044±0.067	3.842±0.865	5.262±1.394	2.159±0.322	1.934±0.483	2.122±0.000	1.796±0.600
S20	4.182±0.728	6.605±0.264	6.503±0.899	5.559±1.311	5.262±0.830	6.195±0.418	6.263±0.767	7.492±1.129
S21	3.679±0.185	2.576±0.332	1.743±0.535	2.567±0.437	2.701±0.267	3.546±0.144	3.726±0.221	5.186±0.692
S22	3.084±0.850	3.295±0.427	6.508±0.324	17.062±1.364	6.904±0.000	4.122±0.338	2.694±0.405	4.560±1.042
S23	2.602±0.433	2.877±0.000	2.465±0.603	5.005±0.369	3.303±0.085	2.404±0.513	3.139±0.690	5.828±1.182
S24	5.101±0.945	6.295±0.481	6.152±0.827	6.728±0.859	5.141±0.239	5.360±0.389	5.907±1.112	7.197±0.168
S28	2.553±0.795	4.285±0.468	5.335±1.748	7.916±1.213	2.407±0.630	2.450±0.477	1.642±0.388	3.084±0.496
S31	3.328±0.083	3.404±0.578	4.755±0.000	3.509±0.000	3.509±0.409	8.134±1.056	8.448±0.000	10.520±0.000
Mean	3.376±1.173	4.349±2.130	6.001±3.081	7.803±4.278	4.610±2.489	5.280±2.653	5.885±2.974	6.841±3.199

Table 57 Knee adduction ROM (°) during level and downhill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	5°	10°	15°	0°	5°	10°	15°
S17	4.602±0.449	7.006±0.562	7.724±1.868	9.745±1.460	4.091±0.259	6.195±0.647	5.588±0.000	7.492±0.567
S25	2.226±0.549	2.224±0.645	6.063±0.846	4.942±0.699	2.479±0.000	5.045±0.561	5.039±0.535	4.590±0.850
S26	4.229±0.174	3.724±0.791	3.876±0.567	9.178±0.000	4.959±0.000	3.621±0.415	4.610±0.158	6.393±0.668
S27	4.710±0.436	4.502±0.422	3.769±0.738	6.020±0.844	5.581±0.227	4.089±0.137	3.554±0.277	4.604±0.825
S29	3.761±0.289	2.306±0.437	1.649±0.196	1.900±0.984	1.990±0.405	4.124±0.000	4.311±0.601	4.368±1.963
S30	3.156±1.066	2.513±0.413	2.454±0.360	5.431±0.508	2.014±0.238	1.522±0.528	1.981±0.214	3.583±0.728
S32	4.206±0.442	4.385±0.883	5.300±0.000	5.467±0.738	2.250±0.790	2.053±0.293	4.512±0.484	8.153±0.738
S33	1.213±0.611	1.872±0.397	4.118±0.000	6.185±0.000	0.805±0.170	3.762±0.448.	6.105±0.601	7.586±0.647
S34	3.498±0.541	3.499±0.000	4.600±1.325	4.337±1.239	4.222±0.647	4.491±0.000	6.540±0.524	5.770±1.655
S35	2.159±0.322	1.934±0.483	2.122±0.000	1.796±0.600	2.824±0.636	3.044±0.067	3.842±0.865	5.262±1.394
Mean	3.122±1.517	3.397±1.604	4.168±1.868	5.500±2.596	3.122±1.517	3.687±0.520	4.608±1.325	6.088±2.138

Table 58 Knee internal rotation ROM (°) during level and downhill walking for TKR patients

Subject	**Replaced limb**				**Non-replaced limb**			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	3.759±0.375	9.001±2.326	8.740±3.525	9.085±1.537	8.978±0.847	10.972±2.336	8.852±1.093	9.767±0.716
S2	4.944±1.500	17.081±1.579	12.226±1.365	11.320±0.159	6.855±0.577	7.423±1.628	9.853±1.197	7.377±1.671
S3	1.149±0.165	4.203±2.560	2.7758±1.439	1.938±0.224	3.321±0.284	0.951±0.000	1.383±2.125	2.563±1.400
S4	1.300±0.066	4.733±0.836	3.407±1.688	4.419±1.662	6.374±0.536	3.940±0.842	3.920±0.968	4.201±0.765
S5	2.806±0.605	1.543±0.166	3.447±1.906	4.144±2.633.	1.916±0.431	0.644±1.164	0.390±1.541	-5.165±1.092
S6	7.506±0.764	5.637±1.788	2.466±1.083	5.322±2.398	5.348±1.233	5.871±0.083	5.369±1.441	4.146±1.132
S7	5.552±0.680	4.785±1.937	7.440±1.189	-	3.009±0.910	2.760±0.107	3.344±1.015	-
S8	6.961±0.000	2.630±0.760	4.939±1.490	6.319±1.915	-3.009±0.933	-3.832±0.819	-4.742±4.490	-4.826±1.929
S9	4.631±0.373	5.020±0.673	3.917±0.530	2.338±0.615	1.692±0.000	4.066±0.751	5.017±0.675	4.346±0.447
S10	5.830±0.665	8.666±2.967	7.649±0.000	7.746±2.592	6.657±0.469	6.589±0.683	5.681±1.567	3.418±0.089
S11	3.364±0.826	8.804±1.382	7.357±1.716	-	7.528±0.888	9.206±2.101	10.280±1.241	-
S12	2.125±0.533	20.026±2.967	13.578±0.817	12.663±0.995	7.119±0.000	9.771±2.062	9.809±0.989	13.199±1.177
S13	7.803±0.000	12.296±1.328	7.924±2.122	8.135±1.936	13.304±1.807	11.650±1.276	13.611±1.569	16.755±1.378
S14	5.886±0.519	12.028±1.680	10.013±1.753.	11.109±1.628	12.077±0.468	9.433±1.244	9.427±3.377	3.565±0.955
S15	2.841±0.000	11.704±1.497	12.266±1.951	14.656±1.627	7.985±1.260	10.242±1.418	9.309±2.324	12.111±0.659
S16	3.266±0.211	3.615±1.130	3.202±2.763	7.082±1.666	1.024±1.284	0.939±0.000	-2.874±1.853	-0.567±0.816
S18	2.618±1.613	9.901±1.568	10.064±1.617	-	1.261±0.000	-2.142±0.000	2.800±1.627	-
S19	2.824±0.636	10.169±3.449	6.926±2.815	9.905±1.974	0.117±0.884	11.697±2.975	11.784±1.626	14.561±1.929
S20	1.232±0.793	7.739±1.133	12.259±0.692	2.673±0.478	10.005±0.590	6.706±2.665	6.829±1.802	3.131±0.816
S21	3.679±0.185	7.549±0.000	11.477±0.382	7.902±0.289	6.017±0.694	5.221±0.939	3.947±1.228	3.780±0.000
S22	3.084±0.850	6.347±1.735	9.478±1.642	12.479±2.231	1.504±0.000	3.827±0.474	6.020±0.000	5.284±0.328
S23	2.602±0.433	4.894±1.484	5.083±1.185	4.445±1.328	4.381±0.590	5.255±0.000	4.635±1.128	2.915±0.714
S24	5.101±0.945	6.097±0.852	4.830±0.645	3.872±0.738	3.156±1.076	1.722±0.484	0.839±0.375	3.115±0.456
S28	3.755±0.497	11.977±2.978	9.633±2.160	6.555±2.538	1.032±0.176	16.694±1.496	13.207±2.296	13.212±1.725
S31	3.328±0.083	8.102±0.260	6.270±1.310	1.693±0.877	5.019±0.659	3.919±2.061	4.354±1.561	6.099±0.571
Mean	3.767±2.110	8.230±4.587	6.800±4.241	7.082±3.782	5.868±4.753	6.077±4.696	5.711±4.815	5.537±5.735

