Influence of Patient Satisfaction of Total Knee Replacement Patients on Stair Negotiation and Walking Biomechanics, Strength, and Balance

A Dissertation Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Kevin Alan Valenzuela

May 2017

DEDICATION

This dissertation is dedicated to my family and friends. I want to thank my parents, John and Penny, who have always encouraged me from the time I was a child to go for it, regardless of what it is. I want to thank Denise for her encouragement to take a chance that I was incredibly unsure of. Without her encouragement and faith, I would not be here as she had faith in me when I had no faith in me. I want to thank my brothers, Danny, Brian, and Mark, for setting the bar ridiculously high on life accomplishments. I appreciate what everyone has done for me and hopefully I've achieved something you can be proud of as I am of all of you. You've all helped me celebrate every success and helped me over every hurdle. My family and friends give my life purpose and everything I do is to be an asset in each of your lives. Without all of you, this never would have been possible. From the bottom of my heart, thank you.

ACKNOWLEDGEMENT

During the course of this dissertation, there have been many people who have aided me in the process. I would like to thank all of the participants who took time out of their schedules to participate in my data collections. I would like to thank all my lab mates who have been involved in this process, either through letting me bounce ideas off of them, clarify things with them, or just generally vent my frustrations periodically, including Tyler Standifird, Hunter Bennett, Chen Wen, Guangping Shen, Derek Yocum, and especially Lauren Schroeder for all her assistance in the data collections and processing. Given the amount of time this process takes, these individuals have made the long hours in the lab much more enjoyable.

I would also like to thank Dr. Harold Cates and Jane Smith of the Tennessee Orthopaedic Clinic. Without their support and assistance for the project and the subject recruitment, this project would not have been possible. Additionally, I would like to thank the International Society of Biomechanics for providing the financial support for this study.

My committee members served an invaluable purpose on this dissertation. I would like to thank Dr. Josh Weinhandl, Dr. Jeff Reinbolt, and Dr. Rebecca Zakrajsek. Each one of them has taught me various aspects of the research process and contributed to my general knowledge of our field, without which I would not be where I am today.

Finally, I would like to thank my advisor, Dr. Songning Zhang. For the last three years, he has been a great teacher and support system for my professional growth. I have learned a great deal about the research process and about the mentoring process. I strive to apply this knowledge to my own future so that I may be a source of pride for him. Your tireless effort on ensuring my success means the world to me. Thank you for taking a chance on me and for everything that you have taught me.

ABSTRACT

Total knee replacement (TKR) patients have shown alterations in lower extremity biomechanics during level ground walking and stair negotiation, strength levels, and balance abilities, however, it is unknown how dissatisfied TKR patients compare to satisfied TKR patients in these activities. Study One examined the lower extremity biomechanics of dissatisfied and satisfied TKR patients during level ground walking. Study Two investigated knee biomechanics during stair ascent and descent activities. Study Three compared isokinetic strength, balance abilities, deep knee flexion abilities, and functional abilities of the dissatisfied patients to the satisfied patients. Study Four performed a logistic regression as a means of examining significant variables in models designed to predict patient satisfaction.

Study One found reduced 1^{st} and 2^{nd} peak VGRF, knee flexion ROM, and peak loading-response knee extension and abduction moments in the dissatisfied patients compared to healthy controls. First and 2^{nd} peak VGRFs and flexion ROM were reduced in the replaced limb of the dissatisfied patients compared to their non-replaced limb. Study Two showed reduced 2^{nd} peak VGRF and loading-response knee extension moments in the replaced limb of the dissatisfied group compared to their non-replaced limb and to satisfied and healthy groups during stair ascent. 1^{st} peak VGRF and both loading-response and push-off abduction moments showed reduced values in replaced limbs compared to non-replaced limbs for all groups. During stair descent, the dissatisfied group showed reduced loading-response and push-off knee extension moments in their replaced limb compared to their non-replaced limb and the healthy group. The loading-response knee extension and abduction moments were also reduced in the dissatisfied group compared to the satisfied group. Study Three showed reduced peak extension (180°/s) and flexion (60°/s) torque in dissatisfied patients compared to satisfied patients. No balance

differences were evident, although an increased percentage of dissatisfied patients were unable to complete the unilateral balance tests. Study Four produced models via the logistic regression analysis which often included peak VGRFs and knee extension moments. Future research should examine the effects of attempting to alter the physical differences between patient satisfaction groups and whether it improves patient satisfaction rates.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER I

INTRODUCTION

Background

Osteoarthritis (OA) is a joint disease characterized by degeneration of joint cartilage. Knee OA is one of the most common forms of OA and it is projected to afflict approximately 25% of the population by the year 2030 (1). As the disease progresses and the cartilage wears away, the knee joint space diminishes, eventually leading to bone on bone contact and unbearable pain. A common treatment option for this end-stage OA is a total knee replacement (TKR). As of 2011, there were over 700,000 TKR operations being performed in the United States each year (2), and an estimated projection of 3.5 million per year by 2030 (3). The number of procedures continues to increase in individuals under the age of 60 (4), which means individuals receiving the replacement will have to live longer with the replaced limb. Restoration of function of the replaced knee is critical given the significant time, pain, and monetary investment associated with the operation.

The primary goals of TKR operations involve pain relief, improvement in knee joint range of motion (ROM), improved joint alignment (if necessary, as malalignment can contribute to degeneration of cartilage), a restored ability to perform activities of daily living (ADL), and a return to more advanced physical activities for some patients (5). Many of the subjective survey tools utilized with the TKR population examine patients' desires and abilities to return to performing more advanced activities, suggesting that there is an expectation that the surgery will help the patient to return to these activities. The desired outcomes are not always present though as some patients continue to have difficulty with function and lingering pain in the replaced knee joint.

Overall, most TKR operations are considered successful as there are often reductions in pain levels and improvements in ROM in the replaced knee (6-9). Patient satisfaction rates for the procedure have been reported between 81-97% (10, 11). This leaves a significant portion of the TKR population as dissatisfied with the outcomes of the replaced knee. Post-operative pain (12) and functional limitations (13) are commonly reported by dissatisfied patients. This often results in decreased performance in common clinical tests (such as timed up and go or a sit to stand test) when compared to healthy controls (14, 15). These tests are often seen as a defining point for "success" of the operation as they are deemed to determine the restoration of function for the replaced joint. However, these test results do not sufficiently explain why the TKR patients are dissatisfied with the TKR outcomes, thereby suggesting that additional research into the mechanisms of dissatisfaction is needed.

Current research on the dissatisfied population has focused on survey data and minimal physical testing (16-18). Lab-based biomechanical studies focusing on level walking, stair negotiation, strength, and balance may provide insight into the movement profiles of the dissatisfied TKR population. For example, one study has shown no difference in functional test scores while showing reduced loading response knee extension moments and increased push-off knee abduction moments in the replaced limb of TKR patients compared to the non-replaced limbs and healthy controls during stair ascent (19). Despite similarities in functional tests, the biomechanical analysis was able to show differences in the movement patterns, which is valuable in movement recovery.

There have been several studies investigating the TKR population as a whole compared to healthy controls. These studies have examined overground walking, with special focus on gait velocity (20, 21), sagittal plane knee ROM (20, 22), and frontal plane knee moments (20, 21).

Knee replacement surgeries should help to restore normal mechanics during level walking as well as more demanding and complex activities such as stair negotiation. Different planar kinematics and kinetics have shown mixed results for TKR patients during level walking. TKR patients have been shown to have reduced maximum knee flexion compared to healthy controls, by an average of 6° (15, 22-24), yet some studies have reported similar maximum flexion angles (25, 26). Internal extension moments have produced mixed results as well, with TKR patients being reported as producing lower moments compared to healthy controls during a walking task (26) while yet other studies have shown no difference between the two groups (20, 25). Peak knee adduction angles for TKR patients have been shown to return to levels similar to healthy controls, which has been linked to the correction of the frontal plane alignment during the surgery (27) Despite the alignment correction, mixed results have been shown with respect to frontal plane moments. There have been no differences between replaced limbs and healthy controls for the peak internal knee abduction moment (KAM) (26), reductions in first and second peak KAM values (20), and increased KAM values due to a lack of change from pre-operative levels which have been shown as increased compared to healthy controls (27, 28). The confounding results impair the clarity of the situation but more results suggest KAM values being closer to those of healthy controls rather than increased. It is currently unknown how dissatisfied patients differ satisfied TKR patients and healthy controls with respect to overground walking kinematics and kinetics.

Stair climbing, as an example of a more demanding activity on the muscles and joints (29, 30), is a common ADL for older and younger adults (31). It has been reported as one of the top five most difficult tasks for individuals over the age of 60 (32). As patients reach end-stage knee OA, many frequently report difficulty with climbing stairs (33). Stair climbing is also measured by most survey tools [including the Western Ontario and McMaster University survey (WOMAC) and the Forgotten Joint Score (FJS]) used on the TKR population (5, 34, 35), thereby suggesting its importance in everyday life for most people. During stair ascent and descent, knee flexion ROM has been frequently shown to be reduced compared to healthy controls (22, 36, 37), although one study did report no differences between the two groups (19). TKR patients have shown reduced knee extension moments during stair ascent, which is often coupled with a reduction in velocity (24). Gait speed, for example, has been shown to increase post-operatively for TKR patients compared to pre-operative levels, however, gait speed does not always reach levels equal to those of healthy controls at one year post-operation (15, 38). Other studies have shown no differences between the two groups though, with TKR patients maintaining their velocity from 12-18 months as far as 46 months after surgery (22, 26). As during walking trials, knee adduction angles have shown no differences for TKR patients compared to healthy controls but an increased 2^{nd} peak KAM was present (19). Other studies have shown mixed results with some showing increased KAM values (39) and some showing values equal to or reduced compared to healthy controls (40-42). For the dissatisfied population, deficits in their movement profiles may be further enhanced during more difficult activities, suggesting a need for examination of these activities.

A return of strength levels following an operation is crucial for a return to normal function. Quadriceps strength is the most commonly measured strength variable for TKR patients however the hamstrings also have significant function at the knee, warranting their examination as well. Significant reductions in quadriceps and hamstring strength are evident early in the rehabilitation process, with upwards of 60% deficits compared to pre-operative levels (43, 44). By six months post-operation, both muscle groups show significant increases in strength (45). However, the strength levels of TKR patients do not always meet levels of healthy controls, with deficits still present 12 months after surgery in the replaced limb and the non-replaced limb not being different from healthy controls (46). There is a lack of research on strength with respect to patient satisfaction. Strength deficits post-operatively may be more pronounced in dissatisfied patients, which may impair functional ability.

Balance is an additional measure of success for TKR operations and return to normal daily activities as falls can be detrimental to the TKR (47). TKR patients have been shown to have decreased stability after surgery compared to healthy controls (48). Improvements in balance have been associated with improvements in functional tests, such as stair climb, 30 second chair rise, timed up and go, and improvements in gait speed (49). Strength and balance have been often measured together as a means of using strength to explain balance abilities. Increased knee extensor strength coupled with an increased gait speed has led to increased anterior-posterior (AP) balance (measured through the range of the AP trajectory for the center of pressure (COP)), but increased knee extensor strength with a reduced gait speed led to a reduced AP balance (50). However, it was shown that peak torque did not predict single leg static balance performance (51). Conversely, it has found that a failure to maintain single limb balance is explained by older age, higher body mass index, and reduced quadriceps strength (52).

Timing may play a role in the analysis of biomechanical variables as differences have been shown to diminish a year after surgery (53). Other differences have been shown at an average of 46 months post-operation (22), suggesting that while there may be improved gait biomechanics through the first year, there may be a regression of improvement over time. The sub-optimal physical outcomes after surgery may contribute to patient dissatisfaction. An understanding of a comprehensive physical profile including gait biomechanics, strength, balance, physical functions and patient perceptions of the dissatisfied patients as it compares to the satisfied patients as well as healthy counterparts is essential for potentially improving the satisfaction rates of patients.

Statement of the Problem

To our knowledge, no studies have examined the 3D biomechanical profiles, strength levels, or balance abilities of dissatisfied TKR patients. Simple motion tasks such as level walking and more demanding tasks such as stair climbing are everyday activities for the TKR population yet no research has examined these activities specifically for the dissatisfied population. Therefore the purposes of proposed studies are listed below:

Study One: The purpose was to compare the lower extremity movement profiles of overground walking for dissatisfied TKR patients to satisfied TKR patients and healthy older-adult controls.

Study Two: The purpose was to compare the lower extremity movement profiles of stair ascent and descent for dissatisfied TKR patients to satisfied TKR patients and healthy older-adult controls.

Study Three: The purpose was to examine the knee flexor and extensor concentric strength levels of both the replaced and non-replaced limbs for dissatisfied TKR patients compared to satisfied TKR patients and healthy older-adult controls. An additional purpose was to compare bilateral and unilateral balance abilities for dissatisfied TKR patients to satisfied TKR patients and healthy older-adult controls.

Study Four: The purpose was to examine associations between TKR dissatisfaction and satisfaction and the gait biomechanics, strength, balance, functional capacities, and survey data (measuring joint awareness, pain, stiffness, and functional ability) using a logistic regression analyses.

Research Hypotheses

Study One

1. It was hypothesized that dissatisfied TKR patients would exhibit increased frontal plane knee joint moments and reduced sagittal plane knee joint moments in their replaced limb compared to their non-replaced limb in level walking.

2. It was hypothesized that dissatisfied TKR patients would exhibit increased frontal plane knee joint moments and reduced sagittal plane knee joint moments compared to satisfied TKR patients and healthy controls in level walking.

Study Two

1. It was hypothesized that dissatisfied TKR patients would exhibit increased frontal plane knee moments and decreased sagittal plane knee moments in their replaced limb compared to their non-replaced limb, but similar in the non-replaced limb to the satisfied TKR patients and healthy controls during stair ascent and descent.

Study Three

1. It was hypothesized that dissatisfied TKR patients would show a knee extensor strength deficit in their replaced limb compared to their non-replaced limb and a deficit in both limbs compared to satisfied TKR patients and healthy controls during concentric isokinetic strength testing.

2. It was hypothesized that dissatisfied TKR patients would have a reduced ability to balance on their replaced limb compared to their non-replaced limb, satisfied TKR patients, and healthy controls.

Study Four

1. It was hypothesized that reduced knee extensor moments, reduced quadriceps strength, increased balance stability indices, and increased pain will contribute to increased dissatisfaction with TKRs.

Significance

Current research regarding the dissatisfied TKR patient population lacks comprehensive examination of the objective data with respect to gait biomechanics and strength and balance abilities. This presents a unique opportunity to potentially identify physical differences between satisfied and dissatisfied patients, which could potentially help to identify treatment objectives for the dissatisfied population and thereby improve satisfaction rates. Deficiencies in gait, strength, and balance are often modifiable and do not require surgical intervention. If there is a potential non-surgical intervention available to help improve patient satisfaction, then it should be explored as the commitment to a TKR procedure is a significant one and therefore should have the optimal outcomes whenever possible. Additionally, the results from this study may provide indirect feedback for the improvement of future TKR implant designs.

Delimitations

The exclusion criteria included for dissatisfied and satisfied TKR patients for all studies:

- Diagnosed osteoarthritis at the ankle, knee (contralateral knee of the TKR side), or hip joint 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.
- Neurologic disease (e.g. Parkinson's disease, stroke patients) as reported by the patient.
- Any additional major lower extremity injuries/surgeries aside from knee replacement.
- Inability to walk without a walking aid.
- Any visual conditions affecting gait or balance.
- Women who are pregnant or nursing.
- Any cardiovascular disease or primary risk factor which precludes participation in aerobic exercise as indicated by the Physical Activity Readiness Survey. If any participant marks "yes" on the survey they will be required to obtain written consent from their doctor indicating they are healthy enough to participate in the study.
- An answer of "neutral" on satisfaction question in pre-screening interview.

The inclusion criteria included for dissatisfied and satisfied TKR patients for all studies:

- Men and women between the ages of 50 and 75.
- Total knee replacement in one knee.
- At least 12-months from TKR.
- No more than 5-years from TKR

The exclusion criteria included for healthy adults for all studies:

- Knee pain for at least 6 months during daily activities.
- Diagnosed with any type of lower extremity joint osteoarthritis (self-reported).
- Any lower extremity joint replacement.

- Any lower extremity joint arthroscopic surgery or intra-articular injection within past 3 months.
- Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) (self-reported).
- BMI greater than 38.
- Inability to ascend/descend stairs without the use of a handrail.
- Inability to walk without a walking aid.
- Neurologic disease (e.g. Parkinson's Disease, stroke patients) (self-reported).
- Any major lower extremity injuries/surgeries.
- Any visual conditions affecting gait or balance.
- Women who are pregnant or nursing.
- Any cardiovascular disease or primary risk factor which precludes participation in aerobic exercise as indicated by the Physical Activity Readiness Survey. If any participant marks “yes” on the survey they will be required to obtain written consent from their doctor indicating they are healthy enough to participate in the study.

The inclusion criteria included for healthy adults for all studies:

- Men and women between the ages of 50 and 75.

Limitations

- All studies were conducted in a laboratory setting.
- Skin marker placement on obese patients may not reflect accurate bony landmark locations given excess tissue
- Reflective markers used to track the feet during motion trials were placed on the shoes, and therefore motion of the foot within the shoe may not have been accurately captured.

- The nature of the staircase set up required placement prior to subjects arriving for testing, therefore level walking tests always occurred after stair ascent and descent.
- There was no training period for the strength and balance tests although practice trials were provided.
- An isokinetic speed of 180°/s may be too fast of a velocity for some TKR patients to contract at, thereby altering torque values.
- The foot placement on the balance system is set by the Biodex and does not allow participants to balance as they naturally would with whatever foot placement they desire.

CHAPTER II

LITERATURE REVIEW

Introduction

The purpose of this study was to examine the gait biomechanics, strength, and balance profiles of dissatisfied total knee replacement (TKR) patients and how they compare to satisfied TKR patients and healthy adults. Information on TKR patient groups has previously been reported with respect to gait biomechanics, strength, and balance, however previous research has failed to disseminate this information based upon patient satisfaction with the TKR procedure. The dominant information relating to the satisfaction grouping has been based upon widely distributed survey data, such as the Western Ontario and McMasters University (WOMAC) survey, which quantifies the pain, stiffness, and function levels of TKR patients. All of this information is self-reported by the patient as is consistent with the patient satisfaction reporting. To date, no study has examined the non-subjective outcomes such as gait biomechanics, strength, and balance profiles to see how these factors relate to the subjective patient assessment of satisfaction.

The primary goals of this chapter were to 1) examine the available motion capture methodologies for biomechanical profiling, 2) summarize the current findings related to TKR patients for gait biomechanics profiles, strength, and balance, 3) examine the creation and application of survey tools which are commonly utilized on the TKR population, and 4) examine the current construct of patient satisfaction and the literature on dissatisfied TKR patients for the purpose of identifying the gap in the available literature.

Comparison of Motion Capture Methods, Markers, and Calculations

Motion capture has become a regularly used tool for the analysis of human movement. Everything from healthy gait to joint replacements to neurological disorders have been studied for their movement deficiencies using various motion capture systems (54, 55). Initially motion capture study was conducted in 2D using a series of cameras to take pictures. Since then, methods and software have evolved to provide a more thorough, albeit complex, understanding of how the body moves through the use of multiple cameras, recognition software, tracking systems, and various imaging tools. This has provided for a more intimate and in-depth understanding of physical function as it relates to movement patterns. The evolution of motion analysis has taken several years and examined several different pieces of equipment in the pursuit of the most accurate assessment of human motion. The goal has been to develop a system that is easily applicable, minimally invasive, and provides an in-depth, accurate analysis of movement with no errors, a concept which likely still eludes the research community. However, many strides have been achieved in this field as it continues to evolve.

Two-dimensional vs Three-dimensional Motion Capture

There are multiple motion capture methods currently available for use in research. Three-dimensional (3D) has become the most common in the laboratory setting, however, two-dimensional (2D) is also currently being used in field and clinical settings when 3D is not as readily available. 2D refers to a projection of body segments onto a single plane of motion while 3D models the body using simplified 3D objects such as cylinders or superquadratics. There is also a system between 2D and 3D called 2.5D which provides some depth information but not at the level of 3D (56). Each system has its own benefits and setbacks.

In general, 2D data is much easier to obtain than 3D as it only requires one camera and a few markers (57). The camera must be placed perpendicular to the plane of motion being studied, a few markers can be applied to the subject to define end points of the segments, and the data can be processed to calculate kinematics (and kinetics if a force plate is combined). This simple data collection can provide useful information with respect to movement in the studied plane. In addition to the minimal equipment, the research can be conducted in almost any environment as the equipment does not take up much space and there are not many additional pieces of equipment to accompany the single camera. This allows for field research much easier than 3D. There are currently several commercial software applications which also allow for kinematic measurements using video from cellular phones which requires even less set up and processing. The 2D data can be further enhanced using silhouette modeling which helps to track the subject through the movement using a constraint mechanism on the model and a weighting scheme on the segments of the model to provide more in-depth data (58), although this requires some more initial work to process the model.

The ease of application in the 2D data is offset by some limitations. First, and most importantly, most human motion is multi-planar. While some motions are largely occurring in one plane (walking in the sagittal plane), the reality is that humans move in all three planes during everything that they do. The assumption of planar motion in 2D data collection is simply not realistic, especially in the more dynamic motions such as dynamic stability during a slip and fall (59). The non-sagittal plane motions are often small, but important nonetheless, and 2D through a single camera can miss these elements. Additionally, the data can be skewed if the camera is not precisely set up, movement occurs out-of-plane (which induces an error in the data), or if the subject moves off the perpendicular line to the field of view (58). If the sagittal plane is the plane of interest, failure to set up a perpendicular field of view to the plane can result in inaccurate data as the perception of the subject changes, which alters the tracking of the subject in the data. The main limitation, as far as common occurrence, is the occlusion of markers (58). When utilizing only one camera and minimal numbers of markers, it can be easy for the markers to become blocked from the camera's field of view, such as an arm swinging in front of a hip marker during walking. This will affect the kinematic data as there is no additional camera to compensate for the temporary loss of vision of the marker, resulting in two possible options. First, the marker could be gap-filled based on the assumed trajectory the next time it comes into view digitally. This may not be accurate, as realistically there is an element of guessing done by the software which fills the missing time points. Second, the researchers tracking the data points do their own guessing of approximately where the marker should be. This is less-likely to be accurate, but may be the only option with some of the commercial applications. When a rough idea of kinematics is all the information desired by the researcher, this may not be a severe limitation, but if there are clinical implications to the changes in body position, this becomes a more significant problem.

The 2D collection can be improved upon through the use of 2D fluoroscopy. These 2D images can be transformed into 3D models of the bones for kinematic measurements (60). Through the use of a 3x3 rotation matrix followed by a 3x1 translational vector matrix, fluoroscopy has resulted in a root mean square error (RMS) of 0.7 mm (61), making the measurements very accurate. The maximum errors in the fluoroscopy were found to be in-plane marker translational errors of 1.5 mm, for translations normal to the image plane, 3 mm, and 0.6° for rotations in all planes (60).

3D data collection does improve upon some of the issues with 2D. In order to successfully obtain 3D data, there must be at least two cameras capturing at least three markers on a segment in order to take the 2D coordinates and reconstruct the markers in 3D space (62). The 3D coordinates of the markers are computed from the 2D marker coordinates of each camera and then matched stereometrically into 3D space (63). This allows for assessment of human motion in all planes, which is more realistic as research has shown motion exists in all three planes simultaneously (64). Proper camera placement is still important but unlike 2D where precision is required, the use of multiple cameras requires less "precise" set up. As long as two of the cameras in the system capture the marker, it is reconstructable in 3D space. This further helps to eliminate occlusion of markers as there are more cameras capable of capturing the marker information from a multitude of angles.

There are limitations however as the equipment can be costly. Unlike 2D where one camera and only a few markers are needed, 3D requires multiple cameras, often as many as 12 are utilized (65). These cameras often require additional expensive software packages for the tracking and processing of the data. Costs aside, the bulk of the equipment makes it difficult to take this type of system out of a laboratory setting (66), rendering much of the field-based data collections impossible due to the complexity of the transportation and set up. While the laboratory is an acceptable environment for some research, for athletic tasks, environment plays a substantial role and the laboratory setting negates that, taking away an element of reality and creating a limitation on the data results. An additional limitation for both 2D and 3D is the clothes worn by the subject as they need to be minimal or tight fitting so as to minimize marker motion related to the underlying bones they represent (66). Loose fitting clothing can cause the markers to swing off of the represented bones, causing inaccurate kinematic calculations. There are tracker programs which can be combined with as little as two cameras in creating 3D data. A model is created based on the subject and attempts to follow it through the motion which can help to eliminate occlusion errors, but most tracker programs have been shown to perform better with the use of more than two cameras (56). Beyond this, recent research has shown that construction of 3D images are possible through the use of one camera and a retro-grade reflector system. This has shown high correlations with movement in all three planes compared to traditional 3D motion capture (67).

When directly comparing the 2D and 3D data collections, the two methods have shown similar joint angle and moment profiles. A 2D versus 3D analysis of the hindlimbs of horses revealed no significant differences in kinematics during a handled trot motion (68). However, the magnitudes of the joint moment profiles were significantly different (despite the similarity of the motion profile pattern). The 3D data exhibited increased dorsiflexion moments, peak knee extensor and hip flexor moments in the second half of stance, decreased knee flexor moments during midstance, and no difference for hip extensor moments (62). The differences could be eliminated for the ankle and hip by using the 3D joint center positions for the 2D calculations, suggesting some sort of offset in the 2D calculations to account for the differences, however even with the change in calculations, differences still existed in the knee joint (62). The calculation differences have yet to be substantiated as far as an acceptable standard is concerned. This means that direct comparisons between 2D and 3D data should be made with caution as the magnitude differences may have significant implications regarding the studied populations.

3D Marker Sets

As motion capture technology has evolved, so too has the marker sets utilized in the data collections. 2D markers were often placed at segment end points and/or joint centers from the perspective of a perpendicular viewpoint to the plane of motion. 3D data has surpassed this in terms of total markers utilized with a minimum of three markers needed to create a segment's position in space (62). This has led to the question of whether the markers being used truly represent the underlying bone motion which they are supposed to mimic. There are two dominant methods of skin-based markers being utilized: the Helen Hayes marker set (69) which is a minimalist approach designed to use fewer markers and a Cleveland Clinic cluster-based approach (70) which uses more markers in an attempt to model the underlying bone motions.