Table 59 Knee internal rotation ROM (°) during level and downhill walking for healthy control participants

Subject	**Limb 1**				**Limb 2**			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	10.340±1.004	9.900±1.604	5.501±0.638	6.312±1.462	6.017±0421.	4.853±0.628	3.453±1.689	5.675±1.115
S25	7.587±0.647	6.223±0.484	6.999±0.647	6.356±0.588	5.641±0.152	7.534±0.591	6.957±1.367	3.772±0.476
S26	7.851±0.144	8.201±0.235	6.253±0.138	7.101±2.001	9.633±0.582	11.032±0.416	10.167±0.460.	10.168±0.647
S27	2.723±0.478	4.060±1.591	4.338±1.292	6.138±0.556	7.182±0.394	5.282±0.173	7.502±0.594	8.383±0.615
S29	1.901±1.370	4.178±0.951	4.876±0.461	6.116±0.458	5.377±0.921	5.674±0.749	5.552±0.452	6.823±0.895
S30	7.710±1.594	8.385±2.523	6.290±0.960	8.297±2.056	4.568±0.318	2.902±0.552	2.935±0.541	2.541±0.515
S32	11.137±1.162.	8.643±0.268	7.579±1.269	4.969±0.000	16.646±0.510	12.686±1.582	10.633±0.338	7.935±0.000
S33	3.642±0.484	5.641±0.919	5.324±1.569	1.719±0.520	2.356±0.182	5.114±0.218	0.904±0.043	4.748±0.827
S34	16.652±0.591	19.832±2.967	13.578±0.817	12.663±0.995	6.624±0.000	9.771±0.938	9.809±0.322	13.199±1.177
S35	10.005±0.199	11.697±0.413	11.784±0.218	14.561±0.582	9.974±0.235	10.169±0.444	10.496±0.416	10.737±1.974
Mean	7.909±4.524	8.661±4.720	7.199±3.055	7.552±3.633	7.573±3.944	7.424±3.308	6.706±3.490	7.419±3.202

Table 60 Peak loading-response KEM (Nm/kg) during level and downhill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.722±0.050	0.777±0.078	0.970±0.073	1.062±0.046	0.710±0.088	0.938±0.127	1.265±0.023	1.722±0.068
S2	0.252±0.093	0.610±0.203	0.838±0.097	1.104±0.073	0.315±0.044	0.699±0.157	0.992±0.148	1.344±0.045
S3	0.277±0.111	0.496±0.127	0.601±0.076	0.692±0.126	0.241±0.073	0.383±0.109	0.506±0.161	0.926±0.108
S4	0.366±0.031	0.519±0.118	0.645±0.037	0.924±0.178	0.332±0.034	0.387±0.077	0.368±0.222	0.697±0.055
S5	0.492±0.037	0.658±0.139	0.830±0.083	0.987±0.061	0.754±0.168	0.906±0.141	1.196±0.047	1.487±0.081
S6	0.132±0.037	0.243±0.088	0.344±0.071	0.718±0.152	0.159±0.074	0.256±0.045	0.377±0.086	0.643±0.142
S7	0.093±0.030	0.083±0.097	0.119±0.028	-	0.172±0.041	0.221±0.098	0.210±0.079	-
S8	0.712±0.041	0.771±0.072	0.895±0.068	1.115±0.049	0.833±0.190	0.931±0.047	1.314±0.070	1.575±0.092
S9	0.315±0.100	0.425±0.089	0.640±0.122	0.787±0.066	0.414±0.134	0.500±0.051	0.789±0.125	0.980±0.089
S10	0.360±0.064	0.328±0.092	0.432±0.065	0.427±0.075	0.238±0.073	0.298±0.106	0.384±0.090	0.479±0.112
S11	0.362±0.033	0.514±0.053	0.692±0.014	-	0.260±0.037	0.261±0.118	0.554±0.081	-
S12	-0.066±0.031	0.054±0.035	-0.002±0.051	0.083±0.054	0.104±0.080	0.440±0.103	0.724±0.132	0.148±0.100
S13	0.526±0.051	0.541±0.070	0.724±0.098	1.044±0.091	0.592±0.060	0.617±0.200	0.936±0.073	1.017±0.137
S14	0.368±0.026	0.320±0.070	0.547±0.075	0.790±0.082	0.306±0.031	0.328±0.058	0.512±0.069	0.552±0.032
S15	0.289±0.140	0.353±0.126	0.614±0.099	0.896±0.041	0.121±0.069	0.299±0.088	0.640±0.136	0.677±0.090
S16	0.595±0.110	0.486±0.094	0.508±0.076	0.686±0.102	0.586±0.081	0.661±0.192	0.872±0.135	0.966±0.126
S18	0.074±0.112	0.091±0.095	0.326±0.086	-	-0.210±0.029	-0.124±0.059	0.001±0.104	-
S19	0.434±0.071	0.370±0.074	0.446±0.059	0.594±0.095	0.290±0.048	0.305±0.067	0.459±0.058	0.603±0.125
S20	0.035±0.053	0.196±0.065	0.460±0.041	0.602±0.035	0.069±0.056	0.197±0.074	0.610±0.080	0.863±0.080
S21	0.349±0.022	0.610±0.080	0.650±0.045	0.844±0.146	0.532±0.068	0.786±0.095	1.031±0.067	1.233±0.167
S22	0.109±0.035	0.156±0.050	0.255±0.027	0.453±0.037	0.242±0.065	0.473±0.070	0.532±0.067	0.793±0.065
S23	0.225±0.066	0.360±0.026	0.261±0.086	0.373±0.028	0.335±0.048	0.492±0.035	0.512±0.101	0.748±0.147
S24	0.636±0.042	0.745±0.067	0.872±0.075	1.073±0.108	0.603±0.089	0.818±0.039	1.048±0.110	1.367±0.060
S28	0.141±0.042	0.155±0.059	0.420±0.082	0.575±0.062	0.230±0.036	0.298±0.052	0.724±0.074	0.955±0.102
S31	0.390±0.101	0.548±0.081	0.816±0.068	0.769±0.117	0.427±0.057	0.628±0.115	0.807±0.137	0.963±0.048
Mean	0.327±0.210	0.436±0.218	0.580±0.243	0.754±0.270	0.346±0.240	0.480±0.267	0.695±0.331	0.943±0.387

Table 61 Peak loading-response KEM (Nm/kg) during level and downhill walking for healthy control participants