Skin marker-based motion capture is the most commonly used method in human motion research, however prior to the in-depth investigation into the different skin-based marker sets, it should be mentioned that neither of these represents the "gold standard" for marker-based motion capture. Bone pins have been identified by several researchers as the "gold standard" for marker-based motion capture (71-78). Bone pins are the surgical insertion of a pin into the bone, with the end of the pin containing the same markers used in skin-based marker motion capture. The same motion capture system is used but the bone pins are believed to represent the actual bone motion since they are directly attached and do not have to contend with movement of the skin and muscles which separate the skin markers from the bones. Bone pins are subject to error though as the bending of pins or impingement can occur as the muscles and tissue still has to act around the pin. This can be alleviated by using shorter threaded pins and fully inserting the threaded part into the bone as the smooth part of the pin is more resistant to bending as are larger diameter pins. Additionally, specific placement of the pins between muscles/tendons where the least amount of movement occurs is beneficial. Dynamic motion on the operating table may help to better guide the pins into the correct position (76). This method is infrequently used due to the invasive, surgical nature of the pin attachments, which would dissuade many potential participants from being involved in the research, not to mention the added expense of the surgical procedure with respect to time, equipment, anesthesia, etc.

Given the complexity of the bone pins, the Helen Hayes and Cleveland Clinic skin marker sets have dominated the research protocols. In beginning with the minimalist approach (Helen Hayes), this marker system was initially developed for low resolution imaging systems with a goal of having as few markers as possible spaced as far apart as possible (79). Markers were placed bilaterally on the anterior superior iliac spine (ASIS), the top of the sacrum, greater trochanter, lateral aspect of knee flexion axis, lateral malleolus, and between second and third metatarsal heads (69). This was done in an attempt to add as little alteration to the natural subject as possible, which is inherently beneficial to simulating realistic research as people do not move with markers on their body in their day to day lives. This marker set constrains the joints with three rotational degrees of freedom (DOF), it creates a thigh segment that relies on a hip joint center estimation from pelvic markers, creates a thigh that shares a knee joint center marker with the shank, and has a foot defined by an ankle joint center created from shank markers (64). Shared markers inherently provide a limitation as joints are not a connection point between two bones, per se. The knee, for example, is not the connection point between the femur and tibia. There is a space that joins the two bones together to create the joint, but they are often modeled as the distal point of the femur being the same as the proximal point of the tibia, which is part of the rigid body model assumption. The axis of rotation for the knee sits in the femoral epicondyles, but user placement errors of markers can be a limitation.

One issue with the minimalist approach is that it is modified quite frequently with respect to placement of the markers. In theory, if the same tests are performed by different researchers on the same subject, the results should be the same. This is not always the case though as interresearcher reliability is not always high. In 2004, Schwartz et al performed an analysis using four different therapists in three different sessions using a modified Helen Hayes marker set. They all used the same marker set, but results showed differences in the examined kinematics. There were higher errors for pelvic tilt than the other pelvic rotations. The frontal plane hip motions were the most reliable with the transverse plane hip motions providing the largest errors. The frontal plane knee had the smallest inter-trial errors, but highest inter-therapist to inter-trial ratio, suggesting experimental errors. The foot progression angle had large inter-trial and inter-therapist errors, which was attributed to improper foot marker placement (65). This could prove problematic for a pathology that needs to examine foot rotation or desires to correct the pathology through a movement intervention.

It has been suggested that more markers are needed with this minimalist approach in order to improve the model. By expanding the markers, the loss of markers can be minimized, which is especially important during faster motions where marker tracking difficulty increases (56). The three DOF is also seen as a problem. A 6 DOF model has been shown to have better construct validity combined with fewer theoretical assumptions embedded in the model, including a lack of joint constraint and independence between segments (64). When comparing the simultaneous measurement of the Helen Hayes markers with a 6 DOF model, altered kinematics were observed. These differences included magnitude differences (frontal/transverse pelvis, frontal hip, knee external rotation) and pattern differences, often with opposing trends (transverse hip, frontal knee) and changes in time occurrence of peaks during stance and swing phases (64). There was increased inconsistency in the frontal plane knee kinematics, suggesting cross talk in the Helen Hayes set with knee flexion, characterized by anatomical identification difficulties (64). The anatomical landmark identification can also be problematic with different types of patients, as increased tissue presence can make identification of the landmarks tough. Given the inconclusive results of the comparisons of the Helen Hayes set and the 6 DOF model, it was suggested that the joint constraints are not the greatest limitation of the Helen Hayes set. However, they are still a significant limitation, meaning that since the results of 6 DOF model are not worse, this would be a better starting point for research than the Helen Hayes set, despite the soft tissue artifact (STA) problems for the 6 DOF model (64).

In opposition to the Helen Hayes set and congruent with a 6 DOF model, the Cleveland Clinic marker set is characterized by a triad of markers attached to a rigid shell and positioned over the lateral aspect of the body segment, allowing for the creation of 6 DOFs in the rigid body model (70). This shell is for tracking the movement while proximal and distal landmarks are chosen to estimate the segment end points for building the rigid body model (80). There are different possible placements for the marker clusters, each of which have been attributed to their own problems. Mid-lateral aspect of the segment tends to be the most common placement, but the distal-lateral segment has been argued as the most accurate placement of the cluster as far as reproducing accurate movements, for both the cluster and the Helen Hayes wand marker (80). The various cluster arrangements possible have shown good agreement within the sagittal plane (81) but movements outside of the sagittal plane are more susceptible to errors. Similar biomechanical patterns were observed and it was hypothesized that this may be linked to a bias in the axis of rotation and related cross-talk between markers rather than poor positioning of the markers (81). They reproduce kinematics well but do not appear to represent the bones well with the given translational and rotational errors (73). This methodology has also been shown to be susceptible to further errors based on their attachment methodology. There is the potential to wrap over the markers, under the markers, or several other methods. An underwrap methodology was shown to be the best method for securing the cluster on the shank, as it was for the wand-projected marker on the Helen Hayes set (80).

There have been multiple comparisons of different marker sets in an attempt to examine errors related to the incorrect motion of the skin-markers to the bones they are targeted to represent. Most 3D data collections with skin-markers treats the body as a rigid body model where the movement of the markers represents the underlying bones, however STA has been shown to be a problem. There is a substantial amount of tissue surrounding the bones and as the body moves, muscles contract and lengthen and can change the positioning of the markers (71), providing a false reading of movement related to the bone. This is largely subject dependent though as there are many different body shapes and sizes which can result in different levels of change (73). In an examination of the lower limbs, STA has been shown to be higher on the thigh than on the shank during open chain knee flexion, hip axial rotation, level walking, step up, land and cut, and stair climbing (60, 82-85). The level of STA is based on the placement of the markers as well as the motion being performed. During a step up activity, the largest mean error related to STA of the thigh was 12.6 mm in the proximodistal direction and during a walking activity, it was 19.1 mm in an anteroposterior direction (60). On the shank, it was during open chain knee flexion with an error of 8.6 mm in the mediolateral direction (60) and during walking it was 9.3 mm in the anteroposterior direction (82). Errors have been shown to be as high as 40 mm (86). Many of the factors in motion analysis interact, for example, where errors of lower than 3 mm have been shown to have no effect on joint angles over a 30° flexion range of motion (69). Large knee flexion motions have shown mid-anterior thigh markers moving distally to the underlying bone (60). This makes sense as the knee flexes, the skin could be pulled in a distal direction, taking the skin-mounted markers with it in the same direction. In a similar manner, a patellar marker had larger RMS errors than any of the thigh markers in the proximodistal direction (60), likely due to movement of the quadriceps muscles which has a direct connection to the patella and is therefore very susceptible to every contraction of those muscles.

These errors can also be phasic, rendering correction factors difficult to implement. During walking, the thigh markers can experience a proximal and anterior shift after heel strike (60). This can manifest as temporary inaccuracies, as it only occurs at certain points. Phasic contractions may contribute to increased STA during gait (77). At 10%, 50%, and 100% of a gait cycle during running, inaccuracies have been reported (86). Most of the STA errors affecting kinematics and kinetics are during the first half of the stance phase (85). The complexity of the movement also impacts it. More dynamic motions increase the error values. When comparing walking to a cutting motion, translational errors have been shown to increase from a range of 3.3-13 mm to 5.6-16.1 mm and rotational errors from a range of 2.4-4.4° to 3.3-13.1° (73). The rotational errors have reached values as high as 19° in the transverse plane during walking (82). As the flexion values increase, the non-sagittal angle errors increase meaning that caution should be taken when comparing different data sets which represent different flexion levels (69).

As a result of these errors, it has been suggested that standard errors be applied for the interpreting of kinematics (73). The issue with this is the large discrepancy in the errors and how to create a standardized calculation for this. Multiple calibration poses have been used in an attempt to alleviate this but have still resulted in translational and rotational errors of 3 mm and 3°, respectively (87). Standardization of marker placement may be an option to help alleviate some of these issues with differences between data sets. The lateral aspect of the thigh and shank are believed to cause minimal errors and therefore the best results (86). Rotational deviations are the smallest when placed laterally and distally, with error values less than 3° in the sagittal and frontal planes, although that number represents 2-3% and 10-25%, respectively, of the total range of motion (80) and should therefore still be interpreted with caution. STA errors for the knee joint have been reported between 2.4-8.3°, but often the non-sagittal values exceed the total range of motion (60). This is on the higher end of the spectrum for absolute values compared to other studies (84), but was likely due to a larger range of motion examined.

These errors may be reduced through certain data processing techniques. An interval deformation technique based on a point cluster technique (88) that can utilize the mathematical concepts to reduce the position and orientation errors of skin markers by 33% and 25%, respectively, in the rigid body model (71). The errors largely depend on the base of reference though. For example, if fluoroscopy is the "gold standard", the RMS errors for the skin markers can reach upwards of 190% (84). Additionally, the sagittal and frontal moments of the skin markers are reported as lower than the fluoroscopy (61).

Irrespective of the marker set used, the biggest errors reported are in the non-sagittal planes. There is good consistency with multiple marker sets in the sagittal plane for the lower limb joints, but the correlations significantly decline once out of the sagittal plane (81, 84). Transverse plane deviations tend to occur during early and late stance (80), lending some support to transverse validity during mid stance. These deviations during the first third of stance may be related to inertial effects of the segments related to heel strike (77) and during the last third may be related to increased shank muscle activation in an attempt to propel the body forward (89). Marker placement is one of the biggest sources of error between labs, with inter-lab differences as high as 26% (pelvic rotation) and 33% (foot progression angle), although most differences were still 8% or less (90). Eight percent can still represent a significant error when comparing data which may have clinical implications. The altered skin marker motion leads to altered joint centers, which can significantly impact the moment arms and joint moments (61). This in conjunction with altered joint angles can impact the interpretation of the data. It has been suggested that data errors in excess of 5° may be large enough to mislead clinical interpretation, between 2° and 5° may be acceptable but requires consideration in interpretation, and smaller than 2° are too small and do not require independent consideration in result interpretation (91). However, as noted earlier, this may represent high percentages of total range of motion. It is believed that a compensation method is necessary and should be both subject and task specific (84), although a generally accepted method has yet to be presented.

One final compensation is a markerless design built to construct 3D images based on 2D camera spatial recognition. The advantages of this system being that no initialization is needed, the subjects can go from the static pose to immediate motion, and there is a direct provision of joint centers and segment volume information during motion to allow for better kinematic calculations (92). However, extensive research has not been completed with this system, leaving discussion regarding its validity and mass application.

3D Joint Angle Measurement

Currently, a frequently used construct for the calculation of 3D joint angles is based on the rigid body model, which as described earlier is with limitations due to the muscles activating and moving the markers (71). However, as this is the commonly utilized system, joint angles are based within this system. There are a multitude of methods for calculating the joint angles based on the marker data. Much of the current research is based on Euler and Cardan angles which are rotations about a given axis as defined in either the global or local systems. There are multiple orientation possibilities within each system, each of which ultimately provides 3 angular numbers which reflect the rotation from the initial static pose (57). Human bodies which are modeled as rigid bodies have rotations assumed to take place around a fixed point. Euler angles have been applied in a manner that allows for the description of one segment rotating about another segment in a 3D space (93). These angular calculations require orthogonal embedded axes for both the moving segment and the reference segment. In the proximal reference frame, unit vectors are applied to rotation matrices from derived equations, although assumptions can be made with respect to the order of the rotational occurrences (69). When the order assumptions exist, the initial axial definition is important. For example, in a sagittal, frontal, transverse order, the sagittal axis can be defined by the skin markers. These markers are placed in a manner where skin movement is minimized around the underlying bone in an attempt to satisfy the rigid body assumption. Correct positioning of these markers is crucial though as all subsequent rotations are affected by the placement of these markers and subsequent axis definition (69). When the initial axis is created based on anatomical landmarks, a line is drawn between the two markers to create the initial axis. For example, the flexion/extension axis of the ankle can be created through joining the medial and lateral malleoli markers. From this midpoint (the ankle joint center), a line is drawn to the knee joint center (which is often the midpoint between the femoral epicondyles or some other anatomical landmarks around the knee) to create the longitudinal axis. The third axis is the cross product of the other two axes which creates the anteroposterior axis (75), although this may not create two axes orthogonal to each other and it therefore cannot be used for Euler/Cardan angle calculations. This gives an orientation about the ankle joint center but this orientation can be changed to reflect a different segment, although this has been shown to alter joint moments in terms of magnitude (sagittal/frontal) and profile (frontal) (75). Singular value decomposition method also utilizes a position vector and orientation matrix which can be obtained from the transformation matrix that was estimated by an algorithm connecting the local coordinate frame of three skin markers (tracking markers) and their global positions (78, 84, 94).

Each coordinate system has its own mathematical constructs which lead to different results. The reported coordinate system for joint angles is a significant variable to take into account. Joint coordinate systems (JCS), global coordinate systems (GCS), and local coordinate systems (LCS) are all utilized on a regular basis within the research community. Each is chosen for its respective application to the research being conducted, however each needs to be carefully analyzed. The non-orthogonal JCS was initially proposed by Grood and Suntay (95). In order to set up the JCS, a Cartesian coordinate system is established for adjoining segments. The axes in this system are defined either by palpable anatomical landmarks or through X-ray imaging. The common origin of both axis systems for the segments becomes the point of reference for the linear translation occurring in the joint. The JCS is then established based on the intersection of the two Cartesian coordinate systems. Two of the axes are fixed in the body while one is "floating". This provides for three rotational and three translational joint motions within the JCS (96). Kinematic data can then be calculated based on the rotational elements, feeding into the calculation of net internal joint moments through a standard inverse dynamics approach. Calculations of external moments using two components for independent effects is also possible: a moment due to the resultant ground reaction force (GRF) and moment arm and a free moment of rotation about the vertical axis through the center of pressure (97). Using the JCS facilitates correspondence between kinematics and kinetics. A projection onto the JCS is suggested as the only method where joint moments correspond to muscle and ligament loading and may be the natural choice for a standardized procedure (98).

The JCS proposed by Grood and Suntay is the same as a Xyz Cardan rotation sequence, where “X” represents a flexion/extension rotation axis, “y” represents an ab/adduction axis, and “z” represents an internal/external rotation axis, which is commonly used in biomechanics research. However, this is not the only available rotation sequence. Cardan and Euler rotations allow for different methods of calculating joint angles, based on different rotation patterns. There are three potential rotations which can be sequenced: X, Y, and Z. These can be placed into different orders of operation which allow for different angle calculations. The resulting angles are known as Cardan angles when the rotation sequence has only one of each letter (i.e. Xyz, Zxy, etc.). When a letter is repeated in the sequence (i.e. Xyx, ZxZ, etc.), it is known as Euler angles (99). This allows for the creation of three independent angles, however the magnitudes of these angles change depending on how the rotational sequence is ordered, thus confining the angles to a “sequence dependency” (100).

An examination of the different rotational sequences has provided some consistent results and some mixed results. During an assessment of lower extremity dynamic tasks, the different Cardan sequences provided good agreement for motion in the X axis, except for during a YXZ sequence (101). This led to a conclusion that the X axis is robust in its usage during the Cardan sequences. Upon choosing a following rotation from Y and Z axes, results become mixed with numerical offsets and profiling changes in some instances (101). Some rotation sequences which have shown higher RMS values may have been due to higher flexion values which can affect the joint center and axis of rotation thereby causing errors in following computations (101). One potential problem with the high angle values is the potential for Gimble lock, which occurs as the second orientation angle approaches 90° (102). In the lower extremity, the flexion/extension motions are typically the only motions which approach (±10°) that value. Therefore implementing the X axis as the second rotation sequence may not be in the best interest of accurate calculation as the mathematical singularity becomes an issue and can cause compounding errors (103). This is further supported by a direct comparison of the different Cardan sequences which showed that the YXZ and ZXY rotation sequences performed the worst (101). In a study examining a Euler rotation sequence beginning with X, there was good agreement with a JCS rotation, but when the Euler sequence began with Z rotation, the kinematics were significantly altered in comparison to the JCS (104).

The rotational sequence should be based on the movement of interest as well as where the largest motions occur. In most lower extremity motion, the bulk of the movement is flexion/extension, thereby suggesting the first rotation in sequence should be X (or whichever letter/symbol represents flexion/extension). This allows for avoidance of Gimble lock as it is less likely that the remaining two rotations (ab/adduction and internal/external rotation) will reach the 90° mark. The secondary rotation should likely be whichever the next plane of motion of interest is. However, in the upper extremity, this is not always the case as many of the rotations occur outside of the sagittal plane, in which rotations approach Gimble lock values. Movements such as a golf swing, baseball throw often involve secondary rotations which approach 90°, thereby making an approach to the singularity possible should the correct rotational sequence not be selected. In a comparison of Cardan and Euler rotation sequences in the upper extremity in examining for the presence of Gimble lock, there were instances of both types of rotation where it was present and instances of both where it was not present (102). This illustrates the necessity of the Euler rotation sequences containing a repeated axis as it is mathematically sounder for certain movements in the upper extremity. An analysis of the desired movement is necessary for determining the most appropriate rotational sequence. Euler may be better suited for the upper extremity, but Cardan seems to be better suited for the lower extremity where the excessive secondary rotations are seldom present.

In using the external GRF method, it was found to be highly sensitive to the reference frame of choice, with altered magnitudes and profiles sometimes occurring (97). The GRF is used with the free bodies of the foot and shank to calculate joint moments about the knee joint center which can be referenced as the midpoint of the transepicondylar axis. However, when combined with skin marker data, there has been a shift in the knee joint center during the first 40% of stance, leading to a reduced knee extensor moment (as high as 12.3%) due to the posterior shift of the knee joint center (85).

Global coordinate systems (GCS) and local coordinate systems (LCS) are additional methods which can be used. The GCS references motion of a segment within the global or laboratory environment, essentially defining the motion within the entire calibrated area in which the data is being collected. A set of axes is defined from a point of origin within the lab space. An LCS is defined by the marker data on the segments and utilized in relation to an additional segment. An orthogonalization process can be used to define the axes for the LCS. Similar to the JCS, a set of markers can be used to define an initial axis. A perpendicular line is then drawn towards an additional marker or an already defined joint center or landmark of some sort. A cross product of the two existing axes then defines the third. This can be done in a sagittal, transverse, frontal order as part of the Gram-Schmidt process (59). Rotations can then be calculated for a segment with respect to the axes defined in the GCS or LCS, which should theoretically be the same when properly expressed, however this is not always the case with data reported between the differing coordinate systems.

In comparing GCS to LCS expressions, there were several differences with respect to the lower limbs at different parts of the stance phase when reporting joint moments. For example, a comparison of global versus local coordinate systems showed an over estimation of ankle moments in the frontal plane at mid stance and the transverse plane at 40%, 60%, and 80% of stance while underestimating the sagittal moments at 20% and 40% of stance. The knee moments were overestimated in the sagittal plane at 20%, 40%, and 100% of stance and the transverse plane at 20% and 100% of stance but underestimated in the frontal plane for the entire stance phase and the transverse plane for 0%, 40%, 60%, and 80% of stance. Finally, the hip was underestimated for all of the frontal plane and 20% and 80% of the sagittal plane, while following the same transverse pattern as the knee (59).

Research has been performed to examine the correlations of joint moment calculations in the GCS, LCS, and JCS. It showed that there were the lowest correlations in the transverse plane. The sagittal plane showed strong correlations while the frontal had moderate (98). Despite the correlation values though, magnitudes can still present as different which requires caution with interpretation. During a side step maneuver, the sagittal knee showed high correlations but the GCS system reported lower values than the LCS and JCS (98). In general, sagittal profiles have little to negligible effects when using global or local frames of reference. There is some discrepancy with the frontal plane though as while some report moderate correlations, others have seen little influence with respect to the coordinate system (97). The transverse plane seems to have a general agreement with errors between the different coordinate systems, rendering these values ones to be interpreted with caution as the coordinate system plays a big difference in the magnitudes and profiles, with the opposite profiles sometimes being present (97, 98, 105). It may be of benefit for researchers to consider the motive of their research prior to choosing a coordinate system as it has been suggested that using a GCS is beneficial for examining the contribution of a joint to movement in a certain direction while using an LCS is better for interpreting loading at a joint (98). As discussed earlier, STA is also a factor in this. When examining the STA of the shank in different coordinate systems, the tibial coordinate system was shown to be less affected that the femur, leading to the suggestion of using the tibial coordinate system for calculations because of the decreased sensitivity (83). This has the advantage of being an orthogonal coordinate system, but has the disadvantage of not providing joint moments in the manner to which the research community has come to understand joint moments. For example, a knee flexion moment in the tibial coordinate system does not entirely correspond to the extension moment generated by the quadriceps muscle if the knee has some simultaneous transverse rotation (98).

For the LCS, the development of the initial axis is an important consideration as there are multiple methods by which to establish it. In a comparison of three different axes, differences were evident in the calculations after the axial establishment. There are three common methods for establishing the axis. In the knee, for example, an axis could be created at which flexion and extension is perceived to occur by the investigator. This can be achieved through a knee alignment device, however misalignment of it does present the potential for cross-talk errors given that these are essentially planes of finite rotation with a mathematical interaction being applied to them (65). Second, a line could be created based on anatomical landmarks, such as between the two epicondyles, thereby creating the flexion/extension axis. For these two methods, the other axis can be created through perpendicular lines to additional landmarks and cross products, as described earlier. These are the two most commonly used methods, but a dynamic method can be implemented based on an optimization procedure in which the longitudinal femoral anatomical axis is defined and then a mediolateral axis is rotated about that axis by a given degree value, designed to minimize the frontal plane profile variance (106). This dynamic method has shown higher repeatability than the first two methods described. The frontal plane inconsistency, which as mentioned earlier can be problematic, was lowest in the dynamic method (106). This is likely due to the optimization procedure but it is significant nonetheless as it was also shown to minimize the joint angle cross-talk at the knee. This method has an assumption of minimal frontal plane knee movement, which appears to be acceptable for reduced knee flexion motions (under 90°) which is accurate for many dynamic movements (106). This method may be inappropriate for certain pathological populations where knee laxity in the frontal plane is present, such as knee replacement patients or ACL-injury patients. A hierarchical model has also been employed for calculations, but the primary issue with it is the trickle-down effect for the errors in which the errors compound onto subsequent joints (65).

Ultimately the use of error estimates with clinical data can be beneficial as it increases the objectivity of the data interpretation. This allows a focus on deviations which exceed the acceptable level of experimental uncertainty (65). It has been suggested that all of these varying methods of calculating kinematics and kinetics are valid, but that the decision should be carefully evaluated for the population it is being applied to because the information is not necessarily directly comparable. The JCS has been suggested as the best option for a standardized system as it best represents what a joint moment actually is (105).

The final decision for what marker system to use, what calculation reference frame to use, and axial creation method to use needs to be evaluated on an individual basis. This should be based on the population of interest, how previous errors with certain styles may affect the data desired to be collected, and whether or not the data will be comparable to other research. The direct comparison between data sets is not always possible due to the fundamental differences in methodology. This renders the need for caution when interpreting data and comparing to other data sets as the results may not actually be as clear as initially seen. Independent analysis for the errors and issues at hand must be taken into consideration before any comparisons are made and definitive conclusions are drawn. Failure to do so may result in inconsistent or inaccurate information being presented, which may have clinical implications that could prove detrimental to the population in question. Great care must be taken in making these choices prior to the execution of the project.

Biomechanics, Strength, and Balance of Total Knee Replacement Patients

Osteoarthritis (OA) is a disease characterized by degradation of cartilage within a joint. According to the Center for Disease Control, approximately 22.7% of adults in the United States (52.5 million) have a form of doctor-diagnosed OA (107). OA can occur in any joint and knee OA is the one of the most common forms. It will afflict approximately 25% of the population by the year 2030 (1). OA is a progressive disease where the wearing down of the cartilage can eventually lead to bone on bone contact. As the disease nears the end-stage, a total knee replacement (TKR) is one of the treatment options. In 2011, there were over 700,000 TKR operations performed in the U.S. (2) with over 3.5 million per year projected by the year 2030 (3). With each replacement, there is a significant financial implication associated with the procedure. In the state of Wisconsin, for example, the average TKR procedure costs approximately $19,169 (108). It is projected that the total costs of TKRs by 2030, based on projections, will exceed a value of $67 billion. In addition, the occurrence of TKR procedures is increasing in patients under the age of 60 (4). Ultimately this means that people who undergo TKR procedures will have longer lives to live with the replacement in their joint, making the longevity of the replacements important as well. While restoration of function is typically the most important factor in considering a TKR procedure, the addition of the high cost make this an important issue worth examining in an attempt to make the outcomes as optimal as possible given the significant financial investment.

The primary goals of a TKR procedure include a reduction in pain, improved knee joint range of motion (ROM), improved knee joint alignment (as a malalignment often contributes to the degeneration of cartilage), and a restored ability to perform activities of daily living (ADL), with some patients having a desire to return to more advanced physical activities such as tennis, cycling, golf, and swimming (5). Many of the common survey tools filled out by the TKR population examine the patients' desire to return to advanced activities beyond simple ADLs, thus indicating a hope of many patients to resume advanced activities post-operation. Overall, the operations are generally considered successful for the majority of patients. Reductions in pain and improvement in ROM have been commonly reported (6-9), with accompanying satisfaction rates ranging from 81-97% (10, 11). However, despite high satisfaction rates, this still leaves a significant percentage of patients dissatisfied with the outcome of the procedure. Many patients still report post-operative pain (12) and functional limitations (13), often resulting in decreased performance on clinical tests (such as the timed up and go, six minute walk test, and sit to stand test) compared to healthy controls (14, 15). These clinical tests are frequently used as a means of assessing the success of an operation due to their ability to determine whether a patient has restored function of the replaced joint. However, the dissatisfaction of TKR patients is not sufficiently explained by the clinical tests and survey data.

Biomechanics data is often utilized to examine TKR gait patterns as a means of assessing the progress of the patients, as there are known gait profiles which contribute to the exacerbation of knee OA which leads to TKR procedures. Researchers have studied everything from simple to complex variables such as gait velocities (20, 21), sagittal plane knee ROM (20, 22), and frontal plane knee moments (20, 21) during overground walking as a means of searching for detrimental movement patterns. Additionally, researchers have examined more demanding movements such as stair climbing since it is a common activity in daily life for both older and younger people (31). Stair climbing has been shown to be a difficult task for people with knee OA (33), the same people who may become candidates for a TKR procedure. Current survey tools such as the Western Ontario and McMasters Universities Arthritis Index (WOMAC), Forgotten Joint Score (FJS), and Knee Society Knee Scoring System (KSS) all use stair climbing as a means of assessing function following TKR and for gauging improvement (5, 34, 35). Advanced physical activities, such as stair negotiation, may highlight movement deficiencies for patients who may or may not show the same deficiencies on less demanding tasks such as level walking (29, 109).

Most of the previously mentioned studies examined the TKR population as a whole and did not differentiate between the satisfied and dissatisfied populations. There is a lack of data regarding the biomechanical profiles of these two subgroups of the TKR population. There have been minor explorations in survey-based data and how certain activities related to patient satisfaction with the TKR procedure (110), how patient expectations were not met (111), and the experienced changes in pain post-operatively (112).

TKR Patient Biomechanics of Level Walking and Stair Climbing

When examining biomechanics data, there are different methods utilized to provide a baseline comparison to the most recent physical state of the TKR patients. These comparisons include pre to post-operative physical states within the TKR patients as a means of assessing progress post-operatively (27, 53, 113), between TKR patients and healthy control subjects (20, 22, 23, 38, 114), and post-operative compared to both pre-operative levels and healthy controls (15, 24-26, 54). Gait is a common measurement protocol as it is the most commonly utilized activity for the general population.

Stair climbing has also been studied as it is a commonly performed activity in daily life for many people. More importantly, stair climbing represents a more physically demanding task as it requires, even at a slow pace, twice the metabolic expenditure of slow walking (115), and subsequent increased demands on the involved muscles and joints (29). This task allows researchers to examine a task with increased demands as a way of assessing advanced physical function for the TKR patients. Given potential limitations for the TKR population both pre-operatively and post-operatively, these differences in the tasks are significant. Climbing stairs has been reported as one of the top five most difficult tasks for people over the age of 60 (32). This task is increasingly difficult for the knee OA population (33), the same people who are candidates for TKR procedures, as they often have increased pain and functional limitations in advanced physical tasks. Additionally, stairs are an infrequently assessed task in most surveys utilized on the TKR population (5, 34, 35). While many people are able to live in homes without stairs, they may eventually encounter them in a public realm where the alternative to the stairs may not be a viable option, thereby highlighting their physical limitation. Within both walking and stair climbing, there are many variables which play a part in the analysis of an individual’s gait profile. These include spatio-temporal variables, ground reaction forces (GRF), kinematics, and kinetics, which can be further subdivided into specific planar assessments.

Spatio-Temporal Gait Variables

Spatio-temporal variables are commonly assessed in both laboratory and non-laboratory settings (such as physical therapy clinics or hospitals) because the data are easy to collect with minimal equipment required. Often times, a simple stop watch and measuring tape allow for recording of this information. This information includes gait velocity, stride length/frequency, and step length/frequency. These values are easily tracked in a longitudinal fashion as a way of assessing improvements in function over time.

Gait velocity is a simple tool for measurement as a fixed distance can be measured and the patient can be timed with a stop watch to assess his/her velocity in covering the known distance. Pre-operative gait velocities for TKR patients have been reported to range from an average of 0.89 m/s (24) to 1.13 m/s (25). These speeds often relate to the severity of the knee OA progression as well as the pain levels associated with the disease at the time of measurement as pain can limit functional ability and cause the patient to reduce speed as a way to control the pain. Post-operative velocities have been shown to increase compared to pre-operative levels (24, 27, 53, 113) with increases ranging from 0.1 m/s to 0.17 m/s at one year post-operative (27, 53). The magnitude of the increase is dependent on the pre-operative value and based on the overall functional increases of the patients. However, these results are not always consistent as some researchers have reported no increase in gait velocity (25) or reduced gait velocities at two months post-operative (15). This may suggest that improvements are recovery and/or time dependent as not all variables have been shown to increase as early as two months, with improvements still manifesting more than 12-months post-operatively. When a patient undergoes a bilateral TKR, the gait velocity may be further impacted. Decreases in gait velocity have been reported as long as 8 years post-operatively (36).

Improvements appear to be continuous throughout the first year post-operatively (27). Different variables reach peak, or "normal", values more than 12-months after the operation while some reach them much earlier. Initial declines in function are common post-operatively (15). It may take as long as one year before the operative leg reaches the same level as the non-operative limb. Asymmetry has been reported at 3 months post-operative but disappearing by 12 months (46).

While improvement is regularly shown for TKR patients in comparison to themselves, it is important to note that these levels of improvement may not reach those of healthy control subjects (116). Gait velocity differences have been reported to be decreased between 0.12 m/s to 0.6 m/s for TKR patients when compared to healthy controls (15, 38). This may be reflective of time from surgery as the magnitude of difference was larger at 2-months post-operatively (0.7 m/s for TKR and 1.3 m/s for healthy) and the smaller magnitude was at 1 year post-operatively (1.31 m/s for TKR and 1.43 m/s for healthy), implying that recovery and restoration of function takes time (15, 38). This result is not always consistent though as some studies have reported no gait velocity differences between the two groups at 12-18 months post-operatively, with the TKR patients retaining their velocity at 46 months post-operatively (22, 26). The inconsistent results may suggest that additional studies are needed in order to provide a definitive conclusion on gait velocity improvements as to whether a return to the levels of healthy controls is possible. It does appear to be consistent that an improvement from pre-operative velocity is possible.

Stride length increases have accompanied the velocity increase when comparing pre-operative and post-operative values. Mean increases of 0.04 to 0.11m have been shown (24, 53, 113). As with gait velocity, initial declines can be expected after the operation, with reductions in stride length being reported at a two month follow-up period (15). Although one study found no difference in stride length between pre-operative levels and post-operative levels at 12 months after surgery (25). This may suggest that the population of TKR patients used here were higher functioning prior to the operation than some other TKR populations. In comparison to healthy controls, the results are mixed. Several studies have found reduced stride length for TKR patients compared to healthy controls (15, 20, 23-25, 38) while two other studies have reported no difference between the two groups (22, 26). Step frequency (how often steps are taken) has been shown to be greater in controls as well (15, 20, 23, 25) with the same two studies who showed no difference in stride length showing no difference in step frequency (22, 26). Peak differences in step frequency reached as high as a 25 steps/minute reduction for the TKR group at 2 months post-operation (110 steps/minute versus 85 steps/minute) although the differences did reduce as time progressed (121 steps/minute versus 115 steps/minute) (15, 25). Improvements did exist for the TKR population after the operation but did not reach the levels of controls.

With stair climbing, there are slight differences as step length is a little more complex to assess given the fixed size of the stair, thereby making alterations tough to achieve. In 2003, Nadeau et al showed reduced stride lengths and frequency on stairs and a decreased forward velocity coupled with a lengthened swing phase compared to overground walking for adults over the age of 40 (29). These alterations are an indication of the complexity of the activity of stair negotiation in comparison to overground walking. Additionally, healthy individuals have been found to have a slower velocity when ascending the stairs (0.49 m/s) compared to descending the stairs (0.56 m/s), further suggesting the complexity of a stair ascending task (117). As a whole, spatio-temporal variables are less frequently reported for stair negotiation compared to overground walking.

Ground Reaction Force

Ground reaction force (GRF) is the force applied to the body from the ground during the stance phase of a motion. It is often used to assess external loading to the body during dynamic tasks, with the reporting often done in a normalized version (usually a percentage of the individual's body weight) of the absolute value in Newton. Additionally, the loading rates are often reported as a descriptive measure of how quickly the external force is applied to the body. There have been similar vertical GRF values and loading rates shown between the operated and non-operated limb for unilateral TKR populations (114). The results of this study did span a wide amount of times post-operatively, with subject times from surgery ranging from 4 to 96 months.

Pre-operatively, research has shown that during walking the non-operated limb has had higher peak vertical GRF values (1.06BW) compared to the operated limb (1.03BW), which has a resultant effect size of 0.297. Post-operatively, this same group saw increased loading to both the non-operated and operated limb (1.10 and 1.06 BW, respectively, effect size=0.244). These increases were significantly different from pre-operation to post-operation as well as from each other. The loading rates for these same subjects increased post-operatively, but the two limbs were not different from each other after the operation (113). Pre-operative favoritism of the healthy leg is to be expected as a way of taking some of the load off of the diseased limb, likely due to pain. However, with continued asymmetry between the limbs, it should come as no surprise that approximately 40% of the patients who have unilateral TKR procedures have their contralateral limb replaced within a ten year time period (118). Other researchers have shown a return to vertical GRF symmetry by 12 months after the procedure despite significant differences occurring at 3 months after the procedure (46).

The VGRF profile is usually a bimodal curve. The first peak represents weight acceptance and the second curve is the force applied during push-off (113). The values of the first peak VGRF are greatest during stair descent compared to stair ascent or level walking (117, 119) with values reaching nearly 1.5 BW (119). The second peak has been reported higher in stair ascent compared to descent and overground walking (117). This is to be expected given the requirement of a higher propulsive peak in order to make the vertical ascent to reach the next step in the stair case. Additional research has shown walking as having higher weight acceptance peak VGRF (1.13BW) compared to stair ascent (1.04BW) with no push-off differences between the two conditions (120). Bone on bone reaction forces of 4.25 BW have been reported when walking up stairs (121). In a more recent study, joint reaction forces (as calculated through musculoskeletal modeling) has shown early stance peak compressive forces reaching 2.76BW and late stance at 3.89BW during stair ascent (122). This number is crucial for the TKR population as altered loading is a part of the contribution to end-stage OA leading to a TKR procedure. Controlling the forces is crucial for longevity of the joint and maintaining joint health.

The highest peak compressive forces are experienced during stair descent in comparison to other ADLs, with knee forces reaching levels of 1.23 BW and hip forces reaching 1.1 BW, both of which were approximately 0.2 BW higher than walking values as assessed through inverse dynamics (123). Patello-femoral contact force has been modeled for both stair ascent and walking, resulting in a contact force 8 times higher during stair ascent in comparison to walking (33). While stairs may be avoidable for some patients, ideally there would be a desire to return to normal function after the TKR procedure, which would include stair negotiation when necessary. Given the increased ground reaction and joint reaction force levels in comparison to walking, it becomes more important for successful control of those forces as they are applied to the body.

Sagittal Plane Kinematics

Level Walking

Studies examining TKR patients have looked at sagittal plane kinematic variables including ROM, flexion contact angles, and maximum knee flexion during both stance and swing phases of gait. One of the goals of the TKR procedure is a restoration of sagittal knee ROM so it is frequently assessed by the surgeon and physical therapists. It functions as a measure of determining success of the procedure. Static ROM is a frequently used measurement tool by surgeons and physical therapists, but biomechanical analysis can add to this assessment by examining more dynamic aspects of movements for patients as the ultimate goal is a return to normal independent functioning.

Knee flexion angle at contact during walking has been reported as similar between TKR patients and control subjects by several studies (20, 23, 25) but most TKR research has reported reductions in maximum knee flexion during the stance phase compared to the control subjects by an average of 6° (15, 22-24). A reduced gait velocity may be related to the reduced active knee flexion ROM. Only two studies have reported similar maximum flexion angles between TKR patients and healthy controls (25, 26). This reduction may carry on through the first year after the procedure. A reduced dependence on the knee in the operated limb has been shown at 12 months post-operatively compared to the non-operated limb and healthy controls (46). There is typically an increase in maximum flexion angles post-operatively, but one study has shown no difference in maximum flexion angle or flexion ROM in comparing pre- and post-operative levels although both values were still reduced in comparison to healthy controls (116). It is important to note that this study examined differences at only three-months post-operatively, and that the dynamic ROM may not have fully recovered yet. Additionally, reduced knee extension during mid-stance has been reported for TKR patients compared to healthy controls, with absolute value differences of 10° pre-operatively and 7° post-operatively (25), suggesting no difference between the two groups for knee contact angle.

During the swing phase of a level walking gait cycle, some reports of reduced knee flexion have shown a reduction of approximately 10° for TKR patients compared to healthy controls, with the TKR patients producing 50° of flexion compared to 60° by the controls (20, 22, 23). Yet other studies have reported no difference between the two groups for swing phase knee flexion (25, 26). Despite this, TKR patients still have less knee flexion for both the stance and swing phases. This leads to a reduction in ROM as it is typically measured as the difference between contact angle and the maximum flexion value achieved during stance or the toe-off angle and the maximum flexion angle during swing. The decreased flexion ROMs have had reported values between 8-15° (20, 116). The reduced flexion by the TKR population has been speculated to be associated with a quadriceps avoidance pattern which the TKR population employs as a method of unloading the knee joint following their operation (124). Furthermore, the differences between these studies where no differences were found (which seems to be in the minority) may indicate a higher level of functioning for the TKR sample population used. Most TKR studies highlight kinematic as well as spatio-temporal parameter differences, thereby attempting to link the two variable types. Similar gait velocities have been shown at the same time as similar sagittal plane kinematics when comparing TKR patients and healthy controls (26), further highlighting this link.

It is important to note that time points from surgery make a difference in the results. Pre-operative and post-operative comparisons highlight recovery over time, but not all post-operative results are directly comparable because of the time differences. At 2 months post-operation, a difference of 9° in peak knee flexion during the stance phase of level walking can be seen in post-operative values compared to pre-operative (15). By 6 months, this value has been shown to decrease to 3° (24). By one year, peak knee flexion has been shown to increase beyond pre-operative levels (53). Although some studies have shown no differences in pre to post-operative differences in peak knee flexion at 3 months post-op, there were also no changes in gait velocity (116), which therefore should require less knee flexion so this result is to be expected.

Stair Ascent and Descent

During stair negotiation, the sagittal kinematics are different than walking. The ankle is in increased dorsiflexion during stair ascent compared to walking as the dorsiflexion is required at the onset of stance during stair ascent (29, 117) whereas in walking the dorsiflexion occurs later in stance. Simultaneously, the knee is in increased flexion at contact (65°) compared to walking (1°), coupled with much higher values of maximum flexion (93° in stair ascent compared to 67° in walking), resulting in an increased flexion ROM when measured from maximum flexion to maximum extension (29, 117, 125). Healthy adults have an increased ROM during stair ascent compared to walking (125), therefore making the increased ROM for TKR patients during stair negotiation expected. Compared to healthy adults, TKR patients have a reduced knee flexion value at contact of between 8.7° and 17.7° (24, 39-41, 126). There is an accompanying reduction in swing phase maximum flexion angles of 11-15° during stair ascent (40-42, 126). One study found no significant difference in maximum knee flexion during swing phase for TKR patients, however they reported absolute mean differences of close to 10°

compared to healthy controls (39). Knee flexion ROM has been shown to be reduced compared to healthy controls in both stair ascent (22, 36, 37, 39-41) and stair descent (22, 36).

The differences in TKR patients may be related to the prosthetic design as when comparing to healthy controls, one study found that TKR patients with a non-resurfaced patella had 17° reductions in flexion ROM (39) while another study found patients with a mobile bearing design only had reductions of 10° (41). However, two additional studies found no difference in flexion ROM when comparing TKR to healthy controls (22) and when comparing the replaced to the non-replaced limb on stair ascent (37). Two other studies also found no differences when making the same comparisons on stair descent for healthy controls (40) and to the non-replaced limb (37). Unfortunately, recent studies have made no comparisons during stair descent in comparison to healthy controls or to pre-operative levels (127, 128), making improvement comparisons difficult as the body of research on the topic is currently very small.

Sagittal Plane Kinetics

Level Walking

Kinetics are often measured along with kinematics as another way of assessing the biomechanical gait profile of a subject. Kinetic data provide information on joint loading through the analysis of joint moments. The most commonly utilized kinetic measurement is the joint moment which is defined as a linear force value multiplied by the perpendicular distance at which that force acts from the axis of rotation (moment arm), causing rotary motion at the joint. These moments are reported as either internal or external moments, depending on the calculation convention used by researchers. The joint moments are frequently normalized to either body mass (Nm/kg) or bodyweight and height (%BW*height).

While internal and external moments are often used interchangeably for comparative purposes, this is not always an exact comparison as the moments effectively represent two different things. They are similar in nature but external moments represent effects by GRF while the internal moments represent the moment by internal muscle forces. These differences are important to highlight in making comparisons between the two measurement conventions.

During walking, peak external knee extension moments (often used interchangeably with internal flexion moments) have been reported to be reduced in TKR patients compared to healthy controls, with group differences of 0.16 Nm/kg and 2.2%BW*height (15, 20, 25, 129). When examining the peak external flexion moments (occurring during early stance), healthy controls were reported to have significantly higher moment values (0.30 Nm/kg) compared to TKR patients (0.22 Nm/kg) during walking tasks (26). Internal extension moments at weight acceptance have been shown to be reduced by 1.9%BW*height for TKR patients compared to healthy controls (24). As with some of the kinematic variables, these differences can be time dependent. At 2 months post-operation, the TKR patients showed a maximum internal knee extension moment of 0.18 Nm/kg, which was significantly lower than the healthy control value of 0.34 Nm/kg while the internal flexion moments were also lower for the TKR patients compared to the healthy controls (15). The reductions have been reported as long as 46 months post-operation (22), although the magnitude of difference appears to shrink over time. Conversely, there are studies which report the maximum external flexion moment in TKR patients as similar to those of healthy controls (20, 25). This lack of difference is speculated to occur possibly as a result of the TKR population retaining their pre-operative gait which was matched with the healthy controls for maximum external flexion moments. The presence of a decreased external extension moment suggests a quadriceps avoidance pattern, which may have been a movement trait retained from prior to the operation. It is suggested that a therapeutic program to rectify this may be necessary (25).

Post-operatively, TKR patients have seen a more bimodal pattern curve for sagittal plane joint moments compared to pre-operatively (53). This pattern is more characteristic of a normal loading pattern seen in healthy individuals, suggesting a return of the TKR patients to a more normal kinematic pattern. There have been reports of no differences in maximum knee extension moments (likely internal moment although they failed to mention if it was internal or external joint moments) from pre- to post-operation, with a decrease in the knee flexion moment of 0.20 Nm/kg at two months post-operation (15). This may have been too early of a time period for a measurement for assessment for return to normal levels of healthy controls as has been seen with other variables. Two tests which reported on subjects at periods of less than 6 months still showed differences between TKR patients and control subjects (15, 24). At one year post-operation, maximum external extension moments in early stance have been reported as being similar between pre- and post-operation time points, but maximum external flexion moment at early stance was increased for TKR patients by 0.93%BW*height (25), further indicating that recovery is definitely not complete by two months as the evidence still indicates changes at one year post-operation. An additional study reported within subject differences for internal extension moments at the weight acceptance phase decreased post-operatively by 0.9%BW*height (24).

An additional study has reported that there was no asymmetry between replaced and non-replaced limbs for sagittal moment patterns during walking (130). This is not always the case though and it may indicate a change in joint dependence as the contribution of the knee extension moment to lower extremity support has been shown to decrease at 12 months compared to three months for the operated limb, but not for the non-operated limb, with both still being lower than healthy controls (46). This may indicate the quadriceps avoidance pattern previously mentioned as a means of unloading the knee joint and thus further relying on the non-operated limb.

Stair Ascent and Descent

When comparing stair ascent to overground walking, peak external knee extension moments are greater in ascent than in walking, with value differences ranging from 0.18 Nm/kg to 0.52 Nm/kg between the two tasks (29, 117, 131). For the peak external knee flexion moment (often considered more important for examination than the external knee extension moment), values reported as three times greater have been seen during stair ascent compared to walking (131), indicating the advanced difficulty of the task and the required muscular effort in order to complete the task. Other studies have shown the values of flexion moments to be 11.9 Nm/%BW during stair ascent which were significantly greater than 7.4 Nm/%BW during level walking (123). Simultaneous maximum external hip flexion moments are also higher during stair ascent (0.76 Nm/kg) compared to level walking (0.52 Nm/kg) and approximately 1.5 times higher during stair descent compared to walking (29, 131).

Maximum internal knee extension moments have been shown to be reduced in TKR patients (2.08-3.3%BW*height) compared to healthy controls (5.10-6.50%BW*height), with the reductions potentially reaching in excess of 50% of %BW*height (24, 39-41). Despite what appears to be substantial differences, there are other studies that have reported no differences between the two groups, although they failed to report velocity of the stair ascent for both groups (22, 36, 42), which as indicated earlier, may play a role in the required loading of the body during gait. Reductions in maximum knee extension moments have been shown to occur during simultaneous reductions in gait velocity for TKR patients (24, 39-41). A review study published in 2014 showed that at the time, four studies had measured velocity and knee moments simultaneously and all four showed decreased moments with reduced gait velocity during stair ascent (132). These reductions in velocity (especially during stair ascent) may be related to strength deficits of the TKR patients thereby reducing their ability to navigate the stairs more quickly or related to pain levels experienced at higher velocities, thereby requiring them to slow down to alleviate the pain. Based on the differences, a reporting of velocities is important as the speed differences may be related to other kinetic differences. For example, a reduced peak knee extension moment was seen in the replaced limb of TKR patients during stair ascent compared to the non-replaced limb and healthy controls when no significant difference between velocity was reported for the two groups, although the absolute mean velocity was lower for the TKR patients (19). In this instance, velocity did not appear to play a role, but based on previous differences, it may still be a significant variable and should be reported either as a means of disqualifying it or highlighting it as a potential confounding factor.

Stair descent is, again, much less studied. One report has shown differences in the maximum external knee flexion moment between healthy controls and TKR patients, with reported values of 16.3%BW*leg length (LL) and 13.1%BW*LL, respectively (22). More recent studies on stair descent have reported no differences between the two groups (36, 40, 127). The conflicting results may indicate a need for more research to be done on stair descent as the volume of research in comparison to overground walking and stair ascent is much smaller.

Frontal Plane Kinematics

Level Walking

It has become well understood that the progression and severity of medial compartment knee OA is directly affected by the frontal plane mechanics an individual employs during gait.

The internal abduction moment has been suggested as a surrogate measure for loading to the medial compartment of the knee joint and has been linked to the progression of medial compartment knee OA (133-136). Additionally, a correction of the frontal plane knee alignment is one of the goals of the TKR procedure.

After the correction of frontal plane knee alignment, TKR patients have shown a reduction in the peak knee adduction angle during gait, with levels returning to close to those of healthy control subjects. TKR patients have shown peak knee adduction during the stance phase of 4.1° while healthy controls show 3.9° peak angles (23, 54). An additional study has shown that by 6 months post-operation, the absolute values of the peak knee adduction angles for TKR patients have returned to levels of 3.6° (27), similar to healthy control levels. These values were not directly compared to healthy controls, but the absolute magnitude is similar to other reported values for healthy controls. While not directly reported in this study, Orishimo et al (2012) displayed an ensemble average curve for knee adduction angles which showed different initial contact angles for TKR patients after surgery. Pre-operatively, initial contact appears to be around 3° of adduction, leading to a peak adduction of 9.7°, while post-operatively initial contact is between 0-1° of abduction, leading to a peak angle of 3.6° (27), suggesting a decreased ROM.

The values for peak knee adduction angles are directly related to frontal plane knee alignment, and given that correction of the alignment is one of the TKR goals, surgeries have been shown to successfully achieve this goal (27). The correction of the alignment is a static measure, but it appears to have dynamic implications given the reductions seen in the peak knee adduction angles during dynamic tasks. A recent study on healthy individuals with different static knee alignments has shown differences in peak frontal-plane knee angles and knee joint moments, although no differences in frontal-plane ROM were present between the different static alignment groups, further supporting different contact angles for the different groups (137). Furthermore, the operated limb has been shown to have reduced peak knee adduction angles (1.8°) in comparison to the non-operated limb (4.3°), and sometimes reported as even being lower than healthy controls (2.4°), although this was on a non-significant level (114).

By fixing the alignment of the knee, less adduction has also been found at the time of the peak knee adduction moment in the operated limb (0.9°) compared to the non-operated limb (3.28°). Neither limb was considered different from healthy controls (2.5°), only from each other, but this continues to highlight the improvement in frontal-plane mechanics for the operated limb (38). At 6 months post-operation, the peak knee adduction angles have been shown to significantly reduce from 9.7° to 3.6° (27), resulting in relatively quick adjustments to the frontal kinematics in comparison to other measures which have been shown to take up to a year to normalize. Reductions in peak addiction angle were also seen at the time of peak VGRF when comparing pre-operation values to post-operation values, with decreases of 4° post-operatively (54), further highlighting the alignment correction benefits.

Stair Ascent and Descent

In stair climbing, peak knee adduction angles significantly increase compared to walking (10.4° and 4.6°, respectively), with simultaneous increases in peak ankle adduction, but no differences in frontal plane hip kinematics (29). At an average of two years post-operatively, there were no differences reported in peak knee adduction angles when comparing the operated-limb, the non-operated limb, and healthy controls (19). This was coupled with reduced ankle eversion angles for the operated-limb compared to the non-replaced and controls (19), suggesting that the alignment correction may have impacted the frontal plane ankle angles as well.

The peak knee adduction angles were also coupled with an increased ROM on stair ascent compared to walking. In one study, walking had a reported frontal-plane ROM of 10.6° while stair ascent had 15.4° (29), although no statistics were reported with respect to this variable. This is primarily the result of the significantly increased peak adduction angle. Other studies have failed to report on frontal-plane ROM as well, although given the similar peak adduction angles reported (19), it is possible that the ROM are similar.