Subject	**Limb 1**				**Limb 2**			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0.254±0.067	0.405±0.033	0.684±0.108	0.990±0.081	0.257±0.106	0.513±0.084	0.715±0.085	0.905±0.080
S25	0.829±0.127	0.928±0.035	1.461±0.099	1.498±0.130	0.892±0.060	0.981±0.060	1.244±0.134	1.289±0.196
S26	0.527±0.042	0.587±0.058	0.928±0.060	1.060±0.177	0.447±0.035	0.518±0.071	0.746±0.110	0.928±0.134
S27	0.457±0.035	0.689±0.132	0.904±0.138	1.073±0.104	0.855±0.052	1.013±0.070	1.239±0.075	1.570±0.109
S29	0.496±0.045	0.588±0.040	0.674±0.052	1.027±0.110	0.570±0.058	0.585±0.053	0.756±0.096	0.747±0.033
S30	0.461±0.100	0.535±0.051	0.913±0.067	1.092±0.089	0.645±0.069	0.779±0.089	1.049±0.027	1.289±0.077
S32	0.650±0.070	0.748±0.148	0.904±0.074	1.054±0.044	0.646±0.059	0.796±0.104	0.952±0.088	0.952±0.131
S33	0.961±0.073	0.965±0.134	1.164±0.047	1.461±0.117	0.802±0.044	0.774±0.101	1.019±0.143	1.203±0.108
S34	-0.066±0.031	-0.054±0.035	-0.002±0.051	0.083±0.054	0.104±0.080	0.440±0.103	0.724±0.132	0.148±0.100
S35	0.290±0.048	0.305±0.067	0.459±0.058	0.603±0.125	0.434±0.071	0.370±0.074	0.446±0.059	0.594±0.095
Mean	0.486±0.292	0.570±0.302	0.809±0.396	0.994±0.405	0.565±0.258	0.677±0.224	0.889±0.255	0.963±0.407

Table 62 Peak push-off KEM (Nm/kg) during level and downhill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	5°	10°	15°	0°	5°	10°	15°
S1	-0.107±0.039	0.414±0.074	0.653±0.052	0.699±0.068	-0.435±0.019	0.353±0.051	0.705±0.077	1.085±0.082
S2	0.305±0.011	0.366±0.095	0.737±0.165	1.010±0.071	0.413±0.047	0.611±0.133	1.030±0.143	1.098±0.133
S3	0.107±0.011	0.556±0.191	0.903±0.072	1.334±0.118	0.076±0.061	0.373±0.042	1.011±0.045	1.353±0.139
S4	0.277±0.111	0.226±0.055	0.555±0.049	0.914±0.042	0.118±0.046	0.150±0.014	0.490±0.069	1.073±0.153
S5	0.165±0.013	0.531±0.033	0.674±0.053	0.821±0.054	0.145±0.011	0.508±0.030	0.714±0.105	0.987±0.098
S6	0.052±0.013	0.513±0.109	0.743±0.051	0.988±0.091	0.051±0.007	0.319±0.088	0.684±0.093	1.148±0.030
S7	0.126±0.004	0.213±0.034	0.255±0.046	-	0.185±0.011	0.450±0.037	0.582±0.025	-
S8	0.192±0.019	0.442±0.041	0.752±0.040	1.086±0.086	0.318±0.042	0.552±0.033	0.986±0.127	1.257±0.092
S9	0.397±0.052	0.707±0.054	0.958±0.056	1.117±0.083	0.320±0.048	0.659±0.059	1.033±0.041	1.200±0.056
S10	0.087±0.026	0.036±0.107	0.594±0.066	0.886±0.086	0.095±0.012	0.183±0.019	0.566±0.082	0.980±0.078
S11	0.196±0.022	0.460±0.038	0.746±0.076	-	0.099±0.013	0.432±0.069	0.900±0.037	-
S12	0.115±0.005	0.174±0.021	0.429±0.093	0.668±0.062	0.176±0.014	0.330±0.049	0.730±0.041	0.511±0.081
S13	0.324±0.026	0.477±0.039	1.039±0.105	1.382±0.042	0.374±0.026	0.656±0.068	1.400±0.101	1.560±0.093
S14	0.091±0.024	0.170±0.012	0.315±0.099	0.692±0.060	0.065±0.004	0.103±0.017	0.170±0.072	0.486±0.066
S15	0.127±0.019	0.186±0.031	0.319±0.083	0.923±0.134	0.087±0.005	0.190±0.012	0.415±0.083	0.812±0.060
S16	0.132±0.020	0.555±0.064	0.976±0.085	1.299±0.113	0.109±0.015	0.729±0.114	1.208±0.080	1.665±0.152
S18	0.053±0.056	0.526±0.059	0.827±0.085	-	0.068±0.005	0.350±0.048	0.610±0.063	-
S19	0.254±0.061	0.370±0.033	0.766±0.151	1.201±0.103	0.176±0.008	0.367±0.048	0.642±0.081	1.047±0.075
S20	0.103±0.020	0.317±0.040	0.639±0.073	0.821±0.055	0.136±0.027	0.489±0.089	0.777±0.021	0.994±0.054
S21	0.116±0.024	0.284±0.017	0.634±0.043	0.965±0.034	0.252±0.033	0.512±0.024	0.923±0.085	1.321±0.124
S22	0.094±0.001	0.139±0.015	0.339±0.067	0.572±0.074	0.089±0.012	0.296±0.044	0.649±0.024	0.801±0.054
S23	0.211±0.013	0.506±0.091	0.783±0.020	0.966±0.057	0.220±0.024	0.465±0.039	0.831±0.113	1.021±0.073
S24	0.220±0.036	0.512±0.061	1.066±0.121	1.311±0.083	0.204±0.013	0.416±0.041	1.000±0.089	1.362±0.062
S28	0.139±0.020	0.204±0.048	0.476±0.019	0.910±0.094	0.203±0.007	0.429±0.069	1.040±0.078	1.515±0.052
S31	0.187±0.018	0.376±0.054	0.741±0.150	0.977±0.074	0.190±0.007	0.515±0.143	0.887±0.070	1.348±0.125
Mean	0.348±0.210	0.373±0.173	0.692±0.226	0.982±0.231	0.155±0.170	0.431±0.165	0.829±0.274	1.122±0.310

Table 63 Peak push-off KEM (Nm/kg) during level and downhill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	5°	10°	15°	0°	5°	10°	15°
S17	0.158±0.010	0.382±0.028	0.732±0.060	1.100±0.093	0.187±0.025	0.409±0.062	0.825±0.068	1.206±0.102
S25	0.291±0.025	0.399±0.054	0.898±0.090	1.295±0.123	0.265±0.021	0.475±0.058	0.752±0.152	1.266±0.097
S26	0.169±0.024	0.378±0.025	0.913±0.049	1.469±0.087	0.119±0.013	0.327±0.040	0.689±0.116	1.153±0.094
S27	0.091±0.023	0.317±0.037	0.762±0.037	1.222±0.098	0.190±0.029	0.377±0.030	0.913±0.038	1.399±0.062
S29	0.097±0.034	0.332±0.022	1.050±0.133	1.554±0.127	0.191±0.019	0.394±0.029	0.797±0.019	1.112±0.033
S30	0.209±0.010	0.292±0.071	0.656±0.072	1.356±0.135	0.334±0.019	0.513±0.044	0.864±0.046	1.263±0.167
S32	0.307±0.006	0.398±0.021	0.573±0.062	1.098±0.103	0.259±0.014	0.379±0.027	0.524±0.021	0.903±0.059
S33	0.177±0.020	0.323±0.031	0.684±0.077	1.178±0.157	0.121±0.012	0.227±0.015	0.545±0.104	1.167±0.179
S34	0.115±0.005	0.174±0.021	0.429±0.093	0.668±0.062	0.176±0.014	0.330±0.049	0.730±0.041	0.511±0.081
S35	0.176±0.008	0.367±0.048	0.642±0.081	1.047±0.075	0.254±0.061	0.370±0.033	0.766±0.151	1.201±0.103
Mean	0.179±0.074	0.336±0.068	0.734±0.181	1.199±0.249	0.210±0.068	0.380±0.079	0.741±0.127	1.118±0.248