Frontal Plane Joint Kinetics

Level Walking

The internal knee abduction moment (or external knee adduction moment; KAM) has been linked to medial compartment knee joint loading, with higher loading suggested as being due to higher moment values (133-136). There is often a bimodal pattern shown during gait for this moment so comparisons are frequently made for both peak values. The first peak (loading) is typically higher than the second peak value. This loading on the joint contributes to the degeneration of cartilage for patients with knee OA and subsequently can contribute to the degradation of the joint replacement, thereby making controlling the loading important. Given the increased frequency of joint replacements and the decreasing age of the recipients, it is important to enhance the longevity of the replacement, and therefore control the loading.

There are contrasting results present with respect to the KAM value and comparing TKR patients to healthy controls. Smith et al. (26) found no significant differences between TKR patients (0.39 Nm/kg) and healthy controls (0.46 Nm/kg), while Benedetti et al. (20) found reduced first and second peak KAM values compared to healthy controls, with the first peak being reduced by 1.4%BW*height and the second peak by 1.0%BW*height (20, 26). This point can be further confounded by research which has shown non-operative limbs to have increased

KAM values, with values reaching 0.07 Nm/kg in one study (38),0.67%BW*Ht in an additional study (138), and 0.012 fat free mass/height in another study (114) compared to the operated limb (38, 114, 138). However no differences were reported between replaced limbs and healthy controls in those studies, which attests to the improvements of faulty mechanics in the operated-limb being partially corrected through the operation, suggesting a return to healthy KAM levels post-operatively. However, a further point of consideration is what this may mean for the contralateral limb. The contralateral limb may be a weak link eventually requiring the same procedure due to the increased loading which likely led to the need for a TKR in the first place or it may be adapting to maintain a symmetry with the replaced limb after the aforementioned adaptations by the replaced limb.

At 6 months post-operation, reductions in the peak KAM values were evident with a decrease to 84% of the pre-operative KAM levels (3.2%BW*height to 2.7%BW*height) (27). At 1 year post-operation, however, the same subject group returned to an increased KAM level (3.0%BW*height) which was not significantly different from pre-operation levels (27). There may be some slight regression in progress occurring over time, which could theoretically be related to any number of factors. This same group saw a non-significant increase in walking speed from pre-operation (0.93 m/s) to 6-months post-operation (0.99 m/s) followed by a significant increase at one year post-operation (1.03 m/s) (27). At an average of 2 years post-operation, another TKR patient group showed increased peak internal abduction moments in their replaced limb compared to healthy controls, but showed no difference between the replaced and non-replaced limbs or the non-replaced and controls (19). There were no gait velocity differences for these two groups so velocity was a non-factor in this assessment, however the knee extension moment was lower in the replaced limb compared to the healthy controls (19). It does illustrate that the TKR patients may undergo a compensatory transformation whereby the load is transferred to another plane as a compensatory mechanism. The reduced knee extension moment may have been moved to the knee abduction moment.

Different time points within the gait cycle are of interest to researchers. At 6 months post-operation, when measuring the internal KAM at peak VGRF, TKR patients experienced a reduction from 4.07%BW*height at pre-operation measurement to 3.01%BW*height at 6 months. Healthy subjects in the same study had a value of 2.7%BW*height, which was not significantly different from the post-operation values of the TKR patients but was significantly lower than the pre-operation values (28). This may illustrate that the time of measurement (time within the gait cycle) may play a difference rather than the absolute peak values. The article fails to mention whether the peak KAM and peak VGRF occurred simultaneously but did state they looked at the first peak VGRF time point since it corresponds to a time when the body is in single-limb support (28).

There seems to be a general consensus that the KAM values will reduce post-operatively (at least temporarily) but they will not be reduced beyond the level of healthy controls, with the exception of one study finding a reduction in the external KAM for TKR patients compared to healthy controls, implying a significantly reduced medial compartment loading (20). Given the similar frontal plane kinematics found post-operatively, most of these findings are to be expected. Reduced peak knee adduction angles following surgery (27, 54) would likely decrease the moment arm, thereby reducing the frontal plane moment experienced at the knee. Reduced varus (adduction) ROM occurred as early as 6 weeks post-operatively with an accompanied reduction in the first peak KAM on the operated limb (138).

Stair Ascent and Descent

In comparison to level ground walking, the first peak KAM has been shown to significantly increase (0.61 Nm/kg compared to 0.78 Nm/kg) for healthy adults with the highest KAM values found during stair descent (29, 123). Additionally, the greatest hip adduction moments are also found during stair descent (8.4%BW*height) in comparison to other common ADLs such as standing, walking, rising from a chair, and bending over (123). It has been suggested that the hip abductor muscles are needed to elevate the pelvis so that the needed clearance is available for the swing leg to move up to the next step (29). When comparing TKR replaced limbs to healthy controls, increased internal hip abduction moments were shown in the replaced limb, with no difference for the non-replaced limb compared to controls. This was coupled with reduced ankle inversion moments for both loading and push off for the replaced limb compared to the non-replaced and healthy controls, however the knee moment differences were mixed, with no differences for extension push-off moments or loading response abduction moments. The replaced limb had reduced knee extension moment during loading and increased abduction moment during push-off (19). This suggests an increased dependence on the hip in the replaced limb upon a return to normal knee function in the frontal plane.

Replacement design also appears to play a significant role in frontal plane kinetics. Posterior stabilized designs have shown KAM values equal to or reduced compared to healthy control subjects as have mobile bearing designs, with KAM values of 1.8%BW*height for the replaced limb compared to 2.7%BW*height for healthy controls (40-42, 54). Designs with non-resurfaced patellas, however, have shown increased peak external KAMs of 3.8%BW*height for TKR limbs compared to 2.7%BW*height for healthy controls (39). There seems to be a general consensus on a restoration of frontal plane knee moments for TKR patients to the levels of healthy controls during stair ascent, part of which is likely based on the restoration of knee alignment post-operation and the increased muscle strength. During stair descent, which is significantly less studied, results from two different studies have shown no differences in peak internal knee abduction moments between TKR patients and healthy controls (42) and no differences in peak external knee adduction moments for the same group comparisons (40).

Ultimately, there needs to be extended research into the biomechanical profiles of the dissatisfied population as this information may provide insight into the reasoning for the dissatisfaction with the procedure. Currently there is a significant lack of research into the biomechanical variables as they relate to patient satisfaction with the TKR procedure. It is possible that there is a connection between movement restoration to the levels of healthy controls and those patients who are satisfied with their procedure. However, to date, this investigation has not been completed, warranting the research into potential movement abnormalities post-operation which may contribute to dissatisfaction with the surgical outcomes.

TKR Patient Knee Strength

In order to have a properly functioning joint, sufficient muscle strength is required. TKR patients, as with almost any operation, experience a disturbance in their strength levels post-operatively, given the invasive nature of the operation. A return of strength levels are imperative for patients to be able to return to normal functioning. Failure to acquire the needed strength post-operatively can impair patients' abilities to perform their normal ADLs as well as more complex activities which they may desire to participate in, such as tennis, hiking, and others. Quadriceps strength is the most commonly measured strength variable for TKR patients, however, hamstring strength is important as well given its functions at the knee joint. The predominant factor referenced when examining strength is the peak torque generated by a muscle, either through isokinetic or isometric measurement.

Isokinetic Strength

Schroer et al. (45) showed a return to pre-operative levels for quadriceps peak torque by three months post-operatively. By 6 months, they were 17% stronger and 30% stronger by one year. The hamstrings for the same population showed strength increases of 10.5% by 3 months, 26.6% at 6 months, and 36.2% by one year. Additionally, there were no differences in quadriceps to hamstrings strength ratio at any time point (45), suggesting that the operation affects both muscle groups equally.

Early on in the rehabilitation process, significant reductions in muscle strength are evident. At one month post-operatively, TKR patients have shown 60% reductions in quadriceps strength compared to pre-operative levels (43). This is likely due to two factors: atrophy of the muscle (which is associated with surgery due to inactivity) as well as likely a reduced voluntary activation of the muscle, which functions as a protective mechanism for the TKR patient as increased activity at the joint can lead to pain. The reduced strength level early in the rehabilitation process is to be expected given the reduced physical function mentioned previously at early time points. An additional group showed deficits in strength compared to pre-operative levels with upwards of 40% reductions in strength for the knee extensors and 34% reductions for the knee flexors at one month after the procedure but a return to pre-operative levels by 3 months (44).

The operated limb and the non-operated limb are both affected by the TKR procedure (likely due to reduced activity levels post-operatively). Both limbs have shown reductions in strength at 6 months post-operatively in comparison to strength levels of healthy controls (52, 139). By 12 months post-operatively, the non-operated limb has shown recovery to healthy control quadriceps strength levels but the operated limb still showed reduced strength levels compared to controls while showing equal strength to the non-operated limb (46). The absolute values of isometric quadriceps strength are highest for the controls (34.2 N/BMI), but statistically the operated limb (24.6 N/BMI), while different from the healthy controls, was similar to the non-operated limb (28.4 N/BMI), which was similar to the healthy controls. There have been instances of strength deficits of 60% in the knee extensors and 11% in the knee flexors occurring as much as 6 years post-operatively when compared to healthy controls (140).

At an average of 10 months post-operatively, the replaced limb compared to the non-replaced limb showed deficits for both knee flexors and extensors (141). The knee extensors showed a 27% peak torque deficit, 23% power deficit, and a 14% cross sectional area deficit. The knee flexor deficits were smaller but still present. Peak torque showed a 13% deficit and peak power showed a 19% deficit (141). These results however, are not consistent across the research. The deficits are frequently different based on the measurement protocol. At 30 days post-operatively, a group of bilateral TKR patients exhibited reduced peak knee extension torque when testing at an isokinetic speed of 180°/s, with a return to pre-operative levels by 60 days after the operation (142). However, at an isokinetic speed of 60°/s, there were still peak extension torque deficits at 60 days after the operation (142).

In a comparison of posterior stabilized and posterior cruciate retaining designs to healthy controls, the TKR populations showed reduced peak torque for both the quadriceps and hamstrings when testing at 180°/s but not at 60°/s compared to controls (there were no differences between the two replacement types though) at an average of 98 months post-operatively (36). For the hamstrings, the posterior stabilizing showed a 55% peak torque reduction while the posterior retaining showed a 69% reduction. For the quadriceps, the posterior stabilized showed 36% reductions while the posterior retaining showed a 43% reduction (36). The failure to achieve higher peak torque values at the higher velocity may imply a decreased ability for high velocity contractions, but does suggest an ability to return to strength at the slower velocities. It may be important to note that while the statistics do not show differences, the absolute values are lower for the TKR groups. One additional study has shown no difference at both speeds of 180°/s and 60°/s between cruciate retaining and cruciate substituting replacement types (143). In this study, the quadriceps and hamstrings were measured at the two aforementioned speeds for isokinetic strength and showed no differences for peak torque between replacement designs (143), illustrating that there is likely no difference between replacement types in terms of strength.

Strength has also been measured for the purposes of comparisons with other elements of physical recovery. Increased levels of pre-operative strength in the quadriceps has been shown to increase functional abilities at one-year post-operation. The probability of lower functional abilities (as assessed by the Short Form 12 for physical function) when displaying poor levels of pre-operative strength is 2.28:1 (144). This lends credence to the idea of doing pre-operative strength training in an attempt to increase functional recovery. At one month post-operation, pre-operative strength training showed significant improvement in a sit to stand task (145). Additionally, the training led to reduced strength asymmetries between the replaced and non-replaced limb, while the asymmetries persisted in the control group due to decreased quadriceps strength in the operated limb and increased quadriceps strength in the non-operated limb (145). However this is not always effective. A pre-operative strength training group showed no difference at 3 months post-operation compared to a group with no pre-operation training, with both groups returning to baseline strength levels (146). Additional testing took place at 6-weeks post-operation, however, neither group had progressed to pre-operation levels (146), suggesting that recovery to pre-operation levels occurs sometime between 6 weeks and 3 months. It is of interest to note that in that study, 90% of the strength training group felt the pre-operative training was beneficial, but based on the results the researchers were unable to conclude that the training was necessary. The argument could be made that the mental wellness given by the program may be just as important as the physical wellness. An aquatic therapy program had an initial increase in quadriceps strength but by 180 days post-operative, the strength levels were similar to regular ward therapy groups (147). However, the aquatic therapy did increase the ROM at both 90 and 180 days post-operation (147). Peak torque values were also not shown to be predictive of single limb static balance after surgery, however this was for a measurement at 11 days after surgery (51).

Knee power has been predictive of stair negotiation speed. Larger extension power deficits in the operated-limb and low flexion power in the non-operated limb were shown to be predictive of slower stair ascending and descending speeds (141). When pre-operative quadriceps strength was added to a regression model with age, flexion ROM, and pain, the model was able to significantly increase its ability to predict post-operative timed up and go test and stair climb performance (43). Knee extensor strength also has a significant positive correlation to gait speed (50).

Isometric Strength

In addition to the differences with testing speed for isokinetic testing, differences have been shown between isokinetic and isometric testing procedures. Isometric tests at a knee angle of 75° have been shown to have more pronounced differences for both flexion and extension strength. When comparing the replaced and non-replaced limbs, the operated limb had 39% flexion deficits and 29% extension deficits compared to the non-replaced limb (148). Isokinetic differences were smaller with 7% reduction during 30°/s for flexion and 22% reduction during 120°/s for extension (148). Time periods between the tests are also of additional consideration as the isometric flexion decreased at 6 months post-operation while the isokinetic flexion increased at both 30°/s and 120°/s (148). This further illustrates the need to take methodological considerations when making comparisons between different studies.

Ultimately, a return to strength levels is crucial for the successful return to a functional life as sufficient muscle strength is necessary for more complex activities such as stair climbing, hiking, or squatting. It is important to return the strength levels from prior to the operation of both the quadriceps and hamstrings in order to maintain the strength ratio as well as to maintain symmetry between both limbs. Deficits are likely to occur early in the rehabilitation process, but the general consensus is that a return to pre-operative strength levels are possible for TKR patients.

Currently, there is a lack of data with respect to strength and patient satisfaction levels. While certain activities have been shown to be more difficult for dissatisfied patients, this has not been studied on connection with knee flexor and extensor strength levels. There is a need for an examination of strength levels with the dissatisfied population to compare their strength with satisfied patients. This may help to examine the causes of dissatisfaction post-operation and thereby potentially help to improve the satisfaction rates should an identifiable cause be present.

TKR Patient Balance Abilities

Static and dynamic balance have become another measure of success for TKR operations as balance is necessary to avoid falls and consequent fractures, which can be detrimental to the

TKR (47). Studies examining balance have occurred, like with strength and kinematic/kinetic studies, with measurements both pre-operatively and post-operatively, single leg versus double leg, static versus dynamic, and eyes open versus eyes closed. Different systems have been used including the Biodex Stability System (51), 3D motion capture (52), COP analysis on a force platform (139), and the Nintendo Wii Balance Board (50). Variables of interest have included anterior-posterior stability index, medial-lateral stability index, overall stability index, velocity, and sway paths for the center of pressure (COP). Anterior-posterior, medial-lateral stability, and overall stability indices are calculated based on degrees of tilt of the balance platform from a flat horizontal plane. The indices are the standard deviations of these degree changes from horizontal, with the overall stability index being for changes with respect to both AP and ML indices (149). Velocity is in reference to the speed at which a COM moves through its pathway deviations (52). Sway path (or postural sway) is defined as taking the anterior-posterior and medial-lateral postural sway lengths to calculate the total postural sway, measured through weight distribution and pressure shifts, often using a stationary force platform (51). It can also be calculated through 3D motion capture methods where the COM movement is tracked in the anterior-posterior and medial-lateral directions for total displacement (52).

Postural sway has been significantly reduced post-operatively compared to pre-operative levels (51). The TKR patients still tend to have an increased sway path compared to the healthy controls after their operation. Prior to any sort of training program, the TKR patients have increased anterior-posterior and medial-lateral sway path when their eyes are opened (48). In comparison to controls, these increased sway paths for the TKR patients have lasted through 6 months post-operation. The anterior-posterior sway path for the operated limb has been shown to be increased compared to healthy controls at the 6 month mark. The increased anterior-posterior sway path has also been shown to be associated with an increased equivalent area, which is defined as the area of the COP path (139), calculated through a temporal sum of the movement of the path in every direction (150). Interestingly though, when testing with their eyes closed, the TKR population has small differences in sway path and area, but no difference in AP and ML sway with no training compared to healthy controls (48).

Training programs specifically geared towards balance improvement have been shown to reduce balance deficits in the TKR population (48, 149). As early as 6 weeks after a TKR procedure, a balance training group showed an improved overall stability index compared to their own pre-operative levels. Additionally, the same group showed an improvement in overall stability index and anterior-posterior stability index in comparison to a control group that received no balance training (149). Another training group showed improved balance on both the operated and non-operated limbs in a single leg balance test for conditions with the eyes open and closed (49). Differences have been shown between the two limbs of the TKR patients. Small medial-lateral velocity of the COM (defined as the speed of the movement through the displacement of the COM) increases have been shown during single leg stance on the operated limb compared to the non-operated limb, but during a bilateral standing task, no differences were reported between the two limbs (52), suggesting a slight increase in ability of the non-operated limb.

During an examination of related balance variables, pre-operative postural sway was seen as a strong predictor of single limb static balance post-operatively for TKR patients (51). In general, improvements in balance have been associated with improvements in gait speed, timed up and go tests, 30 second chair rise tests, and stair climb tests (49). The argument may be made that people may be able to avoid single limb static balance situations, however, the connections between these balance abilities and other functional abilities are evident.

Strength and balance are frequently connected since strength is necessary to maintain balance. Increased knee extensor strength coupled with an increased gait speed has led to increased anterior-posterior balance (measured through the range of the AP trajectory for the COP), but increased knee extensor strength with a reduced gait speed led to a reduced anterior-posterior balance (50). Peak torque did not predict single leg static balance performance (51). Conversely to this point, another study has found that a failure to maintain single limb balance is explained by older age, higher body mass index, and reduced quadriceps strength (52). These unilateral differences do not appear to be related to TKR prosthetic design. A comparison of cruciate retaining versus cruciate substituting designs showed no differences in single-limb stance balance scores (143), suggesting that a retention of the posterior cruciate ligament has no bearing on the balance performance improvements post-operatively.

While balance on a moveable platform may not be considered a "real life" situation, the connections of balance to functional improvement have been well demonstrated. This suggests an examination of balance as an important factor in return to functional improvement. A rehabilitation program post-operatively should include a balance component given the improvement seen in the functional tests with improved balance skills. Currently, as with strength and biomechanics, there is a lack of research regarding TKR satisfaction levels and how it relates to balance variables. An instability may cause individuals with TKRs to not feel comfortable on their feet due to fear of falling, which may lead to an overall dissatisfaction. It is important for investigators to examine balance and how it relates to dissatisfaction, as this is a trainable physical skill. Training, as shown earlier, can improve balance skills in the TKR population (48).

Creation, Examination, and Application of Survey Tools

Patient reported outcome measures (PROMs) are commonly utilized tools in the treatment and rehabilitation process for people with knee osteoarthritis and total knee replacements. PROMs are commonly utilized in conjunction with objective doctor analyses regarding the injury or pathology because the patient's perception of the outcome is considered as important as the doctor's objective measures. However, there are some issues with respect to the PROMs being implemented. In knee arthroplasty alone, there are over 25 survey instruments measuring patient outcomes being applied to the population (151). Based on the opinion of one author, of those 25, only three have been extensively studied with respect to their validity in the research field: the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the Oxford Knee Score (OKS), and the Short Form 36 (SF-36) (151). The validity studies of these tools encompasses the assessment of multiple psychometric properties such as content validity, internal consistency, construct validity, criterion validity, agreement, reliability, responsiveness, floor/ceiling effects, and interpretability. These criteria are assessed based on examination of the creation of the tool, statistical analyses of the results, and application to the population for which it was intended. Often, however, these measures are utilized to assess outcomes in populations for which they were not designed. The SF-36, for example, was created as a general health survey for any population while the WOMAC and OKS were created specifically for an osteoarthritic population (152-154). These tools are all used to help assess patient satisfaction with a medical procedure, recovery, or the rehabilitation of the injury. In doing so, it becomes important to assess patient satisfaction and what that means in addition to the survey tools being implemented to help do so.

Psychometric Properties

As surveys are developed, they are frequently tested for their abilities to perform well under certain measurement conditions. They are evaluated on their "quality criteria" which essentially determines their overall validity as a tool. Quality criteria includes assessments such as content validity, internal consistency, criterion validity, construct validity, reproducibility, responsiveness, and floor/ceiling effects (155). Each tool has multiple measurements of each aspect of the quality criteria, allowing for an overall assessment of the tool based on the results.

Content validity is assessed by the relevance of items in a specific domain being measured on a specific population to whom the tool is applied as well as the adequacy of questions within those domains in being a reflection of the true purpose of the tool (156). The presence of floor or ceiling effects and skewed data can reduce content validity. This may be an insufficient measurement element for content validity as an imposition of limits is applied to the constructs being assessed, such as the constructs within the tool (151). As a whole, the disease-specific questionnaires tend to be less skewed than the general health questionnaires (157). Unfortunately with a multitude of means for assessing any individual psychometric characteristic, there will be multiple responses for whether a tool possesses a high value for any given characteristic. The Forgotten Joint Score, for example, is said to have content validity for the tool as a result of including the patients as part of their expert panel during the development of the tool. Therefore because their opinions were included during the construction of the content, the tool has content validity (158). This may seem like a simple way of assessing content validity, but it is a published and accepted mechanism, regardless of how subjective or imprecise such opinions may be.

Internal consistency is a measure of the degree of correlation or homogeneity of items in a tool (151). There are two commonly used methods for examining the internal consistency of a tool: factor analysis and Cronbach's alpha. Factor analysis is a process of examining data in an attempt to find patterns and dimensionality. Similar items within the tool are expected to provide the same dimension (159). There are two different options: an exploratory factor analysis and a confirmatory factor analysis. An exploratory factor analysis is performed when there are no clear-cut ideas about the factor structure (no clear number of dimensions or what their associations are). A confirmatory analysis is performed when prior hypotheses exist, whether those hypotheses are based on theory or on previous analysis (160). The use of Cronbach's alpha statistic is more commonly reported in the literature in its use for evaluating internal consistency. "Cronbach's alpha estimates the degree of equivalence between responses to sets of items tapping the same underlying concept. The higher the alpha, the higher is the average correlation between responses to all possible combinations of items in the scale" (156).

Construct validity is a description of the relationship of the tool in question to other measures which are attempting to assess the same underlying variables (also known as the constructs). Theory-based hypotheses are created prior to correlation measurements to determine the relationship of the measures (155). When a survey tool receives a positive rating for construct validity, it is typically as a result of containing a priori hypotheses and a confirmation of the majority of those hypotheses (151). A failure to provide a priori hypotheses often reduces the construct validity rating (161, 162). The generation of predefined hypotheses is important as it reduces the bias in the data. Without them, there is a tendency to look at the low correlation values for explanations of the construct validity rather than coming to the conclusion that the tool does not have an adequate level of construct validity (155). This seems to be more of an individual study issue as pre-defined hypotheses can be created and be less of an issue with the actual tool.

Criterion validity is the examination of how scores on a given instrument relate to a “gold standard” (163). This seems to be a rarely examined psychometric within the TKR population as there does not seem to be a general consensus on what the “gold standard” is for the field with respect to surveys utilized to assess pain, function, expectations, and other factors. This has both good and bad elements to it as it allows for the use of multiple surveys to examine different populations and pathologies, but it makes comparisons difficult.

Reproducibility is the extent in which multiple measurements of a patient can produce similar results when no real change has occurred. Variations in the subject or rater could cause changes in the measurements when real change is not present over time, thus contributing to background noise and subsequently affecting the reproducibility of the tool (164). There are two components of reproducibility: agreement and reliability. Agreement references how close scores are on repeated measurements and estimates the absolute measurement error. Agreement is based on the calculation of the standard error of measurement (SEM) and the relationship of the smallest detectable change (SDC) and the minimal important change (MIC, also interchangeable with minimal clinically important difference; MCID). The SEM can be used to derive the SDC. The SDC represents the smallest change in score that can be interpreted as real change beyond measurement error (155). Relating the SDC to the MIC for comparing agreement has been performed but is a newer construct and has not been used in most studies (155). When examining the SDC, the threshold for detecting these “just noticeable” differences is often 0.5 SD (165), which provides a quantifiable difference. When designing studies, it is important to consider that assumed effects below the MCID may be detectable but are essentially clinically meaningless (166). Reliability parameters relate the measurement error to the variability between subjects and thus rely on the heterogeneity of the sample, while agreement parameters, being concerned with measurement errors, reflect the characteristics of the instrument itself (167). Some methods of assessing reliability are considered inappropriate, such as the use of Pearson's correlation coefficient, rho, and paired t-tests (151). The use of these "inappropriate" methods is believed to cause misleading interpretations (168).

In comparing agreement and reliability over different population samples, agreement parameters will be more stable than reliability parameters. Reliability is highly dependent on the variation that exists within a population sample and it is essentially only generalizable to samples which possess a similar variation. Reliability is more of a characteristic of how a tool performs in a certain sample population and is a particularly vulnerable concept in self-rating measures. Agreement is more of an element of the tool itself, and not the population. When the instrument is to be used for evaluation purposes, as it will with most medical based research such as TKR assessments, agreement is the preferable mechanism for evaluating reproducibility (167).
There have been multiple definitions and multiple methods of measuring responsiveness of a tool utilized, which unfortunately shows a lack of consistency for use with standardized terminology and approach (169). The goal of measuring responsiveness is to test the tool for its ability to respond to change that has occurred in the patient, but it is important to note that a general change can be seen as different from "clinically important change", in the sense that statistically significant change does not necessarily indicate any clinical relevance (151). For example, large sample sizes can result in small numerical differences which are seen as statistically significant

(170), but this does not mean that the changes have any clinical meaning. The use of the MCIC to gauge clinically important change is commonly utilized as it quantifies changes in the tool which patients perceive as beneficial (171). As previously mentioned, there are multiple methods of measuring responsiveness (effect size, standardized response mean, Guyatt's statistic, Paired-sample t-test, and relative efficiency) (172), which makes the direct comparisons tough as each statistic measures something different despite trying to explain the same thing, thus only allowing for general comparisons of responsiveness.