Table 64 Peak loading-response KAbM (Nm/kg) during downhill walking for TKR patients

Subject	Replaced limb			Non-replaced limb		
	5°	10°	15°	5°	10°	15°
S1	-0.366±0.037	-0.424±0.054	-0.496±0.030	-0.746±0.062	-0.756±0.038	-0.746±0.057
S2	-0.210±0.042	-0.096±0.042	-0.245±0.086	-0.116±0.030	-0.070±0.069	-0.226±0.063
S3	-0.513±0.054	-0.506±0.042	-0.479±0.047	-0.610±0.057	-0.666±0.038	-0.710±0.038
S4	-0.426±0.042	-0.490±0.043	-0.535±0.053	-0.729±0.020	-0.737±0.021	-0.811±0.081
S5	-0.444±0.037	-0.488±0.038	-0.513±0.037	-0.443±0.026	-0.555±0.042	-0.575±0.022
S6	-0.280±0.097	-0.398±0.034	-0.444±0.066	-0.497±0.069	-0.471±0.022	-0.607±0.021
S7	-0.304±0.032	-0.312±0.026	-	-0.328±0.026	-0.322±0.060	-
S8	-0.540±0.016	-0.508±0.060	-0.512±0.060	-0.686±0.023	-0.739±0.073	-0.694±0.060
S9	-0.425±0.029	-0.450±0.022	-0.464±0.033	-0.580±0.027	-0.594±0.024	-0.644±0.048
S10	-0.178±0.038	-0.167±0.048	-0.222±0.059	-0.361±0.021	-0.333±0.090	-0.269±0.036
S11	-0.292±0.046	-0.258±0.043	-	-0.441±0.019	-0.439±0.067	-
S12	-0.293±0.028	-0.290±0.036	-0.256±0.035	-0.492±0.076	-0.423±0.029	-0.271±0.044
S13	-0.069±0.025	-0.227±0.053	-0.357±0.047	-0.041±0.038	-0.002±0.047	-0.044±0.020
S14	-0.394±0.070	-0.499±0.072	-0.547±0.080	-0.046±0.031	-0.128±0.037	-0.159±0.032
S15	-0.363±0.037	-0.313±0.051	-0.267±0.096	-0.453±0.040	-0.453±0.068	-0.326±0.073
S16	-0.106±0.038	-0.099±0.047	-0.080±0.040	-0.447±0.045	-0.450±0.070	-0.583±0.086
S18	-0.193±0.034	-0.155±0.053	-	-0.372±0.031	-0.413±0.083	-
S19	-0.331±0.023	-0.333±0.024	-0.297±0.027	-0.367±0.013	-0.351±0.046	-0.267±0.055
S20	-0.397±0.051	-0.376±0.060	-0.405±0.070	-0.333±0.033	-0.441±0.024	-0.399±0.019
S21	-0.334±0.033	-0.354±0.023	-0.323±0.059	-0.352±0.035	-0.363±0.029	-0.278±0.027
S22	-0.365±0.011	-0.181±0.035	-0.413±0.043	-0.284±0.019	-0.248±0.084	-0.413±0.046
S23	-0.143±0.009	-0.157±0.050	-0.161±0.035	-0.294±0.038	-0.258±0.036	-0.272±0.054
S24	-0.557±0.028	-0.553±0.039	-0.508±0.024	-0.678±0.026	-0.644±0.015	-0.725±0.023
S28	-0.602±0.025	-0.614±0.049	-0.560±0.029	-0.200±0.088	-0.259±0.025	-0.156±0.034
S31	-0.375±0.017	-0.476±0.077	-0.368±0.059	-0.537±0.046	-0.684±0.042	-0.566±0.073
Mean	-0.350±0.139	-0.363±0.154	-0.384±0.137	-0.422±0.207	-0.437±0.225	-0.443±0.228

Table 65 Peak loading-response KAbM (Nm/kg) during downhill walking for healthy control participants

Subject	Limb 1			Limb 2		
	5°	**10°**	**15°**	**5°**	**10°**	**15°**
S17	-0.475±0.020	-0.531±0.018	-0.478±0.061	-0.423±0.012	-0.453±0.028	-0.509±0.047
S25	-0.458±0.018	-0.584±0.027	-0.528±0.036	-0.689±0.048	-0.732±0.074	-0.685±0.064
S26	-0.405±0.011	-0.464±0.052	-0.361±0.039	-0.274±0.070	-0.253±0.038	-0.300±0.098
S27	-0.658±0.039	-0.593±0.018	-0.581±0.025	-0.575±0.015	-0.598±0.032	-0.583±0.015
S29	-0.310±0.025	-0.265±0.023	-0.296±0.047	-0.102±0.026	-0.052±0.024	-0.076±0.032
S30	-0.311±0.018	-0.368±0.029	-0.359±0.023	-0.275±0.012	-0.336±0.026	-0.352±0.021
S32	-0.513±0.051	-0.572±0.032	-0.579±0.032	-0.320±0.040	-0.382±0.057	-0.440±0.021
S33	-0.394±0.044	-0.497±0.059	-0.497±0.039	-0.636±0.051	-0.678±0.038	-0.638±0.090
S34	-0.293±0.028	-0.290±0.036	-0.256±0.035	-0.492±0.076	-0.423±0.029	-0.271±0.044
S35	-0.367±0.013	-0.351±0.046	-0.267±0.055	-0.331±0.023	-0.333±0.024	-0.297±0.027
Mean	-0.418±0.112	-0.451±0.124	-0.420±0.127	-0.412±0.185	-0.424±0.204	-0.415±0.191