There are two broad approaches to defining clinically meaningful change: distribution-based and anchor-based. There are conceptual differences between the two methods. Distribution-based is centered on statistical criteria, while anchor-based examines the clinical relevance of measures. The examination of distribution-based approaches shows that the study sample characteristics and the use of standardized response means, effect sizes, and t-statistics define change. Conversely, for anchor-based approaches, the changes examined and linked to an external, yet relevant, clinical anchor. These external anchors can be something like a global rating or disease-related outcome and are used to assess whether individual changes possess any clinical significance (173).

A floor effect is when a patient scores the lowest possible score on the tool, suggesting they may actually fall outside of the scoring range. A ceiling effect is the exact opposite where a patient scores the highest possible score, also suggesting they fall outside the upper limit of the scoring range. The presence of floor and/or ceiling effects can affect multiple aspects of a tool's validity, including content validity, reliability, and the ability to detect change. If either of these elements are present, it may mean that the tool is missing the extreme items on either end of the scoring spectrum, thereby suggesting the content validity is limited. This will then decrease the ability of the tool to delineate patients who have the highest scores (ceiling) from the ones who have the lowest scores (floor) and its ability to detect further deterioration or improvement for the patient (155). Essentially, this means that the tool fails to recognize differences between patients who fall outside the range of measurement of the tool, either above or below it (163). Disease-specific surveys score better for floor and ceiling effects than general-health surveys (151, 157, 174). This is a plausible outcome as the application to a TKR population should rarely produce ceiling effects given that a return to full function after a TKR procedure is unlikely. Floor effects are more likely to be experienced as a severe disability is what leads to the TKR procedure so depending on the time of application of the tool, floor effects are possible. The closer to the procedure the tool is administered, the more likely a floor effect.

Interpretability is the ability to change quantitative scores into some sort of qualitative meaning (163). Surveys can receive positive ratings for interpretability for multiple reasons, such as the presentation of a mean and standard deviation, inclusion of multiple relevant subgroups, and the relationship of scores to clinically relevant conditions (151). Interpretability is less a comparison of the different tools to each other and more an aspect of how the information and statistics are presented from the data collected. Each tool mentioned has the ability to have good interpretability with the right amount of data being presented and in the correct manner.

Development of Surveys Used on TKR Populations

WOMAC (Western Ontario and McMaster Universities Osteoarthritis Index). The WOMAC is one of the more widely used tools for the TKR population to measure pain, stiffness, and physical function (www.womac.org). It has been researched and validated for paper, telephone, computer mouse, and touchpad administration and translated into over 60 languages

(175). This tool was developed with the knee and hip osteoarthritic populations in mind. It examines pain (5 items), stiffness (2 items), and physical function (17 items) using an ordinal scale range from 0-4, with lower scores indicating reduced physical function and increased symptoms. This allows for both subscale (pain, stiffness, and physical function) and global (total) scoring. The subscales are summed, with maximum scores of 20 (pain), 8 (stiffness), and 68 (physical functioning). The global score is the sum of all subscale scores, with a higher scores indicating increased function and reduced symptoms related to the knee joint (176). There is also an option to use a visual analogue scale rather than the ordinal scale for responding to the questions.

The WOMAC was developed by a team of four rheumatologists and two clinical epidemiologists. Initially the team developed open-ended questions to examine the characteristics and clinical importance of pain, stiffness, and physical, social, and emotional dysfunction. Closed-ended questions from existing surveys (Functional Status Index, Pilot Geriatric Arthritis Project) were added in an effort to complete each dimension by finding any sources of discomfort or disability (152). Using a 0-4 scale, patients were asked to report on the presence or absence of any discomfort or disability, the frequency of the discomfort/disability, and the importance of the discomfort/disability to them. All questions were asked with respect to what was only specifically linked to the osteoarthritis. Items that were seen as sex-specific in the early 1980s were avoided (such as ironing) and were rephrased to more generic terminology (such as light domestic duties). One hundred patients were interviewed following the final creation of the tool (152), which ultimately left out the social and emotional components. Social dysfunction had mean importance scores of 2.2-2.7, similar to other scores of discomfort and disability. However, it was eliminated due to it having low occurrence rates of 3-27%. While, emotional dysfunction also had similar levels of mean importance (2.1-2.6), a low prevalence (9-56%) was seen. The low occurrence of social and emotional dysfunction led to their elimination from the tool.

Following the final development, the tool was tested for reliability, responsiveness, and validity for TKR and total hip arthroplasty (THA) patients as well as osteoarthritis (OA) patients receiving non-steroidal anti-inflammatory drug (NSAIDs). This allowed for application to both OA and joint replacement patients (177, 178) which is an asset to the tool as TKR is traditionally the treatment option for end-stage OA. It has been tested with other therapeutic interventions (acupuncture) and for patient groups other than knee and hip patients, but with much less frequency (176).

The WOMAC was intended for an osteoarthritic population, which is linked with TKR, but has been applied in wide usage to OA. This may contribute to reduced content validity. The WOMAC has scored well on content validity, but has been reported as lower than other disease-specific surveys (157, 179, 180). A subsequent examination of floor and ceiling effects and skewness of data distribution may help explain the WOMAC scoring as this is also a common assessment for content validity (157). The wide application of the WOMAC has led to the presence of floor and ceiling effects, leading to reduced content validity surveys (157, 179, 180).

The WOMAC has been tested for internal consistency with both factor analysis and with the use of Cronbach's alpha. In a Singaporean TKR population, the Chinese and English WOMAC versions resulted in five and seven factors, respectively (181), which does not support the factor structure because there are not that many subscales in the original version. Another study on the WOMAC showed that the pain and function subscales were not different from each other (182), indicating reduced internal consistency. As a result of this, some research has chosen to investigate the individual subscales independently rather than performing a single analysis (183). The pain subscale has been further shown to lack unidimensionality (184), also implying poor internal consistency. Using Cronbach's alpha, the WOMAC had an alpha score of 0.93. demonstrating good internal consistency (157).

The WOMAC has received mixed ratings for construct validity, with the reduced construct validity coming as a result of failure to provide a priori hypotheses (151, 161, 162). Effect sizes are sometimes utilized to assess construct validity. The WOMAC pain subscale has shown a high effect size (0.95) while stiffness and physical function had moderate effect sizes of 0.78 and 0.76, respectively (162).

Researchers have shown positive and indeterminate ratings for reproducibility for the WOMAC. When reporting reproducibility based on random effects intraclass correlation coefficients (ICC), the WOMAC had ICCs above 0.9 (34, 157). Test-retest reliability on the WOMAC also yielded positive results, suggesting good reproducibility (162). There has been research done in which the clinically important difference (CID has been examined on the WOMAC and been correlated with a subjective assessment response of "a good deal better" with respect to the post-surgical improvement (185). In rehabilitation interventions, the MCID for the WOMAC was reported as 12% of the baseline score or 6% of the maximum score for detecting differences (166). Effects of this size lead to smaller required sample sizes (<300). The larger the effect, the smaller the necessary sample size.

An examination of responsiveness has shown that the WOMAC pain and physical function scales were both responsive to clinical change for knee patients (186, 187), "Relative efficiency" has been compared between WOMAC and the SF-36 (a general-health survey), with the WOMAC scoring better than the SF-36 post-surgery for a TKR population, although the score decreased with time, meaning that initially the WOMAC was more responsive but the values moved closer to each other over time (172, 188). This makes sense as time away from surgery should hopefully see a return to normal health, and thus similar responsive values as the magnitude of change decreases. This seems to be a common trend in which the disease-specific tools outperform the general health scales, as they should, given their narrower focus. Disease-specific tools have increased responsiveness (162, 172, 188) as a whole.

Researchers have shown mixed results for floor and ceiling effects for the WOMAC. Ceiling effects have been reported between 16.7-46.7% and floor effects between 0.4-0.8% (158). In a different study, the WOMAC showed neither ceiling nor floor effects (162), which is contradictory to other research, indicating that it may be a population-specific issue. The disease-specific surveys tend to score better for floor and ceiling effects than do the general-population surveys.

In studies using the WOMAC, means and standard deviations are commonplace for reporting (162, 189) as are reporting at multiple measurement time periods, which gives clinical relevance as it tracks changes over time (34, 188). This provides high levels of interpretability as these quantitative scores can be interpreted with qualitative meaning (163).

FJS (Forgotten Joint Score). The Forgotten Joint Score (FJS) tool was created using similar methods to both the WOMAC and OKS (158). An initial 20 question pool was created to measure joint awareness based on literature research describing the important elements of a TKR/THA procedure and the analysis of a team of expert opinions from clinicians, a methodologist, and a statistician. Patient opinions were then consulted based on the importance they placed upon specific activities of daily living (ADLs). After pilot testing the 20 questions and breaking them down for individual analysis, 6 questions were initially eliminated due to a high percentage of missing items. The remaining 14 questions had high internal consistency (Cronbach's alpha of 0.96). No item significantly reduced the alpha level, so nothing else was deleted. Twelve questions were selected to complete the final tool (Appendix A), with two questions being combined with other questions to place different sporting activities together (158). The FJS uses a five point Likert scale for the scoring of the 12 questions, with each question assessing awareness of the replaced joint during specific activities (sitting, walking, bathing, etc.). The five points represent a response of "never, almost never, seldom, sometimes, mostly" in relation to the awareness question (158). The goal of the tool is to assess whether or not the patient is able to forget the joint is replaced during their everyday lives (163), hence the examination of the awareness of the joint during ADLs. The ability to forget the joint exists had been deemed, by the creators of the tool, the ultimate measure of satisfaction (158), although this does fail to take into account pain, social, and mental constructs which may inhibit satisfaction levels.

In assessing the psychometric properties of the FJS, there is much less research concerning this survey compared to others as it is relatively new. The FJS had a high alpha (0.95) upon its creation and it was reported that none of the 12 items significantly lowered the internal consistency of the tool (158). A subsequent translation of the FJS to Japanese yielded an alpha of 0.97 (190), thus further supporting its internal consistency. Correlations between the FJS and the WOMAC were reported by its creators as -0.69 (opposing scoring methods result in negative correlations) or greater for all subscales and total scoring for the WOMAC, with the total score having an r equal to -0.78 (158). However, when translated to Japanese, correlations to the WOMAC ranged between 0.289 (pain subscale) and 0.522 (total score), indicating a reduced internal consistency across languages. However, the Cronbach's alpha remained high at 0.97, indicating an acceptable level of reliability (190)..

When creating the FJS, the creators sought to eliminate ceiling effects by expanding their responsive values beyond a "good" response to an "excellent" response (158). They still reported a ceiling effect of 9.2% which they reported to be lower than the WOMAC. Although floor effects of 3.3% were higher than the WOMAC, which is expected results since the FJS or for replacement patients while the WOMAC can be for anyone along the OA spectrum (158). Other studies have reported the ceiling effect for the FJS as high as 40%, more specifically for the first five questions of the tool (which are the easier ADLs, therefore the presence of ceiling effects is logical), and a floor effect for 16% of the patients, with significant differences between types of knee replacement procedures (191). The authors did speculate, however, that the presence of a ceiling effect post-surgery may mean reduced chronic pain levels, which is a positive attribute (191).

OKS (Oxford Knee Score). The OKS is a 12-item questionnaire developed specifically for patients undergoing a TKR to assess pain and functionality (34). During its creation, 20 patients were interviewed about their experiences and problems with their knees during the time of surgery. From these interviews, 20 questions were developed. These questions were then given to 20 additional patients and they were asked to add their comments regarding the questions and problems they experience which they felt were not addressed by the survey. Subsequent adjustments were made to the questions in the survey. The adjusted questions were then given to another set of patients. The same process was repeated for a total of three rounds, leading to the final development of 12 questions to complete the survey examining pain and function. There is a 1-5 scoring scale relating to difficulty and/or pain levels with certain activities. Each number has its own description of a corresponding answer to the question on the survey. For example, a question about pain may have anchors of “none (1)” to “severe (5)” while another question has anchors of “Not at all (1)” and “Totally (5)” (34). This survey is often misinterpreted as the score scale is inversed from many other tools, in that a lower score represents a more positive outcome. There is a total possible score of 48. Scoring starts with a total score of 60 and points are subtracted from that based on patient responses to questions. A score of 0-19 may indicate severe OA, 20-29 is moderate to severe OA, 30-39 is mild to moderate OA, and 40-48 indicates satisfactory joint function (163). The survey has many benefits in that it is short, practical, and reliable, leading to it being used more frequently in assessing the TKR population (18, 192-195).

The OKS had mixed results with respect to content validity, with some researchers giving it high, positive ratings (34, 196) and others gave the OKS lower content validity scores (157, 174, 189). In further assessing content validity, when scoring it based on floor/ceiling effects and skewness, the OKS had improved floor and ceiling effects but a lower skewness rating, thereby lowering its content validity rating (157).

In order to measure internal consistency, factor analysis on the OKS has been performed on three different factors for two different language versions (English and Chinese). The English version had pain on one factor, physical function on another, and a combination of the two on the third. The Chinese version had a combination of pain and physical function onto the first factor, limping onto another, and kneeling and night knee pain on a third (196). This illustrates that there can be differences with internal consistency which translate to beyond just the number of factors and how they align, making the creation of those factors an important construct to consider when evaluating them. The factor analysis performed on the OKS was an exploratory factor analysis (196), which seems to be the appropriate method as the OKS does not have clearly defined subscales, whereas the WOMAC does and should therefore be used under a confirmatory analysis.

An examination of internal consistency with Cronbach's alpha has shown the OKS had an alpha score of 0.93 (157). Two other studies have shown the OKS value to be greater than 0.9 (161, 174). An examination of the time of application for the OKS revealed scores of 0.87 prior to TKR operation and 0.93 six months after the operation (34). When divided into subscales of function and pain, the OKS had alpha levels of 0.819 and 0.874, respectively (161) (It should be noted that the OKS does not technically have subscales, as mentioned earlier, however in examining the questions, they are fairly easily placed in a function or pain category based on the wording).

The OKS has received positive ratings for construct validity, when providing a priori hypotheses, however when failing to do so, the construct validity scores have declined (161, 162). The OKS also displayed moderate correlations with the SF-36 physical function subscale. The OKS function and pain subscales (again, not designed with specific subscales, but have been devised by researchers after the creation of the OKS) had Pearson's correlation coefficients of -0.69 and -0.72, respectively (the correlation values are negative not due to an inverse relationship but due to the inverse scoring methods between the two tools. The physical component summary score had values of -0.73 and -0.76 with the same two OKS measures (161). The correlation values did drop as low as 0.19 between the OKS and the mental health component summary score of the SF-36 (34), which is to be expected and suggests good divergent construct validity (174).

Researchers have shown mixed results for reproducibility of the OKS. The OKS received ICCs above 0.9 (34, 157). The negative results are attributed to the use of inappropriate methodologies, such as the use of Pearson's correlation coefficient, rho, and paired t-tests (151). It is believed that these measurements cause misleading interpretations (168). Additional tests examining responsiveness of the OKS showed effect sizes in excess of 2.1, suggesting good responsiveness of the survey. This score was higher than other surveys such as the SF-36 (34).

Floor and ceiling effects have been found for the OKS. The OKS had a 6.8% floor effect and a 0.1% ceiling effect (174). The OKS scored better for the presence of floor and ceiling effects compared to the SF-36 (151) and the WOMAC (157). This indicates the increased ability of the OKS to better measure the TKR and OA populations without the population failing to accurately score due to being too high or too low.

High interpretability scores have been given to the OKS. Similar to the WOMAC, means and standard deviations are commonly reported with the OKS (162, 189) as are reporting at multiple measurement time periods, giving clinical relevance to the information as changes are tracked over time (34, 188). This allows the change of quantifiable information into clinically useful qualitative information, which contributes to the increased interpretability (163).

KOOS (The Knee Injury and Osteoarthritis Outcome Score). The Knee Injury and Osteoarthritis Outcome Score (KOOS (197)) is more comprehensive than the WOMAC, OKS, and FJS in that it assesses more domains. It was designed to assess five different outcome measures: pain, symptoms, ADLs, sport/recreation function, and knee-related quality of life. Like the FJS, a literature search was performed in an attempt to identify areas of importance for patient-relevant outcomes, which led to subscale areas of symptoms, functional status, and satisfaction. An expert panel was then created consisting of patients, surgeons, and physical therapists. They were asked to identify both short and long term symptoms and functional disabilities from meniscus and anterior cruciate ligament injuries, although they desired to have it apply to early OA patients as well, with the reasoning that meniscus and ACL injuries can lead to OA. From this consultation with the expert panel, seven identifiable factors emerged: pain, early disease specific symptoms, late disease specific symptoms, function, quality of life, activity level, and satisfaction. Pilot testing led to the scale being narrowed down to five outcomes, with satisfaction and activity level being left off of the final survey due to the failure to agree to wording which would be relevant to all knee-related situations. For example, the authors could not agree on wording for a question which could be posed to an ACL patient as well as a TKR patient. A total of 42 items were included with a scoring system from 0-4, with higher scores meaning less problems with the knee. Each subscale was scored independently: pain (9 items), symptoms (7 items), ADLs (17 items), sport/recreation function (5 items), and knee-related quality of life (4 items) with each subscale having its own anchors for the Likert-scoring system. Scores were then transformed for each subscale into a 0-100 range. Unlike other surveys with global scoring, a total score was not considered because each individual item was deemed important enough for separate analysis and interpretation (197). In reality a global score could easily be calculated through simple summation of the individual subscales, however, this was not the original intention of the tool and should theoretically be done with caution.

In assessing the psychometric properties of the KOOS, content validity has been reported as high through comparison with the WOMAC (198). The creators of the KOOS implemented a method for calculating the WOMAC scores through the KOOS subscales as a means of insuring content validity. The KOOS physical function component had an alpha of 0.89 and a corresponding correlation with the WOMAC physical function of 0.9, suggesting good internal consistency (199). When applied to five different levels of OA (mild, moderate, severe, TKR, TKR-revision), the KOOS had alpha levels for all subscales above 0.7 with only one exception (symptoms subscale for the severe OA group; 0.56) (200). This suggests that different subsets of a population are more sensitive to specific subsets of the tool, indicating that care should be taken with the interpretation of the results. It has been stated that it is tough to make a generalization on internal consistency as data on dimensionality and factor structure is limited for most of the tools (151).

The KOOS had a high correlation (0.9) with the WOMAC in the physical function subscale (199), indicating similar constructs and good construct validity, which is to be expected given that both are disease-specific tools and investigating similar things. When comparing the KOOS with the SF-36, the highest correlations between the two were on comparing physical function to ADLs, obtaining a value of 0.57, which can be interpreted as a moderate correlation (197). This is likely in the sense that physical function and ADLs are slightly different and may not be exactly the same. Additionally, the KOOS and SF-36 are different surveys measuring different elements. Higher correlations are seen with the physical components of the SF-36 than the mental components compared to the KOOS (197), which should happen given that the KOOS examines physical components, and not mental components.

The criterion validity is less commonly researched. One study has used the WOMAC as the gold standard in comparison to the KOOS to assess criterion validity (199). While the WOMAC is the most commonly utilized tool, it is seldom referred to as the gold standard. The KOOS had standardized response means ranging from 1.4 to 1.7, indicating good responsiveness in comparison to the WOMAC (199). Furthermore in comparing the KOOS to the WOMAC and SF-36 for responsiveness, the effect sizes were all high for the KOOS subscales (0.8-1.64), which was higher than any of the WOMAC or S-36 scores, except for the knee-related quality of life scale (it was the most responsive subscale at 1.64) as this was deemed to have no replicated measure in either the WOMAC or SF-36 (197). Initial testing of the KOOS found high random effects intraclass correlation coefficients (ICC): 0.85 for pain, 0.93 for symptoms, 0.75 for ADL, 0.81 for sport/recreation function, and 0.86 for knee related quality of life (197), which indicates high levels of reproducibility for all the subscales.

Floor and ceiling effects have both been reported for the KOOS. When examined in multiple stages of OA, researchers showed the KOOS had a ceiling effect for the mild OA group for pain, symptoms, and ADLs and for sport/recreation for the severe OA group and also had floor effects for sport/recreation and quality of life in the severe OA and TKR revision groups (200). This suggests that the interpretation of the specific group it is applied to is important as well as the subscales within those specific groups. A ceiling effect may be achieved with disease-specific tools but at the same time, pain, for example, may continue to occur elsewhere as a result of an existing comorbidity (201). When the presence of ceiling or floor effects exist, additional examinations into other areas or extended scoring scales may be necessary.

Short Form 36 and Short Form 12. The WOMAC, OKS, FJS, and KOOS were all created with either a specific disease and/or a specific joint in mind. However, not all tools utilized on the TKR population were developed in this manner. The Short Form 36 (SF-36) and the Short Form 12 (SF-12) are general health surveys which survey a wider array of information than the disease-specific surveys, but are often applied to the TKR population in conjunction with other surveys (17, 202, 203). These general health surveys are seen as more encompassing of an overall picture of health. The SF-36 measures three aspects of health: functional ability, well-being, and overall health. Within these three aspects are 35 questions divided into 8 subcategories: physical function (10 items), bodily pain (2 items), role-physical (4 items), general health (5 items), vitality (4 items), role-emotional (3 items), social functioning (2 items), and mental health (5 items) (204). An additional question regarding overall health status as compared to one year prior is also included, to give the total of 36 questions (154). Responses are scored on a 5 point Likert scale. Scores can be converted to a total score between 0-100 (worst to best) to aid in interpretability. Subscale scores can be provided by summing the responses from the questions in each subscale. A physical component summary score and a mental component summary score are provided when combining subscales. The physical component consists of the physical function, role physical, bodily pain, and general health while the mental component consists of mental health, role emotional, social function, and vitality (175). The SF-36 was created over a seven year period with the intention of improving and updating the 18- and 20-item Medical Outcome Survey (MOS) short form. The goal was to create a more efficient scale for measuring general health (154). It was designed based on previous surveys examining patient limitations in physical, social, and role functioning, general mental health, and general health perceptions. These previous surveys were deemed too long and thus required a shorter, yet still comprehensive, version in order to capture the total picture of health (154). Each independent subcategory had its own construction process, ranging from exact replicas of previous surveys (physical function, mental health) to completely new constructs (vitality) and everything in between (154).

The SF-36 is a generic health survey which allows for comparisons between different patient groups with the same condition as well as different conditions. The problem though is that is does not examine the intimate details of specific injuries/diseases, leading to less insight about the specific nature of problems with a patient for a given issue. When creating this survey, breadth (issues with the comprehensiveness of the tool) and depth (issues with precision in measuring a specific concept) were seen as potential problems. Breadth of the tool was addressed by examining and including the most frequently studied functional status aspects and well-being concepts in previously described and widely accepted definitions of health status. Depth of the tool was addressed by taking the subset of items which best replicated the full length tools. These tools already had proven validity, and thus could be applied to the shorter version (154).

While the SF-36 was created to make a shorter version of a measurement tool, it was still longer than some other tools (WOMAC), leading to the creation of an even shorter version which would become the SF-12. During the creation of the SF-12, the creators had three goals in mind: 1) create a form that could be scored to explain at least 90% of the variance in the physical and mental health measures of the SF-36, 2) create a form that could reproduce the average summary scores and the eight subscale scores with a high degree of comparability, and 3) create a form which could be self-administered on two pages or less or administered by a tester in less than two minutes on average. The creators used data from the National Survey of Functional Health Status to select and score 12 items from the SF-36 and the Medical Outcomes Survey and to cross-validate population-based scoring algorithms for both the summary measures and the subscale measures. It took ten items to produce physical and mental component summary scores of the SF-36 with R^2 values of 0.9 or higher (physical=0.911, mental=0.918). An additional two items were selected, thus allowing the 12 chosen items to represent all eight subscales (205).

As a whole, the OKS and KOOS have shown higher positive ratings for content validity compared to the SF-36 (157, 179, 206) and SF-12 (157, 179), as indicated by increased presence of floor and ceiling effects. The lower ratings for the SF-36 and SF-12 are likely respective of the populations with which they were applied to. Since they are general health surveys whereas the OKS and KOOS are disease-specific, application to a TKR population should warrant higher scores for the OKS and KOOS. An assumption of content validity for the SF-36 and SF-12 may not be appropriate when applying them to a TKR population as they were not originally intended for use in that population (151). The target population is specific for the OKS and KOOS while the SF-36 and SF-12 can be applied to anyone.

On the SF-36, a variety of methods, presentations, and interpretation of factor results have been shown (160). Most of the studies that examined the factor analysis of the SF-36 used exploratory analysis instead of the confirmatory, which would have been a more appropriate choice (160). However, when examining the SF-36 and SF-12, it is important to note that they were constructed with heterogeneity in mind, not homogeneity, based on the generalization of the survey and not the disease-specific element (205). This may indicate overall poor scores of internal consistency given the lack of homogeneity. In using Cronbach's alpha to assess internal consistency, the SF-36 and SF-12 have shown good positive results. The SF-36 had an alpha of 0.85 and the SF-12 had 0.88 (157). All subscales for the SF-36 had alpha values of 0.75 or greater while the SF-12 mental and physical component summaries had alphas of 0.62 in one study (157). The SF-36 sometimes displayed lower values for Cronbach's alpha, but rarely below 0.7 (162). The individual components however had a wide range of values, with a 0.651 for the vitality subscale and a 0.996 for the role physical subscale. The mental health component summary score was reported as 0.511 while the physical health component summary score was 0.709 (161), further helping to illustrate the diversity within the tool.

Like the WOMAC, OKS, and KOOS, the SF-36 has received positive ratings for construct validity (151). Lower ratings have been shown for the SF-36 when the researchers have failed to provide a priori hypotheses (161, 162). In using effect sizes to assess construct validity, values for all the subscales in the SF-36 were all 0.75 (physical function) or lower (162). Generic measures better assess comorbidities than the disease-specific tools do (201). This may be more beneficial during an aging process as these comorbidities are more likely to occur, however it does not help with specific assessment of a specific issue, as the disease-specific tools would. Examination of the comorbidities showed that the WOMAC did not produce any significant differences in effect sizes but the SF-36 did for rheumatology patients, but for TKR patients for both the WOMAC and the SF-36 in some of the subscales, but not all (162).

The SF-36 and SF-12 have had both positive and negative ratings for reproducibility. The WOMAC and OKS had ICCs above 0.9 while the SF-36 had a 0.75 (34, 157). As with any statistic, the acceptability level depends on the interpreter, which means that despite the lower rating for the SF-36, it can still be deemed a higher correlation value and thereby acceptable for reliability standards. In a test-retest reliability for the SF-12, values of 0.89 for the physical component and 0.76 for the mental component were reported (205). The same testing on the and SF-36 also yielded positive results (162), suggesting good reproducibility for both the SF-36 and Sf-12. In rehabilitation interventions, the MCID for the SF-36 was reported as 12% of the baseline score or 6% of the maximum score for detecting differences (166). Each subscale of the SF-36 is different, as the general health scale had the lowest MCID values for both individual and group differences, being almost one-third the value of the other subscales (207).

The SF-36 has decreased responsiveness compared to the WOMAC (188). The SF-36 had large effect sizes for physical aspects of the scale (1.3-2.1), suggesting good responsiveness, but only small to moderate effect sizes for mental (0.3-0.5) and social (0.4-0.6) aspects for a

TKR group (207). Additionally, the SF-36 showed better responsiveness at a group level compared to an individual level for knee patients, and therefore may not be the best tool for assessing change on an individual level (207). Some of the subscales of the generic measures can have more responsive attributes, such as physical functioning, physical component summary score, and bodily pain in the SF-36 exhibiting large effect sizes, thereby suggesting responsiveness (172). These subscales are likely to be more responsive given the issues with which they are being applied to (TKR) and that the physical aspects are the dominant area of interest in this population.

During the creation of the SF-36, the presence of ceiling and floor effects were seen as potential problems. In order to alleviate this, since it is a general health survey, the creators suggested adding possible supplementary questions to the tool based on the population it is being applied to (154). For example, if the tool is being applied to a severely diseased population, it would be beneficial to add questions which better represent the extreme low end of the scoring scale to control for floor effects, or for a very healthy population, add questions on the top end to control for ceiling effects. The SF-36 showed ceiling effects for two of its dimensions: social functioning and role limitations due to emotional problems, but no reported floor effects (162). In a different study, the SF-36 showed a mean floor effect of 17.07%, with subscale values ranging between 0.79% and 36.02%. while the SF-12 showed no mean floor effect, with the subscales having 0.02% (157). In that same study, a mean ceiling effect of 12.52% was evident for the SF-36, with subscale values between 0.59% and 49.50%, and the SF-12 had a -0.09% ceiling effect. The ceiling effects in the SF-36 can be problematic as it does not allow for any improvement (207), so depending on time of application of the tool, it may have limited ability to detect improvement. To further this point, the physical function subscale had no ceiling effects at baseline or follow up (207), which says something different. This may suggest an inability to return to perfect physical form.

In the Sf-12 and SF-36, means and standard deviations are commonplace for reporting (162, 189) as are reporting at multiple measurement time periods, which gives clinical relevance as it tracks changes over time (34, 188). This suggests high levels of interpretability for both survey tools, and thereby allowing qualitative interpretation of the information being presented.

The previously described surveys tend to be the most utilized surveys based upon information collected for review articles on TKR populations (151). As a whole, they provide either a disease-specific or a general health investigation of the patient. There are additional surveys which have other items examined, such as ROM, other more specific activities (triathlons, cross country skiing, etc.) and their difficulties, or a combination of activities in conjunction with the self-reported patient measurements. For example, the Knee Function Score examines specific physical therapy activities (timed walks, stride lengths, hop tests, kneeling tests, etc.) and gives a score based on the patient's performance of the activity while simultaneously investigating the patient's pain on an ordinal scale (208), however, it is much less in depth with respect to any factor outside of the pain associated with the task (i.e. the difficulty of a task). Theoretically, a task could be difficult without being painful so this tool lacks a complete picture of the situation the TKR patient is experiencing. Other tools such as the New Knee Society Scoring System looks at many more activities which require much higher levels of physical functioning, such as jogging, weight lifting, racquet sports, etc. (209). Realistically, it may take a combination of tools in order to successfully evaluate a patient as no single tool seems to be all encompassing. With this in mind, as is evident in the decreasing size of the tools being utilized, time is of great importance to everyone involved and the shortest, yet still comprehensive, survey seems to be the desired entity.

Application of Surveys to TKR Population

A lot of good work has been done in the TKR population through the use of various measurement tools. Physical function has been largely examined using the WOMAC, OKS, FJS, KOOS, and many other tools designed specifically to address knee issues, while the SF-36 and SF-12 have been used on the same population but examining a more general health assessment. The SF-36 and SF-12 have mental health components to them, but they are broad in nature and lack intimate depth in examining the psychological constructs. As has been shown, TKR satisfaction extends beyond the physical into the psychological constructs. When applying measurement tools to the TKR population, the WOMAC, OKS, FJS, or KOOS are important for use as it allows comparison with other studies on the TKR population, but in attempting to explain dissatisfaction, research going forward needs to include some psychological measurement tool. Physical tools alone may not have the information needed to sufficiently explain the dissatisfaction within a certain sample population. The addition of a psychological assessment tool may help to further that explanation and provide a better understanding of why patients experience satisfaction or dissatisfaction with TKR procedures. The survey tools may be combined with additional physical testing which is not patient-subjective, such as biomechanical assessment of walking and stair climbing. Biomechanical assessment has not been done on satisfied and dissatisfied TKR populations. The incorporation of functional testing commonly used in physical therapy may also explain the dissatisfaction in TKR patients. While this creates a large study with the presence of physical surveys, psychological surveys, biomechanical analysis, and functional testing, dissatisfaction is an important construct to examine as the decision to undergo a TKR is not a small decision. It is a major surgery with a long recovery. Patients should be able to expect satisfaction with the process if they are investing this substantial amount of time and money into the procedure.

The research on the dissatisfaction has provided a substantial amount of information, however there are some areas which need further examination. First, there is minimal biomechanical data on the dissatisfied population. Kinematics and kinetics play a large part on the evaluation of TKR patients, yet there has been relatively little information provided on the kinematics and kinetics of the dissatisfied population and how they compare to satisfied TKR patients and healthy controls. Additionally, it may be of interest to note how biomechanical variables relate to strength, balance, and functional tasks for these same populations. This enhancement of information available on the TKR population may help to dictate treatment of dissatisfied patients. By identifying physical factors which may contribute to dissatisfaction, researchers may be able to provide information for rehabilitating TKR patients towards satisfaction with their joint replacement.

Patient Satisfaction

Meaning of Satisfaction

Satisfaction is a complex construct which could be argued as a psychological construct rooted in physical properties, especially in pertaining to the TKR population. The vast majority of the studies examining satisfaction in the TKR population have done so with a simple question used to divide the population: "How satisfied are you with your knee replacement?". The patients are then provided with a 5 point scale which corresponds to options of very satisfied (5), somewhat satisfied (4), neutral (3), somewhat dissatisfied (2), and very dissatisfied (1), possibly with some slight wording deviations but still arriving at the ability to be able to distinguish between satisfied and dissatisfied patients (9, 11, 17, 18, 111, 192, 194, 203, 210). A visual analogue scale can also be used to assess the same question, with the ability to have scores which are not whole numbers as the above mentioned scale is (211). The 1-5 scale is the most commonly utilized assessment for determining TKR patient satisfaction and subsequent division into different groupings (i.e. very satisfied and satisfied vs dissatisfied and very dissatisfied).

Some measurement tools have chosen to elaborate on this construct with questions relating to satisfaction with particular activities as a means of gauging a possible change in satisfaction with tasks of varying difficulty. One researcher asks an additional question to the original satisfaction question of whether the patient is satisfied with his/her level of activity after the TKR procedure (212). Another researcher furthered the investigation of the dissatisfied patients with follow up questions of the symptoms or functional disabilities which may have led to the dissatisfaction as a means of trying to get to the root cause of dissatisfaction (9). As mentioned earlier, the FJS creators believe the ultimate level of satisfaction is the ability to forget the replaced joint exists in everyday life (158). This is a construct of the authors though and was never actually used to subdivide a population into satisfied and dissatisfied groups. A threshold score for the tool would need to be set to deem a patient satisfied/dissatisfied. It could then be statistically analyzed against an additional determinant of satisfaction to see its effect. In general, every measure of satisfaction reverts back to the simple question of asking patients to rate their overall satisfaction with the TKR. While this is a subjective assessment, it is an essential query as patient satisfaction is the ultimate goal of TKR. A more sophisticated analysis, such as a logistic regression, may provide additional insight into this complex construct.

The terms “satisfaction” and “success” are often used interchangeable, but the two constructs are substantially different. In reference to a total knee replacement (TKR) population, “satisfaction” is a patient-based term while “success” is most appropriately determined by medical personnel (surgeon, doctor, physical therapist, etc.). “Satisfaction” has been defined by a subjective question posed to patients, “Are you satisfied with your knee replacement?” Patients are given a four or five point Likert scale (different researchers have used different scales as there is no standardized scale) with responses gauged between very dissatisfied and very satisfied (17, 202). Conversely, “success” for an operation has been defined by the reduction of pain, restoration of joint flexion range of motion, improved joint alignment, and a restored ability to perform activities of daily living, as is evident in the Knee Society System scoring tool (5). There have been several instances where the patients and the medical personnel do not agree on the success of the TKR procedure, with the medical personnel often having a more positive outlook on the outcome of the procedure than the patient population (13, 195, 210). The surgeons will typically base their evaluation of the success of a TKR procedure on a multitude of physical aspects of the procedure, such as range of motion (ROM) of the knee post-surgery, ability to perform physical activities, and the surgical alignment of the knee (as in a correction of an alignment deformation from prior to the surgery). Patients will evaluate their satisfaction based on the surgery meeting their pre-surgery expectations, pain relief, and the ability to return to activity post-surgery (13). Patients hope for an ability to return to the functioning they had prior to the onset of their knee issues. When making this assessment, some expectations for the operation become unrealistic as a passage of time and neglect of fitness levels may impair a patient’s abilities. Surgeons take this into account when evaluating success of the surgery (13). A 70 year old patient who has been neglecting their fitness since the onset of knee pain 15 years earlier may not be able to return to the same level of activity as prior to the onset of knee pain.

Like the surgeons, patients also assess the physical aspects of the procedure, but mostly based on their expectations of how the procedure will affect their physical function abilities and pain levels. The total level of pain and function does not seem to be as important to the patient as the relative reduction in overall pain post-surgery (18). There can be additional factors contributing to satisfaction levels for the patients that are not directly related to the surgery site (i.e. pain relief in the knee, ability of the knee to function normally), such as the need for outside assistance (help completing certain tasks), lack of social interaction or a social support network, or the presence of comorbidities, all of which have been shown to reduce satisfaction levels (17). These factors do not necessarily affect the determination of good clinical outcomes (success) for the medical team but may factor into the patient's level of satisfaction. Given that the patients and medical teams have different criteria for judging the procedure, there is the possibility of disagreements between the two. There have been reports of good clinical outcomes with dissatisfied patients as well as bad clinical outcomes with satisfied patients (17), illustrating the discontinuity between the patients and the medical personnel with respect to the evaluation.

An interesting, albeit rarely used, construct for assessing patient satisfaction is the ability to forget about the replaced joint during everyday life (158). It could be argued that the ability to forget about the presence of an artificial joint may mean that pain is minimal to non-existent and that functional limitations are the same, thus adding to satisfaction. At the same time, it could be argued that the patient is merely coping with the pain or functional limitations and found a way to deal with a continuing presence of them through compensatory strategies or mindsets which reduce the experience of discomfort or dissatisfaction. This examination of proprioception has been suggested as the "ultimate goal in joint arthroplasty" (158), but it should be combined with assessing the above mentioned factors.

Psychological Factors of Satisfaction

While the question for determining satisfaction is relatively simple in that it is a single question assessing the global outcome, in reality many factors influence satisfaction beyond the physical components traditionally investigated in the TKR population. In a comparison of psychological tools to the WOMAC and FJS, 54.3% of the variance in the WOMAC scoring and 30% of the FJS scoring were explained in a multivariate regression model using two psychological measurement tools: the Catastrophizing scale and the Brief Symptom Inventory. This led to the conclusion that there is a strong relationship between psychological status and orthopedic outcomes (213). The WOMAC total score had a high correlation with the Catastrophizing scale (up to a correlation value of 0.79). The WOMAC subscales are not designed to represent any psychological component, but based on the correlations, there are clearly psychological factors which may be related to the physical components (213). Based on content alone, the WOMAC is a physical tool, but there seems to be underlying psychological factors which contribute to the scoring within those physical dimensions, based on correlations between the two tools. The FJS, on the other hand, while being largely deemed a physical tool, the "joint awareness" it references could easily be argued as possessing a psychological construct in that it deals with awareness of a feeling of the knee replacement. The tool measures the awareness of a patient's knee replacement, thereby asking them to assess their proprioception of the area of the knee, where the prosthetic exists.

In further enhancing the psychological construct, types of joints replaced were compared to the psychological components (Catastrophizing Scale and Brief Symptom Inventory). The psychological components had stronger associations than the location of the joint replacement, suggesting that the idea behind surgery is more important than the surgery itself (213). Having a joint replaced is a major operation which requires some mental skills to deal with. Injury and the subsequent recovery is certainly a physical event; however it is also a psychological and emotional event (214). The recovery can be long and very defeating if progress does not occur as quickly as anticipated, leading to a decreased level of satisfaction as the patient may not be able to return to the physical abilities as previously anticipated (111). Successful coping behaviors (such as positive attitude, positive outlook on treatment, rehabilitation adherence) have been instrumental in aiding in the recovery process while unsuccessful coping behaviors hinder recovery (poor adherence, poor attitude) (215). It should be noted that the relationship between orthopedic measures and psychological measures may suggest poor divergent validity, which can impair the accurate assessment of orthopedic outcomes (213).

Patient Satisfaction for TKR Procedures

Satisfaction is a complex construct which could be argued as a psychological construct rooted in physical properties, especially in pertaining to the TKR population. The vast majority of the studies examining satisfaction in the TKR population have done so with a simple question used to divide the population: "How satisfied are you with your knee replacement?". The patients are then provided with a 5 point scale which corresponds to options of very satisfied (5), somewhat satisfied (4), neutral (3), somewhat dissatisfied (2), and very dissatisfied (1), possibly with some slight wording deviations but still arriving at the ability to be able to distinguish between satisfied and dissatisfied patients (9, 11, 17, 18, 111, 192, 194, 203, 210). A visual analogue scale can also be used to assess the same question, with the ability to have scores which are not whole numbers as the above mentioned scale is (211). The 1-5 scale is the most commonly utilized assessment for determining TKR patient satisfaction and subsequent division into different groupings (i.e. very satisfied and satisfied vs dissatisfied and very dissatisfied).

Some measurement tools have chosen to elaborate on this construct with questions relating to satisfaction with particular activities as a means of gauging a possible change in satisfaction with tasks of varying difficulty. One researcher asks an additional question to the original satisfaction question of whether the patient is satisfied with his/her level of activity after the TKR procedure (212). Another researcher furthered the investigation of the dissatisfied patients with follow up questions of the symptoms or functional disabilities which may have led to the dissatisfaction as a means of trying to get to the root cause of dissatisfaction (9). The Forgotten Joint Score creators believe the ultimate level of satisfaction is the ability to forget the replaced joint exists in everyday life (158). This is a construct of the authors' though and was never actually used to subdivide a population into satisfied and dissatisfied groups. A threshold score for the tool would need to be set to deem a patient satisfied/dissatisfied. It could then be statistically analyzed against an additional determinant of satisfaction to see its effect. In general, every measure of satisfaction reverts back to the simple question of asking patients to rate their overall satisfaction with the TKR. While this is a subjective assessment, it is an essential query as patient satisfaction is the ultimate goal of TKR.

An examination of the satisfaction results for TKA patients has yielded some wide ranges of responses. The rate of dissatisfaction ranges between 6 and 19%, neutral from 2 to 12%, and satisfied from 70-89% (9, 11, 17, 18, 111, 192, 194, 203, 210, 216). Best case scenario is an 89% satisfaction rate which still leaves 11% of the population in a neutral or dissatisfied state, which is a significant portion of the population. A visual analogue scale measurement of satisfaction revealed 68% of the people sampled had an 80/100 mm score or better (211), which still leaves a lot to be desired for increasing the satisfaction level. These outcomes will, however, differ with respect to time as short term and long term time periods have been shown to be different with respect to improvement relating to satisfaction (217). Additionally, the type of procedure done with respect to knee replacements plays a role as TKR patients have been shown to have higher dissatisfaction rates compared to bicompartmental knee replacement patients when the ACL is retained (218).

Patient satisfaction with TKA procedures have been shown to have significant correlations with improved SF-36 scores, WOMAC pain scores, improved knee function (assessed through self-evaluation using a functional outcome assessment questionnaire), and overall physical function (assessed with same functional outcome questionnaire) (17). The dissatisfied patients have also been shown to have decreased WOMAC pain, stiffness, and function scores (meaning the patients experienced an increase in pain and stiffness and a decrease in function), and decreased SF-36 physical functioning, role physical, pain, vitality, social function, and role emotional scores (9). The OKS scores also improved with patient satisfaction, showing a worse pain score for dissatisfied patients and a strong correlation between pain and function (18, 192). The visual analogue scale had reported that 84% of patients surveyed had pain scores less than 20/100 mm (211). In reporting correlations of satisfaction with specific measurement tools, the OKS reported the highest correlation value followed by the WOMAC and then the SF-36 and SF-12 physical component summary and then mental component summary (194). In a study examining both pre-operative and post-operative measurements, the only pre-operative measurement which was shown to be related to dissatisfaction was self-reported mental functioning (219), illustrating that state of mind prior to the procedure is crucial. A good state of mind should be obtained prior to committing to the procedure given the dedication needed to successfully rehabilitate. This same group showed increased 6 minute walk test times, increased pain, increased physical limitations, and reduced WOMAC and SF-36 scores (219).

In an examination of demographic components, men were more satisfied with the procedure than women and older patients were more satisfied than younger patients (18). It has been reported that 7% of those older than 70 were dissatisfied while 10% of those under 70 were dissatisfied (212). An additional study reported the highest dissatisfaction (19%) was for patients in the age group of 60-75 (111). Yet another study rated the highest dissatisfaction (19%) with those patients under the age of 55 (220). This is to be expected as the younger the individual, the likely the higher desire to return to a more active lifestyle than the older adults. Consequently, the assessment of highest dissatisfaction being within the 60-75 age group is likely because this population is still young enough to desire to return to a more active lifestyle, but not as capable of returning to an active lifestyle as the population under 60, based on physical components of healing and strength. Age can play a large role in recovery as well as perceptions of what their physical abilities should be. It has been suggested though that the age of a patient is not nearly as important as their physiological age, as a 70 year old may be younger physiologically than a 50 year old based on how well their body was taken care of (221).

The dissatisfied population has a decreased desire to have the procedure done again (meaning if presented with the option of a TKR procedure, they would not have the surgery done) compared to the satisfied (192). There is no single underlying construct to this perception, and may actually be a combination of both physical and mental components of the procedure. This may suggest that the dissatisfied patients' lives were more satisfying prior to the surgery, although this has yet to be confirmed. Different replacement types also showed different levels of satisfaction, with cemented TKAs being more satisfied than unicompartmental procedures

(18). However, no satisfaction differences were present when examining the different types of implants (such as posterior stabilizing or posterior cruciate ligament retaining) or whether there was patellar resurfacing (203, 210).

Aside from overall satisfaction with the TKR, a few studies have assessed patient's satisfaction with specific situations related to the TKR. A few of the assessed components did have differences with satisfaction. Satisfaction for pain relief varied between 72-86%. There was 70% satisfaction with pain relief during stair negotiation, 85% during walking, and 84% during sitting (210). Higher pain has been associated with lower satisfaction levels (222). Knee stiffness or the use of analgesics at least once a week have been associated with dissatisfaction (111). Satisfaction also largely varied between functional activities, ranging from 70-84%. There was 86% satisfaction with walking on a flat surface, 70% satisfaction with getting out of a car, 73% with ascending stairs, 82% with getting out of bed, 84% with lying in bed, and 83% with household chores (210). Over half of the dissatisfied patients are not as active as they thought they would be, 32% are less active after surgery than they were before, 53% could not perform the activities they desired to, and 71% reported some difficulty with ADLs (111). The dissatisfaction with given tasks reflects the dissatisfied patient groups' difficulty with certain tasks. Dissatisfied groups have been shown to have increased difficulty with kneeling, recreational activities, siting/rising from a chair, stairs, working, and walking, often requiring them to employ a gait pattern with a limp (223). Activities with high flexion have been rated as more important to dissatisfied groups, likely due to their inability to perform them, leading to a desire for the ability to be able to successfully perform high flexion activities without limitation or pain (223, 224). The more capable a person is of participating in ADLs and athletic activities, the higher the satisfaction rates. In order to achieve this, a behavioral contract has been suggested as means of implementing weight loss and regular exercise as they have been shown to improve a person's ability to perform ADLs (225). The contract serves as a more formal commitment to the activity program, thereby increasing participation.

Even with patients with an unlimited ability to walk and climb stairs, 17% were still unsatisfied, suggesting that additional underlying factors outside of physical limitations may be contributing to dissatisfaction (11). From that same data set, 72% of sedentary patients who could only walk five minutes or less were still satisfied (11). This strongly suggests factors outside of physical limitations play significant roles in determining patient satisfaction, warranting examinations outside of just the physical components when investigating patient satisfaction with TKA procedures. This statement is not made to suggest that physical limitations do not play a role in satisfaction, as they clearly do. Dissatisfied patients have been shown to have decreased knee flexion and ROM at the knee (9), which can obviously hinder physical performance and possibly contribute to pain. In a study which split TKR patients based on flexion ROM levels, the high flexion group showed no dissatisfaction while the midflexion group showed a 17% dissatisfaction rate and the low flexion group showed 16% dissatisfaction. However, the magnitude of the maximum degree of knee flexion did not affect satisfaction, only the total ROM (226). Moderate correlations have been shown between functional ROM and patient satisfaction, leading some to conclude that functional outcome is not necessarily an indicator of patient satisfaction (227) and that single factors are likely not going to explain satisfaction (226). One study has shown a decrease in ROM by 11° which was coupled with increased anxiety, depression, and pain, but interestingly, there were no differences in the 6 minute walk test, chair stand test, knee laxity, patellar tenderness, or mechanical axis angles when compared to the satisfied TKR patients (16). However, 48% of the variance in satisfaction can be explained by the mental health, emotional role function, and social function subscales in the SF-36 (17). In additional research, 97% of the variance on patient satisfaction is related to the meeting of the pre-op expectations, achievement of satisfactory pain relief, the patient's hospital experience (subjective), their pre-op OKS score, and their 12-month physical status post-op (192). Other reports for the greatest predictors of dissatisfaction were the presence of other joint problems, increased pain at 2 years post-operatively, and greater functional limitations (228). It is evident that examination of the physical components is not enough to truly derive an accurate assessment of patient satisfaction and the underlying causes of dissatisfaction.

Post-operative walking limitations for TKR patients were predicted by pre-operative walking limitations, high BMI, lower gait speed at 1 month post-operatively, the presence of contralateral knee pain, and the use of a quadstick (a four-pronged walking cane which is more stable than a regular, single prong cane) pre-operatively (229). This helps to illustrate the complexity of satisfaction as a multitude of factors play into the outcomes for the patients. An additional consideration is management of expectations for the patients. Unrealistic expectations of recovery or outcome of the procedure have been shown to decrease satisfaction levels (221, 230). At the same time, while managing expectations, dissatisfaction can increase despite no significantly noticeable functional limitations (231). Patients who reported higher expectations for the outcome of the operation have shown 4.3% dissatisfaction rates, but more importantly, 37% neutral rates, meaning neither satisfied nor dissatisfied (202). While a neutral outlook can be argued as better than dissatisfied, it still does not meet expectations for the procedure. The measure of satisfaction is subjective for the patient and largely based on their own perception of their situation. How a patient rates their satisfaction may partially depend on their overall mood as well. In a comparison of two different icing treatment groups, satisfaction was seen to be higher for a group using a cryopneumatic cooling device compared to a group using traditional ice treatments, but both groups reported being satisfied (231). This illustrates that is may not make sense to disseminate between “satisfied” and “very satisfied” patients as there are no qualifying criteria to separate the two responses. The majority of studies place these two responses in a group together (192, 203, 226), which seems to be the more appropriate classification than splitting them up.

The research on the dissatisfaction has provided a substantial amount of information, however there are some areas which need further examination. First, there is minimal biomechanical data on the dissatisfied population. There is a lack of research on the biomechanics of gait and stair climbing for the TKR population which have reported on patient satisfaction. Kinematics and kinetics play a large part on the evaluation of TKR patients, yet there has been relatively little information provided on the kinematics and kinetics of the dissatisfied population and how they compare to satisfied TKR patients and healthy controls. Additionally, it may be of interest to note how biomechanical variables relate to strength, balance, and functional tasks for these same populations.

Closing Statement

The current literature review illustrates some of the current research examining the TKR population with respect to biomechanics, strength, balance, and survey data. The research in the TKR field has been continuously expanding, however there is currently a lack of research on the dissatisfied patient population. Research on biomechanical gait profiles, strength, and balance needs to be conducted on the dissatisfied population for the purpose of identifying areas of deficit which could be addressed to potentially improve patient outcomes and therefore patient satisfaction with the TKR procedure. Additionally, information obtained through this research may provide information to help improve future TKR implant designs, which could potentially improve patient satisfaction. A more complete biomechanical profile assessment of the dissatisfied population may provide opportunities to reduce the percentage of dissatisfied patients by providing information which is addressable in regards to how a patient performs in various testing scenarios.