Table 66 Peak push-off KAbM (Nm/kg) during downhill walking for TKR patients

Subject	Replaced limb			Non-replaced limb		
	5°	10°	15°	5°	10°	15°
S1	-0.282±0.038	-0.349±0.034	-0.346±0.028	-0.548±0.042	-0.540±0.019	-0.471±0.032
S2	-0.160±0.071	-0.168±0.022	-0.291±0.031	-0.094±0.080	-0.208±0.048	-0.300±0.058
S3	-0.403±0.026	-0.487±0.016	-0.518±0.090	-0.506±0.032	-0.554±0.056	-0.580±0.105
S4	-0.526±0.048	-0.558±0.018	-0.521±0.031	-0.696±0.035	-0.753±0.010	-0.798±0.039
S5	-0.404±0.022	-0.368±0.048	-0.401±0.036	-0.420±0.022	-0.371±0.042	-0.335±0.042
S6	-0.413±0.041	-0.433±0.046	-0.427±0.042	-0.450±0.046	-0.569±0.044	-0.655±0.054
S7	-0.226±0.036	-0.287±0.009	-	-0.374±0.017	-0.362±0.023	-
S8	-0.459±0.034	-0.450±0.040	-0.502±0.045	-0.438±0.019	-0.550±0.039	-0.568±0.026
S9	-0.455±0.023	-0.425±0.046	-0.577±0.058	-0.578±0.016	-0.544±0.054	-0.611±0.052
S10	-0.197±0.031	-0.266±0.032	-0.280±0.052	-0.347±0.043	-0.344±0.019	-0.304±0.045
S11	-0.361±0.012	-0.347±0.027	-	-0.437±0.024	-0.410±0.039	-
S12	-0.185±0.018	-0.099±0.021	-0.151±0.016	-0.324±0.043	-0.393±0.019	-0.127±0.042
S13	-0.019±0.026	-0.457±0.021	-0.618±0.087	0.029±0.036	-0.033±0.041	-0.058±0.033
S14	-0.297±0.052	-0.265±0.030	-0.232±0.034	-0.102±0.032	-0.059±0.019	-0.088±0.030
S15	-0.181±0.035	-0.232±0.039	-0.175±0.050	-0.194±0.024	-0.262±0.045	-0.259±0.040
S16	-0.072±0.020	-0.090±0.036	-0.105±0.036	-0.493±0.023	-0.518±0.022	-0.584±0.046
S18	-0.221±0.057	-0.184±0.057	-	-0.512±0.052	-0.580±0.024	-
S19	-0.297±0.023	-0.326±0.050	-0.401±0.046	-0.379±0.009	-0.334±0.009	-0.300±0.032
S20	-0.431±0.014	-0.361±0.044	-0.412±0.061	-0.331±0.028	-0.330±0.030	-0.382±0.040
S21	-0.281±0.008	-0.313±0.049	-0.338±0.031	-0.281±0.026	-0.338±0.051	-0.365±0.030
S22	-0.306±0.027	-0.315±0.180	-0.413±0.055	-0.297±0.017	-0.302±0.040	-0.353±0.040
S23	-0.172±0.027	-0.166±0.026	-0.203±0.022	-0.339±0.024	-0.388±0.032	-0.363±0.027
S24	-0.571±0.033	-0.512±0.015	-0.532±0.035	-0.617±0.025	-0.620±0.017	-0.659±0.017
S28	-0.500±0.064	-0.559±0.043	-0.588±0.058	-0.080±0.080	-0.165±0.024	-0.157±0.042
S31	-0.392±0.052	-0.432±0.057	-0.392±0.037	-0.538±0.071	-0.576±0.027	-0.564±0.047
Mean	-0.318±0.150	-0.347±0.138	-0.383±0.148	-0.365±0.190	-0.398±0.186	-0.404±0.203

Table 67 Peak push-off KAbM (Nm/kg) during downhill walking for healthy control participants

Subject	Limb 1			Limb 2		
	5°	10°	15°	5°	10°	15°
S17	-0.431±0.020	-0.494±0.025	-0.462±0.061	-0.437±0.019	-0.511±0.053	-0.500±0.058
S25	-0.206±0.024	-0.291±0.082	-0.391±0.076	-0.526±0.019	-0.506±0.057	-0.505±0.073
S26	-0.310±0.002	-0.373±0.050	-0.475±0.047	-0.251±0.010	-0.241±0.009	-0.326±0.004
S27	-0.557±0.016	-0.515±0.021	-0.557±0.063	-0.526±0.021	-0.497±0.011	-0.532±0.041
S29	-0.191±0.013	-0.163±0.014	-0.142±0.051	-0.044±0.017	0.033±0.035	-0.097±0.043
S30	-0.109±0.012	-0.090±0.026	-0.149±0.031	-0.096±0.023	-0.095±0.024	-0.182±0.067
S32	-0.182±0.030	-0.274±0.057	-0.357±0.072	-0.099±0.040	-0.159±0.038	-0.324±0.049
S33	-0.256±0.026	-0.341±0.029	-0.341±0.049	-0.458±0.028	-0.538±0.062	-0.623±0.043
S34	-0.185±0.018	-0.099±0.021	-0.151±0.016	-0.324±0.043	-0.393±0.019	-0.127±0.042
S35	-0.379±0.009	-0.334±0.009	-0.300±0.032	-0.297±0.023	-0.326±0.050	-0.401±0.046
Mean	-0.281±0.138	-0.297±0.147	-0.332±0.147	-0.306±0.181	-0.323±0.201	-0.362±0.182

Table 68 Peak internal rotation moment (Nm/kg) during level and downhill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.131±0.017	0.148±0.024	0.191±0.024	0.233±0.023	0.196±0.017	0.219±0.029	0.260±0.017	0.334±0.016
S2	0.057±0.007	0.091±0.025	0.099±0.017	0.164±0.022	0.061±0.010	0.104±0.023	0.136±0.030	0.200±0.021
S3	0.146±0.016	0.131±0.027	0.148±0.050	0.186±0.043	0.181±0.009	0.128±0.034	0.168±0.037	0.234±0.035
S4	0.077±0.009	0.127±0.027	0.126±0.009	0.230±0.033	0.090±0.006	0.096±0.018	0.068±0.012	0.155±0.040
S5	0.152±0.019	0.154±0.016	0.192±0.010	0.236±0.013	0.082±0.038	0.108±0.016	0.171±0.015	0.174±0.011
S6	0.066±0.019	0.094±0.017	0.125±0.017	0.162±0.015	0.053±0.012	0.107±0.017	0.122±0.012	0.181±0.014
S7	0.020±0.008	0.034±0.013	0.039±0.014	-	0.127±0.007	0.079±0.014	0.088±0.013	-
S8	0.185±0.022	0.211±0.008	0.223±0.027	0.303±0.036	0.372±0.045	0.282±0.018	0.363±0.032	0.409±0.029
S9	0.115±0.018	0.095±0.019	0.119±0.013	0.192±0.017	0.078±0.014	0.081±0.010	0.132±0.015	0.222±0.023
S10	0.063±0.016	0.079±0.012	0.100±0.018	0.108±0.019	0.137±0.013	0.145±0.023	0.143±0.016	0.158±0.019
S11	0.118±0.012	0.132±0.013	0.150±0.015	-	0.048±0.008	0.070±0.028	0.129±0.022	-
S12	-0.001±0.004	-0.010±0.005	0.014±0.021	0.030±0.012	0.052±0.017	0.119±0.027	0.169±0.027	0.033±0.009
S13	0.077±0.022	0.136±0.030	0.099±0.022	0.156±0.023	0.178±0.022	0.173±0.053	0.218±0.022	0.257±0.036
S14	0.092±0.015	0.095±0.012	0.137±0.018	0.191±0.028	0.097±0.020	0.085±0.017	0.126±0.025	0.143±0.026
S15	0.047±0.056	0.053±0.028	0.106±0.009	0.194±0.030	0.080±0.018	0.117±0.033	0.169±0.026	0.183±0.031
S16	0.155±0.031	0.108±0.023	0.108±0.015	0.140±0.023	0.076±0.005	0.126±0.043	0.184±0.026	0.293±0.056
S18	0.038±0.035	0.026±0.022	0.070±0.027	-	-0.028±0.009	-0.024±0.017	0.008±0.024	-
S19	0.091±0.027	0.063±0.014	0.085±0.018	0.111±0.020	0.069±0.014	0.069±0.015	0.102±0.011	0.143±0.019
S20	0.025±0.013	0.027±0.017	0.072±0.006	0.125±0.017	0.021±0.022	0.044±0.015	0.091±0.016	0.131±0.011
S21	0.045±0.011	0.120±0.011	0.121±0.016	0.178±0.042	0.169±0.021	0.185±0.026	0.213±0.023	0.274±0.028
S22	0.032±0.016	0.028±0.007	0.105±0.009	0.087±0.009	0.132±0.012	0.105±0.012	0.130±0.011	0.143±0.024
S23	0.043±0.014	0.141±0.020	0.072±0.018	0.092±0.011	0.106±0.011	0.056±0.059	0.101±0.020	0.164±0.028
S24	0.132±0.001	0.158±0.014	0.212±0.017	0.221±0.016	0.293±0.009	0.208±0.013	0.289±0.022	0.337±0.010
S28	0.075±0.016	0.116±0.034	0.136±0.021	0.150±0.021	0.068±0.018	0.171±0.055	0.227±0.023	0.259±0.033
S31	0.090±0.009	0.095±0.020	0.137±0.028	0.146±0.017	0.068±0.014	0.125±0.034	0.171±0.021	0.184±0.024
Mean	0.086±0.048	0.086±0.052	0.123±0.048	0.165±0.061	0.121±0.084	0.119±0.063	0.159±0.075	0.207±0.087

Table 69 Peak internal rotation moment (Nm/kg) during level and downhill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0.057±0.017	0.121±0.005	0.186±0.018	0.231±0.035	0.121±0.025	0.142±0.008	0.162±0.022	0.274±0.019
S25	0.197±0.011	0.206±0.012	0.267±0.012	0.281±0.026	0.131±0.012	0.170±0.012	0.193±0.014	0.221±0.020
S26	0.156±0.015	0.127±0.020	0.185±0.018	0.174±0.030	0.128±0.011	0.153±0.003	0.187±0.024	0.226±0.042
S27	0.096±0.004	0.145±0.018	0.198±0.025	0.215±0.007	0.221±0.014	0.240±0.019	0.278±0.021	0.385±0.035
S29	0.124±0.013	0.155±0.015	0.166±0.016	0.254±0.023	0.136±0.013	0.146±0.008	0.166±0.018	0.168±0.003
S30	0.069±0.013	0.089±0.008	0.142±0.008	0.161±0.009	0.081±0.017	0.087±0.016	0.120±0.005	0.171±0.016
S32	0.043±0.009	0.042±0.008	0.069±0.008	0.114±0.015	0.102±0.021	0.107±0.014	0.113±0.004	0.172±0.019
S33	0.224±0.009	0.182±0.022	0.214±0.014	0.260±0.025	0.190±0.007	0.163±0.009	0.239±0.015	0.250±0.054
S34	-0.001±0.004	-0.010±0.005	0.014±0.021	0.030±0.012	0.052±0.017	0.119±0.027	0.169±0.027	0.033±0.009
S35	0.069±0.014	0.069±0.015	0.102±0.011	0.143±0.019	0.091±0.027	0.063±0.014	0.085±0.018	0.111±0.020
Mean	0.103±0.071	0.113±0.066	0.154±0.075	0.186±0.078	0.125±0.050	0.139±0.049	0.171±0.058	0.201±0.095

Table 70 Root mean square of normalized EMG for semitendinosus during level and downhill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	5°	10°	15°	0°	5°	10°	15°
S1	0.099±0.086	0.194±0.045	0.194±0.049	0.188±0.095	0.103±0.054	0.138±0.056	0.144±0.091	0.171±0.074
S2	0.369±0.063	0.340±0.095	0.400±0.095	0.259±0.038	0.316±0.038	0.222±0.059	0.478±0.082	0.686±0.045
S3	0.245±0.058	0.212±0.042	0.193±0.062	0.166±0.002	0.295±0.046	0.289±0.049	0.401±0.078	0.273±0.072
S4	0.159±0.053	0.136±0.088	0.120±0.082	0.111±0.011	0.206±0.051	0.178±0.099	0.169±0.045	0.166±0.054
S5	0.483±0.018	0.334±0.090	0.457±0.007	0.471±0.079	0.197±0.081	0.153±0.039	0.268±0.068	0.229±0.061
S6	0.174±0.074	0.208±0.061	0.248±0.004	0.355±0.049	0.169±0.023	0.168±0.025	0.223±0.053	0.293±0.025
S7	0.026±0.055	0.181±0.049	0.315±0.052	-	0.127±0.036	0.221±0.035	0.230±0.065	-
S8	0.130±0.024	0.127±0.019	0.095±0.087	0.123±0.011	0.287±0.045	0.250±0.096	0.141±0.045	0.154±0.013
S9	0.207±0.013	0.135±0.086	0.212±0.099	0.120±0.077	0.258±0.015	0.127±0.064	0.217±0.045	0.217±0.087
S10	0.085±0.057	0.083±0.043	0.105±0.032	0.175±0.053	0.092±0.017	0.119±0.047	0.096±0.037	0.166±0.032
S11	0.225±0.012	0.244±0.036	0.378±0.025	-	0.228±0.083	0.254±0.081	0.438±0.069	-
S12	0.235±0.097	0.175±0.089	0.149±0.005	0.167±0.044	0.090±0.068	0.120±0.082	0.258±0.009	0.255±0.012
S13	0.249±0.060	0.225±0.028	0.352±0.081	0.340±0.046	0.189±0.052	0.199±0.080	0.312±0.059	0.322±0.078
S14	0.292±0.031	0.292±0.097	0.268±0.001	0.429±0.054	0.243±0.023	0.217±0.024	0.265±0.044	0.346±0.033
S15	0.176±0.056	0.102±0.013	0.109±0.079	0.150±0.024	0.283±0.037	0.273±0.078	0.212±0.079	0.316±0.083
S16	0.468±0.060	0.334±0.068	0.360±0.028	0.418±0.097	0.265±0.045	0.200±0.011	0.286±0.041	0.335±0.042
S18	0.461±0.087	0.419±0.042	0.439±0.602	-	0.701±0.005	0.470±0.067	0.469±0.053	-
S19	0.111±0.043	0.120±0.042	0.192±0.091	0.240±0.056	0.094±0.073	0.094±0.088	0.156±0.803	0.248±0.043
S20	0.222±0.058	0.193±0.036	0.257±0.012	0.319±0.042	0.162±0.099	0.120±0.063	0.186±0.015	0.206±0.027
S21	0.400±0.094	0.277±0.037	0.399±0.011	0.389±0.063	0.462±0.073	0.411±0.052	0.494±0.022	0.448±0.081
S22	0.336±0.065	0.415±0.086	0.254±0.055	0.372±0.071	0.406±0.075	0.375±0.071	0.264±0.060	0.471±0.037
S23	0.059±0.023	0.047±0.087	0.089±0.081	0.093±0.072	0.087±0.006	0.072±0.038	0.100±0.052	0.112±0.045
S24	0.128±0.094	0.102±0.058	0.052±0.045	0.099±0.009	0.148±0.083	0.114±0.018	0.084±0.085	0.107±0.032
S28	0.163±0.082	0.098±0.061	0.140±0.052	0.151±0.024	0.234±0.035	0.201±0.084	0.197±0.046	0.192±0.025
S31	0.358±0.041	0.213±0.039	0.163±0.099	0.303±0.088	0.394±0.068	0.281±0.046	0.248±0.089	0.363±0.057
Mean	0.235±0.123	0.199±0.099	0.219±0.115	0.248±0.122	0.227±0.108	0.197±0.089	0.237±0.111	0.277±0.135

Table 71 Root mean square of normalized EMG for semitendinosus during level and downhill walking for healthy control participants