CHAPTER III

OVERGROUND WALKING BIOMECHANICS OF SATISFIED AND DISSATISFIED TOTAL KNEE REPLACEMENT PATIENTS

Abstract

Patient dissatisfaction after total knee replacement (TKR) procedures is likely influenced by both subjective and objective aspects. Increased pain and reduced performance on clinical tests have been shown in the dissatisfied patients, however, it is unknown how overground walking kinematics and kinetics are different between dissatisfied and satisfied TKR patients. Therefore, the purpose of this study was to compare overground walking lower extremity kinematics and kinetics of dissatisfied TKR patients to satisfied patients and healthy controls. Nine dissatisfied TKR patients, fifteen satisfied TKR patients, and fifteen healthy controls performed overground walking trials. A 2 x 3 repeated measures ANOVA was used to assess differences between groups and limbs ($p<0.05$). The dissatisfied patients showed reduced 1st and 2nd peak VGRFs, flexion ROM, loading-response extension moments, and loading-response abduction moments compared to healthy controls. First and 2nd peak VGRFs and flexion ROM were reduced in the replaced limb of the dissatisfied patients compared to their non-replaced limb. Push-off plantarflexion moments were reduced in the dissatisfied patients compared to healthy controls and satisfied patients. Dissatisfied patients also reported increased knee joint pain and reduced preferred gait speed. Limb asymmetry was evident in the dissatisfied patients for VGRF and knee extension moments. Future research should examine methods to address the asymmetrical loading as a potential means to improve patient satisfaction rates.
Keywords: total knee replacement, arthroplasty, satisfaction, overground walking

Introduction

Overall, most total knee replacement (TKR) operations are considered successful as there are often reductions in pain levels and improvements in range of motion (ROM) in the replaced knee (6-9). Patient satisfaction rates for the procedure have been reported between 81-97% (10, 11). This leaves a significant portion of the TKR population as dissatisfied with the outcomes of the replaced knee. Post-operative pain (12) and functional limitations (13) are commonly reported by dissatisfied patients. This often results in decreased performance in common clinical tests (such as timed-up–and-go or sit to stand test) when compared to healthy controls (14, 15). These tests are often seen as a defining point for "success" of the operation. However, these test results do not sufficiently explain why the TKR patients are dissatisfied with the TKR outcomes. Examination of walking biomechanics may help to provide quantifiable and detail insights into their dissatisfaction.

There have been several studies investigating the TKR population as a whole compared to healthy controls. These studies have examined overground walking, with special focus on gait velocity (20, 21), sagittal plane knee ROM (20, 22), and frontal plane knee moments (20, 21). Some research has shown a return to vertical ground reaction force (VGRF) symmetry between the replaced and non-replaced limb in TKR patients (46), a knee flexion ROM comparable to healthy controls (25, 26), and similar peak knee abduction moments in replaced limbs compared to healthy controls (26). However, not all studies are in agreement with these results as differences have been shown with respect to VGRF, ROM, and joint moments (24, 26, 46). Reduced peak knee extension moments have been shown in TKR patients (46), likely due to a reduced quadriceps strength, resulting in a quadriceps avoidance gait pattern. This reduction in knee extension moments sometimes results in an increase in knee abduction moments (38, 114, 138). These changes in joint moments may indicate a reduced level of recovery given the differences compared to healthy controls, which may be further amplified in the dissatisfied patient population, although this has yet to be examined.

Patient dissatisfaction is likely influenced by multiple factors, including both subjective and objective aspects. Issues with pain, perceived function, and physical abilities may all contribute to dissatisfaction. Currently, patient dissatisfaction has been largely quantified based on survey and functional test data with very little information with respect to the three-dimensional kinematics and kinetics of TKR patients, including overground walking, a simple but necessary daily task. How dissatisfied patients differ from satisfied patients and healthy controls in overground walking mechanics is largely unknown. Therefore, the purpose of this study was to compare the lower extremity kinematics and kinetics of dissatisfied TKR patients to satisfied TKR patients and healthy controls during overground walking. It was hypothesized that dissatisfied TKR patients would exhibit reduced knee extension moments and increased knee abduction moments in their replaced limb compared to their non-replaced limb in level walking. Additionally, it was hypothesized that dissatisfied TKR patients would exhibit increased reduced knee extension moments and knee abduction moments compared to satisfied TKR patients and healthy controls in level walking.

Materials and Methods

Participants

Twenty four TKR participants were recruited from a local orthopaedic clinic. There were nine dissatisfied TKR patients (68.0±4.2 years, 1.69±0.07m, 81.0±18.6 kg, 34.6±14.3 months post-surgery) and 15 satisfied TKR patients (66.6±6.3 years, 1.76±0.10m, 90.2±17.0 kg, 29.3±12.8 months post-surgery). The inclusion criteria for TKR patients were the presence of a unilateral total knee replacement performed by a single surgeon, at least 12 months but less than 60 months post-operative, and between the ages of 50 and 75. Exclusion criteria were any additional lower extremity joint replacements, any additional diagnosed osteoarthritis of the hip, knee, or ankle, BMI greater than 38 or neurological diseases. TKR patients were then asked, "How satisfied are you with your total knee replacement?" The available responses were "very dissatisfied, dissatisfied, neutral, satisfied, or very satisfied." "Neutral" responses were excluded. "Very dissatisfied" or "dissatisfied" was placed into the Dissatisfied group and "satisfied" or "very satisfied" were placed into the Satisfied group. Fifteen healthy controls (60.7±9.2 years, 1.75±0.09m, 77.7±11.8 kg) were recruited with the same exclusion criteria as the TKR groups.

Instrumentation

A twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain three-dimensional (3D) kinematics during testing. All participants wore standardized running shoes (Noveto, Adidas, Herzogenaurach, Germany). Anatomical retroreflective markers were placed bilaterally on the acromion processes, iliac crests, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads, and 2nd toe. A cluster of four retroreflective markers on a semi-rigid thermoplastic shell was placed on the lateral aspects of both shanks and thighs, and on the posterior aspect of the pelvis and the thoracic cage, attached via an elastic neoprene wrap with hooks and loops of Velcro. Four individual tracking markers were placed on the heel counter of the shoe. Anatomical and tracking markers were kept on for the static trial and anatomical markers were removed prior to testing trials. One force platform (1200 Hz, BP600600, American Mechanical Technology Inc., Watertown, MA, USA) was used to measure the ground reaction force (GRF) and moments of forces. Walking speed during all trials was monitored by two sets of photo cells (63501 IR, Lafayette Instrument Inc., IN, USA) and electronic timers (54035A, Lafayette Instrument Inc., IN, USA).

Experimental Procedures

All participants signed an informed consent form, and completed a physical activity readiness survey (PAR-Q) to assess cardiovascular risks to exercise and a Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) for both knees (178). TKR participants also completed a Forgotten Joint Score (FJS, (158)). Following completion of the surveys, all participants completed a five-minute warm up on a treadmill, walking at a self-selected speed. Participants were then fitted with the retroreflective markers. Participants performed three practice walking trials over a 10 meter runway at a self-selected speed. The practice trials were to familiarize themselves with the lab setup, find a starting position to ensure proper foot contact with the force platform without stutter stepping or targeting, and determine average walking speed. A speed range (mean speed ± 5%) was used to control participant speed during experimental trials. All participants performed five trials in two randomized conditions, one with the left foot in contact with the force plate and one with the right foot. A trial was discarded and repeated if the speed range was not met, the foot was not in full contact within the bounds of the force platform, or targeting occurred. A numerical visual analogue pain (VAS) scale was used to assess pain level in both knees for TKR and healthy participants at the end of the test conditions.

Data Analyses

Visual3D biomechanical analysis software suite (version 5.0, C-Motion, Inc., Germantown, MD, USA) was used for 3D kinematic and kinetic variable computations for overground walking data. A Cardan rotational sequence (X-y-z) was used for 3D angular kinematics computations and the conventions of the angular kinematic and kinetic variables were defined using the right-hand rule. Positive values indicate ankle dorsiflexion, inversion, and internal rotation, knee extension, adduction, and internal rotation, and hip flexion, adduction, and internal rotation angles and joint moments (computed as internal moments). Kinematic and GRF data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 8Hz before kinematics and joint moment calculations. Raw GRF were filtered separately using a fourth-order low-pass Butterworth filter with a cut-off frequency of 50 Hz to calculate GRF variables. Critical events and values, including peak VGRF, knee extension, abduction, and internal rotation moments, loading-response knee flexion, adduction, and external rotation ROM, and sagittal plane hip and ankle ROM and moments, were chosen using customized computer programs (VB_V3D and VB_Table, MS Visual Basic 6.0, USA). Joint moments represent internally applied moments, were reported in the proximal reference system and were normalized to body mass (Nm/kg). GRF variables were normalized to body weight (BW). Averages across the five trials of selected variables for every condition for each participant were used in statistical analyses.

Statistical Analyses

A 2 x 3 (limb x group) mixed model analysis of variance (ANOVA, $p<0.05$) was performed to detect differences between limbs and groups for kinematic and kinetic variables (Version 9.4, SAS, Cary, NC, USA). A one-way ANOVA ($p<0.05$) was performed on demographic and survey data to test for differences between the three groups. When the ANOVA revealed a significant interaction or main effect, post-hoc comparisons for multiple pairwise comparisons were used to compare means between limbs and groups. Post-hoc comparisons were made using adjusted p values of 0.00625 for 2x3 ANOVA significant interactions, 0.0167 for 1x3 ANOVA comparisons and group main effects, and 0.05 for limb main effects. Post hoc comparisons were only made between the TKR replaced limbs against healthy dominant limbs and TKR non-replaced limbs against the healthy non-dominant limbs, under the assumption that any differences between the dominant and non-dominant limbs are random and small when present in the healthy participants.

Results

There were significant differences (p=0.0034) in age for the dissatisfied and satisfied group groups compared to the healthy group. Walking speed for the walking trials revealed a significant difference between the groups, with the dissatisfied group walking slower than both satisfied and healthy groups.

Significant interactions were present for 1st and 2nd peak VGRF (Table 1). Both the dissatisfied and satisfied groups had reduced 1st peak VGRF in their replaced limb compared to their non-replaced limb and the healthy group (p<0.0060 for both comparisons). The 2nd peak VGRF was reduced in the replaced limb of the dissatisfied group compared to their non-replaced limb and both satisfied and healthy groups (p<0.0021 for all comparisons). A significant interaction was present for knee flexion loading ROM, which was significantly reduced for both dissatisfied and satisfied groups in their replaced limbs compared to their non-replaced limbs and healthy participants (p<0.0061 for all comparisons). A significant interaction was present for peak knee loading-response abduction moments, with reduced moments for the dissatisfied patients in their replaced limb compared to the healthy group (p=0.0061). Transverse plane knee ROM showed a significant interaction, exhibiting a reduction in the replaced limb of the dissatisfied group compared to their non-replaced limb (p=0.0040). Both peak knee loading-response internal rotation and push-off external rotation moments showed significant interactions. The dissatisfied patients showed reduced peak internal rotation moments in their replaced limb compared to their non-replaced limb and both satisfied and healthy groups ($p<0.0058$ for all comparisons). Push-off external rotation moments were reduced for the replaced limbs of both TKR groups compared to the healthy group ($p<0.0023$ for all comparisons). Significant limb main effects were present for knee extension loading moments and push-off moments, with reductions in the replaced limbs compared to the non-replaced limbs ($p < 0.0317$for all comparisons, Table 1). Significant group main effects were also present for peak knee extension loading moment and loading-response knee adduction ROM. The dissatisfied group showed reductions in peak loading-response extension moments compared to the healthy group ($p=0.0052$). The satisfied group showed reduced loading-response knee adduction ROM compared to the healthy group ($p=0.0139$).

A significant interaction was present for ankle dorsiflexion ROM (Table 2). Both dissatisfied and satisfied groups had increased ankle dorsiflexion ROM in their replaced limbs compared to their non-replaced limbs as well as reductions compared to the healthy group ($p<0.0032$ for all comparisons). Significant limb main effects were present for both peak loading-response dorsiflexion and push-off plantarflexion moments. Peak loading-response dorsiflexion moments were higher in the replaced limb compared to the non-replaced limb ($p=0.0287$) while push-off plantarflexion moments were lower in the replaced limb compared to the non-replaced limb ($p=0.0110$). A significant group main effect was present for the ankle push-off plantarflexion moment, with reduced moments in the dissatisfied group compared to the satisfied ($p=0.0005$) and healthy ($p=0.0006$) groups.

Significant interactions were present for the WOMAC total and all subscale scores ($p<0.0007$ for all tests, Table 3). The dissatisfied group showed increased scores for the total and all subscale scores compared to their non-replaced limb and the satisfied and healthy groups. Significant interactions for passive knee flexion ROM revealed reduced ROM for the replaced limb compared to the non-replaced limb for both the dissatisfied and satisfied groups, with additional reductions for both groups compared to the healthy group ($p<0.0041$ for all comparisons). Additional significant interactions were present for all pain measurements ($p<0.0013$ for all tests), with increased pain for the dissatisfied group in their replaced limb compared to their non-replaced limb and both satisfied and healthy groups.

Discussion

The purpose of this study was to examine lower extremity kinematics and kinetics of dissatisfied TKR patients during overground walking in comparison to satisfied TKR patients and healthy participants. The first hypothesis was that the dissatisfied patients would exhibit decreased knee extension moments and increased knee abduction moments in their replaced limb compared to their non-replaced limb. The results of this study were in partial agreement with our first hypothesis. Interactions and post-hoc comparisons did not show any differences between the replaced and non-replaced limbs for knee extension and abduction moments. However, there was a significant limb main effect for the loading-response and push-off knee extension moments, with replaced limb's being lower than the non-replaced limbs. Some studies have reported increased peak knee extension moments (external flexion moments) in healthy controls compared to TKR patients during the loading-response phase (24, 26) while others have reported no difference between patients and healthy controls (20, 25). In this study, there was a significant main group and limb effect for the loading response extension moment, whereby the dissatisfied group had lower extension moments than the satisfied and healthy group and the replaced limb had lower moments than the non-replaced limb. It has been suggested that these reductions are due to a quadriceps avoidance gait pattern and that targeted therapy is necessary to remedy this (25). It should be of note though, that the bi-modal knee extension pattern are more common post-operatively compared to pre-operatively (53), indicating a return to normal movement patterns. In this study, all patients except for one per group displayed a bi-modal knee extension pattern. Despite reduced values, this could be considered a step in the right direction for rehabilitation. Increased quadriceps strength may help with improving ability to handle increased joint loads, although it is unlikely the replaced knee will ever function as well as a non-replaced knee. The dissatisfied group showed decreases in quadriceps strength in their replaced limb compared to their non-replaced limb (Chapter V), suggesting their reduced ability to handle the knee joint loading during gait.

The peak knee extension moment during stance phase has been shown to be reduced in TKR patients compared to healthy controls, likely due to reductions in quadriceps strength and therefore an avoidance pattern, resulting in the hip compensating for the knee (46). This study did not support this hip compensation strategy as no hip extension moments or extension ROM differences were present in either patient group. However, there were differences with respect to sagittal ankle patterns. The dissatisfied and satisfied groups both showed increased ankle dorsiflexion ROM during loading response in their replaced limbs compared to their non-replaced limbs and the healthy group. This may be linked to the reduced knee flexion ROM in both groups. Yet, the satisfied group was able to achieve gait velocity similar to the healthy controls while the dissatisfied group was not.

The flexion ROM during loading was significantly reduced in both dissatisfied and satisfied replaced limbs compared to non-replaced limbs and healthy limbs. This may be in part due to reduced gait velocity and therefore reduced need for knee flexion for dissatisfied patients, but does not hold true for the satisfied patients. Similar amounts of knee flexion ROM have been reported between TKR patients and healthy controls (25, 26), which is not in agreement with this study. This reduction has been seen to carry on for the first year after surgery, with a reduced dependence on the operated knee having been shown at 12 months post-operatively compared to the non-operated limb and healthy controls (46), which still exists for both patient groups in this study at an average of over two years post-operation.

Initially, it should be noted that the dissatisfied group walked with a reduced gait speed compared to the other two groups, averaging 1.16 m/s. This is close to previously reported pre-operative values of 1.13 m/s for TKR patients (25). The reduced speed could be due to the increased pain levels experienced by the dissatisfied group in their replaced limb compared to all other groups, which subsequently has an effect on their level walking profiles. Additional studies have reported no differences in gait velocity at 12-18 months post-operation for TKR patients compared to healthy participants, with velocity being retained at an average of 46 months after surgery (22, 26). This held true for our satisfied TKR participants at an average of 29.3 months after surgery (with no gait velocity differences compared to healthy participants) but not for the dissatisfied patients at 34.6 months after surgery. With this reduction in speed and increase in pain came several other mechanical changes for the dissatisfied patients. An additional decrease in peak push-off plantarflexion moments was present in the dissatisfied group, which may explain the reduced gait velocity. The impairment of the knee extensors also appeared to negatively affect the plantarflexors, which should be further examined in future research.

The second hypothesis, which hypothesized reduced knee extension moments and increased knee abduction moments for the dissatisfied patients compared to the satisfied and healthy participants, was partially confirmed. The loading response knee extension moment showed a group main effect, whereby the dissatisfied group showed reduced moments compared to the satisfied and healthy groups. Additionally the dissatisfied group showed a reduced loading-response knee abduction moment in their replaced limb compared to the dominant limb of the healthy group.

There are mixed results with respect to peak knee abduction moments during gait in the literature. Some research has shown no difference between TKR patients and healthy controls (26), reduced loading-response and push-off peaks (20), and increased peaks in non-replaced limbs compared to replaced limbs but no difference between the replaced limb and healthy controls (38, 114, 138). In this study, only the dissatisfied replaced-limb showed lower peak loading-response abduction moments than the healthy participants, with no other differences evident. This is partially in agreement with previously mentioned research with reduced loading-response peaks (20). Other research has shown at an average of 2 years post-operation, TKR patients showed increased peak abduction moments in their replaced limb compared to healthy controls, but no difference between the replaced and non-replaced limbs or the non-replaced and controls (19). No gait velocity differences were evident, however the knee extension moment was lower in the replaced limb compared to the healthy controls (19). It does illustrate that the TKR patients may undergo a compensatory transformation whereby the load is transferred to another plane. The reduced knee extension moment may have been transferred to the frontal plane. This was not the case for the dissatisfied patients as the reduced gait velocity was experienced along with reduced knee extension moments. This may be indicative of avoiding increased pain associated with increases in frontal-plane medial knee loading.

Asymmetry was a problem for the dissatisfied participants, indicating a failure to perform equally on both limbs. For both 1st and 2nd peak VGRF, the dissatisfied group showed reduced forces on their replaced limb compared to their non-replaced as well as compared to the healthy group. The satisfied group also showed the similar imbalance in their 1st peak VGRF. A return to VGRF symmetry between the two limbs has been previously reported in TKR patients by 12 months after surgery (46), however this was not the case for either patient group in this study. . Asymmetry in the movement pattern often indicates increased dependence on one limb, which can prove problematic as this could lead to the contralateral knee needing replacement, as happens in approximately 40% of TKR patients within ten years (118). A reduction in VGRF in the replaced limb may lead to the non-replaced limb bearing increased overall loading to the body, which can lead to long-term joint health issues. The changes in VGRF can also impact the joint moments, as is evidenced in this study where simultaneous VGRF and knee extension moments were seen for the dissatisfied patients in their replaced limb. Additional reductions in the flexion ROM on the replaced limb contribute to the idea of increased dependence on the non-replaced limb, which may place it at risk for further joint issues.

Pain levels were increased for the dissatisfied patients in their replaced limbs compared to their non-replaced limbs and both other groups. It is well known that higher pain has been associated with lower satisfaction levels (222), which is in agreement with the results of the dissatisfied group in this study. The increased pain levels may have contributed to the quadriceps avoidance pattern, which led to a reduced gait velocity. The total level of pain and function does not seem to be as important to the patient as the relative reduction in overall pain post-surgery (18). While the pain may manifest at the surgery site (i.e. the knee) and subsequently contribute to dissatisfaction, additional factors have been shown to contribute to patient satisfaction, including the need for outside assistance, lack of social interaction, or presence of comorbidities, all of which have been shown to contribute to reduced satisfaction levels (17). Physical comorbidities were controlled for in this study, however psychological issues were not. It may be of benefit to further examine psychological distresses experienced by the patients and how they impact movement and pain profiles. Addressing the psychological issues may help patients to cope with the pain experienced and subsequently the physical limitations. Something similar to guided imagery which can reduce the pain and anxiety experienced post-operatively (232) may help with the psychological issues experienced which contribute to dissatisfaction.

This study is not without its limitations. First, the ages of the TKR groups and healthy controls were different and the age range for each of the three groups was quite wide (50 to 75). This could have potentially influenced the results, although the average age difference was 6 years between the healthy group and the two TKR groups. Additionally, a small sample size was used for the dissatisfied group. This may have impacted the significance of the results and future studies may benefit from increased samples of dissatisfied patients which fit within the inclusion criteria.

Conclusion

In summary, the level ground walking kinematics and kinetics of the dissatisfied TKR patients do differ from satisfied patients and healthy controls. Reductions in peak loading-response knee extension moments and abduction moments were evident in the dissatisfied group.

Additionally, both 1st and 2nd peak VGRF values were reduced in the replaced limb of the dissatisfied group compared to their non-replaced limb, suggesting an asymmetry in limb loading. Future research should examine methods to correct the asymmetrical loading experienced by the patients as a potential means to improve patient satisfaction. This may partially involve pain management as pain was more prevalent in the dissatisfied patients than the satisfied patients. Both rehabilitation methods and implant design improvements should be further evaluated for means of improving patient satisfaction.

Chapter III Appendix: Tables and Figures

Table 1. Peak VGRF (BW) and joint moments (Nm/kg), and knee angle and ROM (°): Mean ± STD.

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
1st Peak VGRF#*	1.03±0.07^AC	1.08±0.07^C	1.08±0.06^AC	1.13±0.08	1.15±0.06	1.14±0.06	**0.0041**
2nd Peak VGRF#*	1.01±0.05^ABC	1.04±0.05	1.07±0.05	1.09±0.05	1.10±0.08	1.09±0.07	**0.0440**
Flexion Loading-response ROM#*	-11.1±6.4^AC	-15.4±3.3	-12.7±5.0^AC	-17.0±5.1	-18.1±4.1	-17.8±4.2	**0.0136**
Loading-response Extension Moment#*	0.42±0.18^BC	0.56±0.32^BC	0.55±0.20	0.70±0.24	0.74±0.22	0.74±0.22	0.1739
Push-Off Extension Mom#	0.16±0.08	0.20±0.10	0.26±0.09	0.26±0.08	0.20±0.11	0.21±0.11	0.0721
Adduction Loading-response ROM*	2.6±1.4	2.7±1.2	2.3±2.4^C	0.9±1.4^C	3.3±1.9	2.2±1.6	0.3317
Loading-response Abduction Moment	-0.42±0.17^C	-0.50±0.08	-0.48±0.13	-0.48±0.14	-0.55±0.13	-0.42±0.13	**0.0248**
Push-Off Abduction Moment	-0.29±0.15	-0.35±0.10	-0.33±0.09	-0.38±0.13	-0.33±0.10	-0.32±0.12	0.1982
Internal Rotation Loading-response ROM	9.8±6.2^A	13.8±6.8	10.6±5.6	9.7±5.1	13.8±6.9	12.5±5.8	**0.0060**
Loading-response Internal Rotation Moment#	0.08±0.05^ABC	0.15±0.09	0.13±0.06	0.15±0.06	0.14±0.05	0.13±0.04	**0.0260**
Push-Off External Rotation Moment*	-0.08±0.04^C	-0.08±0.04	-0.05±0.04^AC	-0.08±0.04^C	-0.13±0.04	-0.12±0.04	**0.0469**

^A Significantly different from contralateral leg of same TKR group, ^B Significantly different from same leg of satisfied TKR group, ^C Significantly different from same leg of healthy group, #Limb main effect, *Group main effect.

Table 2. Ankle and Hip ROM (°) and Joint Moments (Nm/kg): Mean±STD

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
Ankle Dorsiflexion ROM	23.9±2.1^{AC}	20.9±3.9	24.9±3.1^{AC}	22.1±4.3^{C}	18.6±3.9	19.2±3.8	**0.0438**
Loading-response Dorsiflexion Moment$^{\#}$	0.28±0.10	0.25±0.07	0.34±0.10	0.31±0.08	0.32±0.09	0.31±0.07	0.8607
Push-Off Plantarflexion Moment$^{\#*}$	-1.20±0.12^{BC}	-1.25±0.14^{BC}	-1.37±0.14	-1.45±0.13	-1.39±0.14	-1.42±0.11	0.6360
Hip Extension ROM	-34.7±5.4	-35.5±7.9	-34.9±5.3	-35.4±4.4	-38.1±4.0	-38.0±5.0	0.9345
Loading-response Hip Extension Moment	-0.47±0.15	-0.52±0.12	-0.67±0.19	-0.65±0.24	-0.61±0.19	-0.55±0.19	0.1635
Push-Off Hip Flexion Moment	0.56±0.20	0.59±0.16	0.65±0.15	0.65±0.17	0.70±0.19	0.68±0.19	0.7148

^{A} Significantly different from contralateral leg of same TKR group, ^{B} Significantly different from same leg of satisfied TKR group, ^{C} Significantly different from same leg of healthy group, $^{\#}$Limb main effect, *Group main effect.

Table 3. WOMAC Scores Pain for individual tests (0-10 VAS)

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
WOMAC Total#*	794.9±484.2[ABC]	67.2±64.5	251.2±179.2[C]	196.5±175.8[C]	29.9±73.5	18.5±40.2	**<0.0001**
WOMAC Physical Function#*	525.2±323.9[ABC]	38.3±30.3	179.2±141.3[C]	144.5±131.1[C]	16.1±39.3	12.5±26.8	**<0.0001**
WOMAC Stiffness#*	76.1±58.3[ABC]	8.2±8.6	38.1±41.8[C]	26.8±44.4	6.5±18.3	2.9±6.3	**0.0007**
WOMAC Pain#*	193.7±138.6[ABC]	20.7±34.0	33.9±30.1	25.1±22.8	7.3±17.3	3.1±7.6	**<0.0001**
Walking Replaced limb#*	1.94±1.98[ABC]	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**<0.0001**
Walking Non-replaced limb#*	1.78±1.77[ABC]	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**<0.0001**

[A] Significantly different from contralateral leg of same TKR group, [B] Significantly different from same leg of satisfied TKR group, [C] Significantly different from same leg of healthy group, #Limb main effect, *Group main effect.