Subject	Limb 1				Limb 2			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0.212±0.084	0.223±0.072	0.235±0.085	0.302±0.098	0.233±0.046	0.192±0.043	0.228±0.069	0.262±0.042
S25	0.162±0.026	0.168±0.011	0.160±0.041	0.182±0.054	0.161±0.043	0.129±0.034	0.141±0.042	0.164±0.007
S26	0.458±0.022	0.358±0.072	0.342±0.042	0.420±0.013	0.367±0.058	0.303±0.096	0.391±0.019	0.474±0.033
S27	0.490±0.036	0.349±0.053	0.311±0.025	0.335±0.057	0.278±0.049	0.214±0.058	0.231±0.049	0.340±0.026
S29	0.258±0.012	0.236±0.032	0.269±0.013	0.281±0.005	0.168±0.071	0.192±0.014	0.224±0.017	0.253±0.073
S30	0.347±0.044	0.282±0.045	0.334±0.064	0.283±0.074	0.226±0.073	0.168±0.071	0.188±0.003	0.212±0.061
S32	0.693±0.047	0.387±0.026	0.253±0.046	0.210±0.042	0.458±0.026	0.408±0.029	0.357±0.075	0.295±0.037
S33	0.308±0.066	0.269±0.078	0.232±0.034	0.250±0.084	0.198±0.013	0.218±0.034	0.209±0.014	0.241±0.043
S34	0.212±0.053	0.176±0.076	0.189±0.069	0.166±0.069	0.141±0.058	0.131±0.014	0.166±0.017	0.167±0.082
S35	0.251±0.058	0.236±0.059	0.219±0.018	0.231±0.036	0.239±0.021	0.199±0.013	0.206±0.014	0.207±0.061
Mean	0.235±0.123	0.199±0.099	0.255±0.06	0.266±0.076	0.247±0.099	0.216±0.084	0.235±0.079	0.262±0.092

Table 72 Root mean square of normalized EMG for medial gastrocnemius during level and downhill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.022±0.058	0.022±0.092	0.019±0.015	0.017±0.035	0.126±0.069	0.078±0.081	0.099±0.042	0.143±0.037
S2	0.402±0.039	0.350±0.013	0.321±0.026	0.291±0.045	0.198±0.049	0.191±0.061	0.206±0.045	0.175±0.007
S3	0.168±0.024	0.150±0.092	0.111±0.071	0.098±0.027	0.139±0.091	0.110±0.054	0.145±0.034	0.155±0.059
S4	0.176±0.092	0.092±0.048	0.087±0.027	0.088±0.049	0.136±0.016	0.075±0.061	0.073±0.088	0.087±0.067
S5	0.145±0.048	0.113±0.043	0.118±0.055	0.143±0.045	0.102±0.014	0.061±0.007	0.132±0.073	0.105±0.079
S6	0.183±0.077	0.156±0.019	0.199±0.089	0.253±0.085	0.182±0.081	0.178±0.021	0.211±0.075	0.284±0.008
S7	0.095±0.094	0.121±0.013	0.053±0.003	-	0.156±0.092	0.255±0.093	0.152±0.032	-
S8	0.122±0.052	0.128±0.043	0.093±0.036	0.111±0.029	0.111±0.074	0.120±0.078	0.120±0.017	0.130±0.075
S9	0.139±0.014	0.103±0.014	0.141±0.074	0.114±0.054	0.209±0.097	0.134±0.065	0.157±0.038	0.238±0.045
S10	0.279±0.026	0.303±0.043	0.183±0.094	0.285±0.006	0.206±0.009	0.201±0.029	0.298±0.067	0.249±0.045
S11	0.126±0.062	0.112±0.068	0.145±0.043	-	0.012±0.096	0.099±0.068	0.098±0.034	-
S12	0.193±0.073	0.134±0.054	0.152±0.016	0.133±0.018	0.184±0.093	0.127±0.017	0.110±0.049	0.109±0.056
S13	0.326±0.029	0.242±0.095	0.218±0.065	0.120±0.029	0.079±0.063	0.065±0.067	0.059±0.054	0.064±0.057
S14	0.321±0.037	0.296±0.088	0.244±0.016	0.244±0.003	0.311±0.057	0.237±0.074	0.215±0.052	0.228±0.071
S15	0.326±0.052	0.246±0.067	0.218±0.034	0.080±0.016	0.152±0.071	0.122±0.088	0.078±0.068	0.071±0.067
S16	0.159±0.062	0.081±0.064	0.056±0.036	0.065±0.019	0.346±0.082	0.232±0.087	0.191±0.058	0.209±0.087
S18	0.150±0.037	0.132±0.076	0.133±0.095	-	0.190±0.038	0.123±0.006	0.171±0.095	-
S19	0.229±0.054	0.175±0.016	0.232±0.011	0.230±0.062	0.380±0.099	0.289±0.028	0.335±0.051	0.315±0.017
S20	0.195±0.041	0.131±0.078	0.147±0.092	0.152±0.032	0.298±0.033	0.156±0.032	0.172±0.032	0.212±0.069
S21	0.137±0.033	0.097±0.063	0.104±0.056	0.087±0.051	0.046±0.069	0.040±0.086	0.061±0.007	0.051±0.068
S22	0.109±0.069	0.151±0.011	0.102±0.013	0.151±0.012	0.155±0.049	0.136±0.049	0.183±0.073	0.243±0.016
S23	0.179±0.023	0.133±0.066	0.161±0.014	0.168±0.051	0.093±0.021	0.080±0.057	0.139±0.062	0.085±0.073
S24	0.087±0.036	0.051±0.014	0.028±0.027	0.028±0.095	0.117±0.065	0.056±0.016	0.045±0.059	0.059±0.001
S28	0.345±0.047	0.127±0.093	0.129±0.095	0.124±0.023	0.083±0.032	0.050±0.056	0.088±0.045	0.117±0.032
S31	0.175±0.063	0.140±0.046	0.140±0.041	0.205±0.022	0.167±0.025	0.171±0.041	0.160±0.015	0.189±0.058
Mean	0.201±0.095	0.156±0.083	0.146±0.073	0.145±0.078	0.174±0.089	0.132±0.068	0.149±0.075	0.160±0.079

Table 73 Root mean square of normalized EMG for medial gastrocnemius during level and downhill walking for Healthy control participants

Subject	Limb 1				Limb 2			
	0°	5°	10°	15°	0°	5°	10°	15°
S17	0.201±0.064	0.217±0.076	0.214±0.095	0.360±0.094	0.221±0.081	0.180±0.052	0.206±0.079	0.201±0.074
S25	0.278±0.027	0.206±0.011	0.189±0.095	0.195±0.087	0.230±0.041	0.157±0.062	0.159±0.021	0.177±0.072
S26	0.245±0.015	0.198±0.079	0.185±0.059	0.213±0.019	0.268±0.017	0.220±0.024	0.212±0.024	0.204±0.031
S27	0.199±0.073	0.166±0.089	0.162±0.039	0.201±0.086	0.260±0.059	0.197±0.027	0.176±0.033	0.214±0.007
S29	0.162±0.067	0.144±0.075	0.156±0.023	0.169±0.083	0.154±0.049	0.184±0.004	0.224±0.098	0.261±0.044
S30	0.132±0.089	0.120±0.018	0.136±0.094	0.118±0.025	0.128±0.023	0.120±0.081	0.132±0.025	0.130±0.085
S32	0.149±0.041	0.148±0.039	0.155±0.084	0.148±0.058	0.208±0.059	0.126±0.007	0.152±0.063	0.144±0.091
S33	0.232±0.027	0.217±0.076	0.235±0.006	0.239±0.077	0.359±0.071	0.314±0.023	0.316±0.064	0.339±0.003
S34	0.290±0.065	0.223±0.094	0.283±0.042	0.274±0.075	0.347±0.049	0.290±0.077	0.284±0.019	0.306±0.013
S35	0.183±0.037	0.155±0.056	0.184±0.088	0.178±0.069	0.184±0.066	0.162±0.034	0.155±0.049	0.167±0.019
Mean	0.208±0.053	0.180±0.037	0.190±0.044	0.210±0.069	0.236±0.075	0.195±0.064	0.202±0.060	0.215±0.068

Table 74 Root mean square of normalized EMG for vastus medialis during level and downhill walking for TKR patients

Subject	Replaced limb				Non-replaced limb			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S1	0.271±0.086	0.419±0.028	0.240±0.052	0.893±0.012	0.165±0.052	0.231±0.024	0.254±0.088	0.603±0.031
S2	0.342±0.081	0.293±0.052	0.340±0.083	0.475±0.077	0.299±0.082	0.433±0.083	0.710±0.062	0.540±0.046
S3	0.112±0.029	0.237±0.079	0.349±0.016	0.481±0.028	0.183±0.024	0.269±0.084	0.475±0.049	0.587±0.031
S4	0.105±0.059	0.154±0.027	0.201±0.018	0.262±0.058	0.240±0.083	0.243±0.024	0.280±0.083	0.392±0.063
S5	0.453±0.069	0.423±0.041	0.535±0.082	0.573±0.041	0.568±0.093	0.613±0.021	0.652±0.039	0.735±0.023
S6	0.236±0.026	0.257±0.078	0.391±0.055	0.471±0.045	0.243±0.063	0.335±0.004	0.466±0.034	0.617±0.017
S7	0.131±0.031	0.250±0.085	0.249±0.099	-	0.265±0.05	0.288±0.057	0.259±0.094	-
S8	0.148±0.053	0.157±0.058	0.265±0.041	0.374±0.013	0.289±0.014	0.436±0.035	0.399±0.087	0.556±0.076
S9	0.101±0.072	0.122±0.073	0.163±0.061	0.174±0.074	0.091±0.046	0.133±0.083	0.191±0.059	0.205±0.097
S10	0.177±0.019	0.183±0.066	0.229±0.028	0.479±0.023	0.251±0.073	0.368±0.018	0.394±0.017	0.661±0.067
S11	0.382±0.064	0.299±0.064	0.279±0.094	-	0.128±0.084	0.268±0.063	0.333±0.004	-
S12	0.102±0.015	0.173±0.029	0.319±0.035	0.469±0.048	0.234±0.023	0.264±0.077	0.428±0.003	0.558±0.025
S13	0.181±0.037	0.211±0.083	0.269±0.058	0.315±0.028	0.058±0.079	0.077±0.026	0.130±0.065	0.149±0.028
S14	0.167±0.071	0.182±0.084	0.199±0.099	0.235±0.036	0.390±0.078	0.521±0.042	0.642±0.051	0.779±0.043
S15	0.177±0.088	0.231±0.057	0.302±0.045	0.407±0.081	0.141±0.069	0.156±0.018	0.234±0.022	0.486±0.087
S16	0.131±0.038	0.143±0.044	0.241±0.067	0.363±0.022	0.068±0.023	0.106±0.003	0.118±0.036	0.132±0.033
S18	0.112±0.088	0.121±0.055	0.178±0.096	-	0.241±0.028	0.231±0.099	0.431±0.057	-
S19	0.208±0.026	0.201±0.043	0.321±0.059	0.531±0.038	0.280±0.061	0.271±0.064	0.399±0.078	0.463±0.045
S20	0.104±0.068	0.158±0.059	0.203±0.082	0.264±0.036	0.181±0.065	0.257±0.065	0.469±0.062	0.721±0.043
S21	0.142±0.019	0.176±0.004	0.249±0.097	0.294±0.041	0.168±0.085	0.189±0.071	0.299±0.075	0.291±0.023
S22	0.244±0.086	0.368±0.035	0.459±0.064	0.661±0.036	0.084±0.064	0.087±0.042	0.102±0.049	0.193±0.057
S23	0.163±0.064	0.187±0.068	0.239±0.026	0.275±0.007	0.215±0.046	0.222±0.023	0.289±0.095	0.307±0.054
S24	0.077±0.052	0.092±0.066	0.219±0.082	0.328±0.093	0.097±0.074	0.104±0.073	0.147±0.002	0.209±0.006
S28	0.088±0.053	0.063±0.056	0.109±0.078	0.149±0.033	0.380±0.048	0.177±0.046	0.242±0.004	0.304±0.073
S31	0.153±0.003	0.266±0.038	0.316±0.094	0.432±0.048	0.308±0.009	0.529±0.086	0.653±0.087	0.694±0.097
Mean	0.177±0.090	0.214±0.094	0.281±0.097	0.405±0.170	0.225±0.122	0.274±0.153	0.363±0.186	0.463±0.208

Table 75 Root mean square of normalized EMG for vastus medialis during level and downhill walking for Healthy control participants

Subject	**Limb 1**				**Limb 2**			
	0°	**5°**	**10°**	**15°**	**0°**	**5°**	**10°**	**15°**
S17	0.240±0.079	0.349±0.075	0.393±0.071	0.459±0.088	0.198±0.096	0.238±0.062	0.312±0.045	0.332±0.017
S25	0.312±0.011	0.301±0.006	0.352±0.035	0.415±0.057	0.186±0.016	0.194±0.063	0.208±0.066	0.2367±0.099
S26	0.443±0.086	0.446±0.031	0.544±0.019	0.709±0.094	0.367±0.021	0.379±0.016	0.574±0.067	0.664±0.088
S27	0.271±0.047	0.302±0.028	0.418±0.095	0.351±0.053	0.278±0.069	0.342±0.093	0.386±0.088	0.442±0.056
S29	0.259±0.034	0.301±0.047	0.295±0.099	0.303±0.092	0.247±0.051	0.253±0.074	0.301±0.056	0.356±0.058
S30	0.268±0.065	0.311±0.057	0.376±0.075	0.438±0.068	0.221±0.025	0.224±0.076	0.252±0.084	0.343±0.027
S32	0.224±0.091	0.248±0.033	0.297±0.076	0.339±0.087	0.240±0.024	0.240±0.060	0.263±0.087	0.281±0.064
S33	0.143±0.069	0.155±0.028	0.197±0.048	0.297±0.052	0.127±0.099	0.138±0.047	0.150±0.029	0.175±0.039
S34	0.249±0.069	0.348±0.045	0.503±0.044	0.643±0.023	0.225±0.029	0.316±0.081	0.433±0.054	0.503±0.069
S35	0.261±0.096	0.272±0.055	0.303±0.095	0.388±0.031	0.208±0.043	0.267±0.083	0.311±0.088	0.364±0.029
Mean	0.268±0.075	0.304±0.075	0.368±0.103	0.435±0.139	0.230±0.063	0.260±0.071	0.320±0.121	0.370±0.140

VITA

Chen Wen has grown up in Beijing, China. She received Bachelor of Science degree in Bioengineering from Hefei University of Technology, Anhui, China in 2010. In 2014, she completed a Master's degree at University of Tennessee, Knoxville, TN in Kinesiology with a concentration in Biomechanics. Following the completion of her Master's degree, she continued her doctoral work at University of Tennessee under the advisement of Dr. Songning Zhang. Her major interests of the research included biomechanical mechanisms of the lower extremity injury and prevention, gait analysis, knee osteoarthritis and total knee replacement rehabilitation and human movement simulation using computer software to estimate joint contact and muscle forces.