CHAPTER IV

STAIR AMBULATION PATTERNS AND ASYMETRICAL LOADING OF DISSATISFIED TOTAL KNEE REPLACEMENT PATIENTS

Abstract

Total knee replacement (TKR) patients have shown alterations in lower extremity biomechanics in comparison to healthy controls during stair ascent and stair descent. However, it is unknown how dissatisfied TKR patients differ from satisfied TKR patients and healthy controls during more difficult activities such as stair negotiation. Therefore, the purpose of this study was to compare knee biomechanics of dissatisfied TKR patients to satisfied TKR patients and healthy controls during stair ascent and descent. Nine dissatisfied and fifteen satisfied TKR patients and fifteen healthy controls participated, completing stair ascent and descent trials on an instrumented stair case. A 2 x 3 ANOVA was used to analyze biomechanical differences between groups and limbs during both activities. Dissatisfied patients showed reduced 2nd peak VGRF and loading-response knee extension moments in their replaced limb compared to their non-replaced limb and to satisfied and healthy groups during stair ascent. 1st peak VGRF and both loading-response and push-off abduction moments showed reduced values in replaced limbs compared to non-replaced limbs for all groups. During stair descent, the dissatisfied group showed reduced loading-response and push-off knee extension moments in their replaced limb compared to their non-replaced limb and the healthy group. Additional reductions in the loading-response and push-off abduction moments in the dissatisfied group compared to the healthy group were evident. The loading-response knee extension and abduction moments were also reduced in the dissatisfied group compared to the satisfied group. Increased pain was present in the replaced knee of the dissatisfied patients compared to both other groups. Future research should examine ways to improve the symmetrical loading of the dissatisfied patients and to alleviate the pain experienced during stair negotiation as a means of improving patient satisfaction.

Keywords: total knee replacement, arthroplasty, stair biomechanics, asymmetry, satisfaction

Introduction

Stair climbing is a common activity of daily living (31) and one of the most difficult tasks for older adults (32) due to the increased muscle and joint demands (29, 30). As patients reach end-stage knee osteoarthritis, many frequently report difficulty with climbing stairs (33). Stair climbing is also measured by most survey tools [including the Western Ontario and McMaster University survey (WOMAC) and the Forgotten Joint Score (FJS)] used on the total knee replacement (TKR) population (5, 34, 35), thereby suggesting its importance in everyday life for most people. However, stair negotiation is less commonly studied in the TKR population compared to level ground walking.

During stair ascent and descent, knee flexion range of motion (ROM) has been frequently shown to be reduced in TKR patients compared to healthy controls (22, 36, 37), although one study did report no differences between the two groups (19). TKR patients have shown reduced peak knee extension moments during stair ascent, which is often coupled with a reduction in speed (24), although this specific study did not investigate stair descent. Another study has shown reductions in loading-response knee extension moments during stair ascent with no reductions in gait speed compared to healthy controls (19). Gait speed, for example, has been shown to increase post-operatively for TKR patients compared to pre-operative levels, however, gait speed does not always reach levels equal to those of healthy controls at one year post-operation (15, 38). Other studies have shown no differences between the two groups though, with TKR patients maintaining their speed from 12-18 months as far as 46 months after surgery (22, 26). Knee adduction angles have shown no differences for TKR patients compared to healthy controls but an increased push-off peak knee internal abduction moment (KAM) was present during stair ascent (19). Other studies have shown mixed results with some showing increased KAM values (39) and some showing values equal to (41, 42) or reduced compared to healthy controls (40, 41). A shift in joint loading has been seen with reduced knee extension moments sometimes being ”transferred” to KAM (19) in an effort to keep up gait speed and compensate for a reduced capacity in loading the knee joint.

Asymmetrical gait patterns can be problematic for TKR patients as the imbalance can cause issues for the contralateral knee. Approximately 40-50% of unilateral TKR patients have their contralateral knees replaced within ten years (118, 233). An examination of asymmetries in older asymptomatic older adults revealed small insignificant levels of imbalance for the 1st and 2nd peak vertical ground reaction force (VGRF) during stair ascent (4.1% and 6.8%, respectively) and stair descent (8.5% and 6.3%, respectively), suggesting well-balanced movement between limbs with respect to loading (234). VGRF symmetry comparisons between TKR patients and healthy controls revealed no significant differences, although there were evident reductions in 2nd peak VGRF levels for TKR patients during preferred walking speeds (235). However, most comparisons on TKR symmetry has been related to ground reaction force or temporal gait characteristics, with no studies to date on joint kinematics and kinetics. This information may provide added insight into the mechanical deficits between limbs for TKR patients.

For the dissatisfied TKR population, deficits in their movement profiles may be further enhanced during more difficult activities (such as stair negotiation), suggesting a need for examination of these activities. To date, no studies have been conducted examining the three-dimensional biomechanical profile of dissatisfied TKR patients during stair ascent and descent activities. Therefore, the purpose of this study was to compare the knee biomechanics profiles of stair ascent and descent for dissatisfied TKR patients to satisfied TKR patients and healthy older-adult controls. It was hypothesized that dissatisfied TKR patients would exhibit decreased knee extension moments and increased knee abduction moments in their replaced limb compared to their non-replaced limb and compared to the satisfied TKR patients and healthy controls during stair ascent and descent.

Materials and Methods

Participants

Participants were recruited from a local orthopaedic clinic: nine dissatisfied TKR patients (68.0±4.2 years, 1.69±0.07m, 80.99±18.59 kg, 34.6±14.3 months since surgery) and fifteen satisfied TKR patients (66.6±6.3 years, 1.76±0.10m, 90.19±16.98 kg, 29.3±12.8 months since surgery). Fifteen healthy controls (60.7±9.2 years, 1.75±0.09m, 77.74±11.75 kg) were recruited with the same exclusion criteria as the TKR groups. The inclusion criteria for TKR patients were having a unilateral total knee replacement (conducted by a single surgeon) at least 12 months but less than 60 months prior to testing and between the ages of 50 and 75 at the time of testing. Potential participants were excluded if they had any additional lower extremity joint replacements, any additional diagnosed osteoarthritis of the hip, knee, or ankle, BMI greater than 38, or neurological diseases. TKR patients were then asked (with a 5-point Likert scale available for response), “How satisfied are you with your total knee replacement?” “Neutral” responses were excluded. Any participant who responded “very dissatisfied” or “dissatisfied” was placed into the dissatisfied group and participants who answered “satisfied” or “very satisfied” were placed into the satisfied group.

Instrumentation

A twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain three-dimensional (3D) kinematics during all testing sessions. All participants wore standardized running shoes (Noveto, Adidas, Herzogenaurach, Germany). Anatomical retroreflective markers were placed bilaterally on the acromion processes, iliac crests, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads, and 2nd toe. Four retroreflective markers clustered on a semi-rigid thermoplastic shell was placed on the lateral aspects of both shanks and thighs, and on the posterior aspect of the pelvis and the thoracic cage, attached via an elastic neoprene wrap. A cluster of three retroreflective markers was placed on the dorsal aspect of both shoes and affixed by duct tape. Anatomical and tracking markers were kept on for the static trials and anatomical markers were removed prior to testing trials. An instrumented 3-step stair case (FP-Stairs, American Mechanical Technology Inc., Watertown, MA, USA) was used in conjunction with two force platforms (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA) to measure the ground reaction force (GRF) and moments of forces (19). The FP-Stairs were independently bolted to the two force platforms. An additional two non-instrumented customized wooden steps and a landing platform were used to ensure continuous motion after the instrumented steps (Figure 1). Each step had a depth of 29.9 cm, a width of 60.0 cm, and a rise of 17.8 cm. A handrail was available in case of loss of balance (right side during ascent and left side during descent). Walking speed during all trials was monitored by two sets of photo cells (63501 IR, Lafayette Instrument Inc., IN, USA) placed on the 1st and 4th steps and electronic timers (54035A, Lafayette Instrument Inc., IN, USA).

Experimental Procedures

On day one, all participants signed an informed consent form, completed a physical activity readiness survey (PAR-Q) to assess cardiovascular risks to exercise, and completed a WOMAC for both knees (178)and TKR participants also completed an FJS (158). Following completion of the surveys, all participants completed a five-minute walking warm up on a treadmill at a self-selected speed. Participants were then fitted with the retroreflective marker set described earlier. Participants then performed three practice stair ascent and descent trials at a self-selected speed. The practice trials were to familiarize themselves with the stair set up and to collect average ascent and descent speeds. Participants took three steps over level ground, allowing achievement of a consistent level walking speed prior to stair ascent. A speed range (mean ascent/descent speed ± 5%) was used to control participant speed during experimental trials. All subjects then performed five trials in four different conditions: with the replaced limb (TKR) or right limb (healthy) on second step (step of interest) during stair ascent, with the non-replaced limb (TKR) or left limb (healthy) on second step during ascent, with the replaced limb (TKR) or right limb (healthy) on second step during descent, and with the non-replaced limb (TKR) or left limb (healthy) on second step during descent. The testing order of the limbs were randomized, although a descent condition always followed an ascent condition in order to minimize the number of required trials for the TKR participants. Subjects were asked to perform the stairs in a step over manner. A trial was considered successful if the predetermined speed range was met, and a step-over manner gait was utilized. A handrail was provided for balance purposes if needed, but not for propulsion. Unsuccessful trials were repeated. On day two, participants completed a five-minute warm up walking on a treadmill at a self-selected speed. Two trials of a stair ascent/descent test using an 11-step stair case and a chair rise test were performed, with the best times being reported. A numerical visual analogue pain (VAS) scale was used to assess pain in both knees for TKR subjects and healthy subjects at the end of the test conditions.

Data Analyses

Visual3D biomechanical analysis software suite (version 5.0, C-Motion, Inc., Germantown, MD, USA) was used for 3D kinematic and kinetic variable computations for stair ascent/descent data. A Cardan rotational sequence (X-y-z) was used for 3D angular kinematics computations and the conventions of the angular kinematic and kinetic variables were defined using the right-hand rule. Positive values indicate ankle dorsiflexion, inversion, and internal rotation, knee extension, adduction, and internal rotation, and hip flexion, adduction, and internal rotation angle, ROM and internal joint moments. Kinematic and GRF data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 8Hz before kinematics and joint moment calculations. Raw GRF were filtered separately using a fourth-order low-pass Butterworth filter with a cut-off frequency of 50 Hz to calculate GRF variables. Critical events and values, including peak VGRF, knee extension, abduction, and internal rotation moments, loading-response knee flexion, adduction, and external rotation ROM, and sagittal plane hip and ankle ROM and moments, were chosen using customized computer programs (VB_V3D and VB_Table, MS Visual Basic 6.0, USA). Joint moments represent internally applied moments, were reported in the proximal reference system and were normalized to body mass (Nm/kg). GRF variables were normalized to body weight (BW). Averages across the five trials of selected variables for every condition for each participant were used in statistical analyses.

Asymmetry indices (AI) were calculated to quantify asymmetries for peak VGRFs and knee extension moments using the equation (236).

$$AI = \frac{X_R - X_N}{\frac{1}{2}(X_R - X_N)} \times 100\%$$

where X_R is the replaced limb of the TKR patients or the dominant limb of the healthy subjects and X_N is the non-replaced limb or non-dominant limb of the healthy controls. An AI value of zero indicates perfect symmetry, negative values indicate non-replaced limb dominance, and positive values indicate replaced limb dominance.

Statistical Analyses

A 2x3 (limb x group) mixed model analysis of variance (ANOVA, $p<0.05$) was performed to detect differences between limbs and groups for kinematic and kinetic variables, using SAS 9.4 (Cary, NC, USA). A one-way ANOVA ($p<0.05$) was performed on AI, demographic, survey, and functional test data to test for differences between the three groups. When the ANOVA revealed a significant interaction or main effect, post-hoc comparisons with Bonferroni adjustments were evaluated using adjusted p values of 0.00625 for 2x3 ANOVA comparisons and 0.0167 for 1x3 ANOVA comparisons. Post hoc comparisons were only made between the TKR replaced limbs and healthy dominant limbs and TKR non-replaced limbs against the healthy non-dominant limbs. This was performed under the assumption that any differences between the dominant and non-dominant limb are random and small when present in the healthy population.

Results

During both stair ascent and descent trials, the dissatisfied group walked significantly slower than both the satisfied and healthy groups ($p=0.0006$ and $p=0.0005$, respectively) at preferred gait speeds. In the stair ascent condition, the dissatisfied group (0.53±0.16 m/s) was approximately 40% slower than the satisfied group (0.74±0.10 m/s) and 30% slower than the healthy group (0.69±0.12 m/s, $p<0.0099$ for both tests). In the descent condition, the dissatisfied group (0.45±0.17 m/s) was approximately 40% slower than both the satisfied (0.64±0.08 m/s) and healthy (0.63±0.09 m/s, $p<0.0008$ for both tests) groups. Additionally, during the stair ascent and descent functional tests, the dissatisfied group was significantly slower than the satisfied and healthy groups ($p<0.0117$ for both tests).

Significant interactions were present during stair ascent trials for 2nd peak VGRF, peak loading-response knee extension moment, knee abduction ROM, and peak loading-response internal rotation moment (Table 4). Post-hoc analysis revealed that the dissatisfied group had lower 2nd peak VGRFs compared to their non-replaced limb and both the satisfied and healthy groups ($p<0.0040$ for all tests). The peak loading-response extension moment was lower in the replaced-limb of the dissatisfied group compared to their non-replaced limb and both the satisfied and healthy groups ($p<0.0041$ for all tests). For all four significant interactions, the satisfied group was different in their replaced limb compared to their non-replaced limb, experiencing reduced VGRF, peak loading-response extension moment, and peak loading-response internal rotation moments along with an increased knee abduction ROM ($p<0.0038$ for all tests). In addition, significant limb main effects were present in the 1st peak VGRF, peak loading-response abduction moment, and peak push-off abduction moment, with the replaced limbs showing reduced values compared to the non-replaced limbs for all three variables (Table 4).

During stair descent, significant interactions were present for the peak loading-response and push-off knee extension moment, peak abduction moment, and knee internal rotation ROM (Table 5). The peak loading-response extension moment was reduced for the replaced-limb of the dissatisfied group compared to their non-replaced limb and to both the satisfied and healthy groups ($p<0.006$ for all tests). The peak push-off extension moment was reduced in the replaced limb of the dissatisfied group compared to their non-replaced limb and the healthy group ($p<0.0032$ for both tests), but not the satisfied group. The satisfied group showed a reduced peak push-off extension moment in their replaced limb compared to their non-replaced limb. The peak loading-response abduction moment was lower in the dissatisfied replaced limb compared to the satisfied and healthy groups ($p<0.0048$). The peak push-off abduction moments were lower in the replaced limb of the dissatisfied group compared to the healthy group and higher in the non-replaced limb compared to the healthy group ($p<0.00111$ for both). Internal rotation ROM was reduced in the replaced limb of the dissatisfied group compared to their non-replaced limb ($p=0.0010$). A significant group main effect was present for 1st peak VGRF, with the dissatisfied group showing reduced VGRF compared to the satisfied group, with neither group being different from the healthy group. Significant limb main effects were present with the 2nd peak VGRF and internal rotation moments were reduced in the replaced limbs compared to the non-replaced limbs while the adduction ROM was increased in the replaced limbs compared to the non-replaced limbs.

During stair ascent, AIs revealed a significantly increased 2nd peak VGRF for the dissatisfied patients compared to healthy controls (Table 6). The AI in the loading-response extension moment during ascent was increased in the dissatisfied group compared to both the satisfied and healthy groups. During stair descent, the AI was increased in the dissatisfied group for both the loading response and push-off knee extension moments compared to the healthy group.

Discussion

The purpose of this study was to examine the knee biomechanics profiles of dissatisfied and satisfied TKR patients in comparison to healthy controls. It was hypothesized that dissatisfied patients would exhibit decreased knee extension moments and increased knee abduction moments in their replaced limb compared to their non-replaced limb and both the satisfied and healthy groups. The dissatisfied group did show reduced peak loading-response knee extension moments during both stair ascent and descent in their replaced limb compared to their non-replaced limb and both the satisfied and healthy groups, partially confirming our hypothesis about the knee extension moments. During stair descent, the peak push-off knee extension moment was reduced in the replaced limb of the dissatisfied group compared to their non-replaced limb and the healthy group, also providing partial confirmation of our hypothesis for knee extension moments.

Stair climbing has been shown to have increased demands on the involved muscles and joints compared to activities such as walking (29), thereby highlighting the increased difficulty of the task. External knee flexion moments have been reported as greater during stair ascent than walking (131), indicating the increased knee joint demands. Some studies have reported reduced knee extension moments during stair ascent for TKR patients compared to healthy controls (24, 39-41), which is in agreement with our results. However, some studies have reported no differences in knee extension moments (22, 36, 42), although it should be noted that these studies did not report gait speed. During similar gait speeds, one study showed no difference in either loading-response or push-off knee extension moments (127), while an additional study showed reduced loading-response knee extension moments in the replaced limb compared to the non-replaced but no push-off differences during stair ascent (19). Reduced knee extension moments have been often related to a quadriceps avoidance gait due to weaker quadriceps muscles and a desire to avoid loading the knee joint (24, 129). The dissatisfied patients showed reduced peak loading-response knee extension moments during stair ascent (over 30% reduction compared to satisfied and healthy groups) coupled with a reduced gait speed of over 30% in comparison to the satisfied and healthy groups. This may in part be due to reduced quadriceps strength, which has been shown to be reduced in the dissatisfied group (Chapter V).

Similar discrepancies have been reported during stair descent with one study showing reduced knee extension moments in TKR patients compared to healthy controls (22) while other studies have reported no differences (36, 40, 127). Reductions in knee extension moments have been shown to occur during simultaneous reductions in gait speed for TKR patients (24, 39-41), which may help to partially explain the reductions in the dissatisfied patients. Dissatisfied patients walked over 30% slower than both the satisfied and healthy groups during stair descent and had peak loading-response knee extension moment reductions of over 40%. Past research has shown that speed is not always the cause of reduction in knee extension moments as reductions in peak knee extension moments have been evident compared to the non-replaced limb with no speed differences compared to healthy controls (19), suggesting increased compensation from the non-replaced limb. This was not the case for the dissatisfied group as the increases in their non-replaced limb peak extension moments during ascent and descent (which were not different from the other two groups) were not big enough to accommodate an increased speed. Some research has shown similar speeds in TKR patients compared to healthy controls (19) while others have reported reductions in speed for TKR patients during stair ascent (24, 39-41). In the current study, satisfied TKR patients had similar gait speeds during stair ascent and descent compared to healthy controls, but the dissatisfied group had reduced gait speed in both conditions. However, pain levels were significantly increased in the replaced limb of the dissatisfied group compared to their non-replaced limb and both the satisfied and healthy groups. The increased pain may have been a barrier to increasing their replaced limb knee extension moments and therefore their gait speed, despite higher moments in their non-replaced limbs to compensate for the replaced limb in generation of desired speed.

Asymmetries may offer an additional insight in examining the knee biomechanics of unilateral TKR patients. Loading-response knee extension moment AIs were increased in the dissatisfied group (-48%) during stair ascent compared to the satisfied and healthy groups (-14% and 3%, respectively). During stair descent, both loading-response (-55%) and push-off (-33%) knee extension moment AI values were increased compared to healthy controls (16% and 3%, respectively). The contralateral knee has been reported as the most common joint for replacement after a primary TKR (118, 233, 237), with 40-50% needing the contralateral replacement within ten years of the primary TKR (118, 233)(118, 233). Asymmetrical loading in the joint can contribute to this as some patients will have increasing dependence on their non-replaced limb. Sagittal plane knee moments have been shown as lower in the replaced limb compared to the non-replaced limb in measures of asymmetry (238), which is evident in both TKR groups during stair ascent and descent in this research. Of more significance though is the increased levels of asymmetry in the dissatisfied group. During stair ascent, the loading-response extension moment AI was significantly higher in the dissatisfied group (-48%) compared to both the satisfied (-14%) and healthy (3%) groups. During stair descent, both the loading-response and push-off knee extension moments AI were also higher for the dissatisfied group (-55% and -33%, respectively) compared to the healthy group (16% and 3%, respectively). The standard deviations of these AIs were quite high for the TKR groups, suggesting large variability. This is something that should be further examined in patients during their recovery process in order to minimize the risk of future contralateral TKR surgery. Peak VGRF AI values were not different between the three groups, except for the 2nd peak VGRF, whereby the dissatisfied group was higher than the healthy group, although the differences were much smaller than the peak knee extension moment AI values. This is in agreement with previous research which has shown 1st and 2nd peak VGRF asymmetries of 4.1% and 6.8%, respectively, during stair ascent and 8.5% and 6.3%, respectively during stair descent has been shown in asymptomatic older adults (234), suggesting a fairly equal limb balance. These values were higher than those reported for healthy controls in this study, but similar to those reported by the TKR groups. This lack of difference is in agreement with other research which has shown no difference in AI between TKR patients and controls during preferred walking speed (235). So while force loading may be the relatively symmetrical, how the joints are loaded still appears different given the different joint moment SI values. This is further evidence for monitoring the symmetry of patients during their recovery from a TKR procedure. In addition to the reduced speed and given relatively equal overall loading but reduced knee extension moment symmetry, this likely means the forces are being placed onto other joints to compensate for the replaced knee, which may be examined in future research.

The changes in joint moments were accompanied with some changes in the VGRF levels. First peak VGRF levels have been shown to be higher during stair descent than stair ascent (117, 119) and 2nd peak VGRF higher during ascent than descent (117), which is consistent with the results here. During stair ascent, there were no differences in 1st peak VGRF, but decreases in the 2nd peak VGRF in the replaced limb of the dissatisfied group compared to their non-replaced limb and the satisfied and healthy groups. A group main effect was present for the 1st peak VGRF during stair descent, with the dissatisfied group showing lower VGRF values than the satisfied group, which also contributes to a reduced gait speed. What is of further interest is that knee extension ROM during stair ascent has been shown as reduced in TKR patients compared to healthy controls in multiple studies (22, 36, 37, 39-41) as has knee flexion ROM during stair descent (22, 36), however this was not the case for either TKR group during stair ascent or descent, as no ROM differences were evident. ROM limitations during more advanced tasks such as stair climbing do not seem to be an issue for the dissatisfied population and this further suggests that the pain they experience is likely not related to the motion of the knee, but the loading of the joint experienced through the joint moments. The lack of ROM differences is in agreement with other studies which have shown no difference when comparing TKR patients to healthy controls during stair ascent (22) and comparing replaced to non-replaced limbs (37). During stair descent, no differences have also been reported comparing TKR patients to healthy controls (40) and their non-replaced limbs (37). However, there seem to be more studies with reported differences, suggesting further examination is needed to determine what causes the ROM differences.

Peak loading-response abduction moments were not different between groups during stair ascent while peak loading-response abduction moments during descent were reduced in the replaced limb of the dissatisfied compared to the satisfied and healthy group. Peak push-off abduction moments were reduced in the replaced limb of the dissatisfied group compared to the healthy group, providing partial confirmation of our hypotheses with respect to frontal plane joint moments. Past research has been mixed with respect to frontal plane knee joint moments, as it has been suggested that increased loading in the frontal plane occurs in order to increase stability in the frontal plane of the replaced knee (19). Results with respect to this are mixed, as some research has shown similar loading-response abduction moment results between replaced limbs and healthy controls during stair ascent (19, 40, 41) but push-off moments have been shown to increase in the replaced limb (19) by some research and reduced or no difference in other research (28, 40, 41). These results are in partial agreement with this research as there were no differences in either loading-response or push-off abduction moments in the dissatisfied group compared to either the satisfied or healthy group (although a significant limb interaction existed showing reduced loads in the replaced limbs compared to the non-replaced limbs). Frontal plane joint moments have been suggested to play an important role in stability and propulsion during stair ascent (19, 29, 131). In this instance, stability may be a factor as the dissatisfied group did not have different abduction moments from the other two groups but still showed reduced speed, suggesting the moments were employed for stability and not propulsion.

During stair descent, the internal abduction and external adduction moments have been reported as no different in TKR patients compared to healthy controls (40, 42), which is not in complete agreement with this study. Both loading-response and push-off abduction moments were reduced in the dissatisfied group compared to the healthy group. Additionally, the replaced limb of the dissatisfied group was lower than the satisfied group. Knee abduction moments have been shown to be similar or reduced to healthy controls whether a posterior stabilized or mobile bearing design is used (40-42, 54), so it is unlikely that implant design is a factor. In this study, of the nine dissatisfied patients, seven had cruciate retaining (CR) designs and three had posterior stabilized (PS) designs. Of the 15 satisfied patients, ten had CR designs, three had PS designs, and two had bi-cruciate stabilized designs. The more likely scenario is the reduced gait speed during stair ascent and increased pain levels forced the dissatisfied group to adjust their gait patterns in order to try to alleviate pain and maintain their stability during a much more difficult task such as stair descent.

In addition, the objective results presented in this study were also supported by the subjective WOMAC and FJS scores for the dissatisfied group, which were worse compared to the satisfied group. The dissatisfied group reported increased scores for all WOMAC subscales and the total score in their replaced limb, indicating perceived reduced functional ability, increased joint stiffness, and increased pain (see Chapter V). Their joint awareness, as evidenced by the FJS, was significantly higher than the satisfied group, which may indicate an increased discomfort and reduced ability of the joint to perform normally, as the dissatisfied patients are more frequently aware of its presence. The increased WOMAC scores are in agreement with previous literature (9, 194), with this research indicating that not only are the dissatisfied patients subjectively worse, but also have physical moment alterations.

In this study, there were three instrumented steps with which analysis could have been performed. The second step was chosen as the step of interest as previous research has shown that the 1st step is different in terms of sagittal plane kinematics and kinetics in comparison to the 2nd and 3rd steps (120). The first step has been suggested to be a transition step from the level ground walking (239) which occurs prior to the stair case and as such should not be compared with the 2nd and 3rd steps, which have been shown to be similar (120). Additionally the size of the steps could have an impact on the biomechanical factors, but the dimensions of the steps in this study are similar to those of past research (126). Therefore we employed the second step as our step of interest because it should be similar to the 3rd step.

This study has some limitations. First, stair climbing can be a difficult activity and as such, we sought to make it as safe for our dissatisfied patients as possible. We did permit the use of the handrail on our stair case for balance purposes, which may have affected the kinematics and kinetics of some of the subjects in this study (two of the nine dissatisfied patients and one of 15 satisfied patients employed the handrail, and they were adamant they did not use it for anything other than reassurance). However, we did not allow the use of the handrail for propulsion purposes. Additionally, a step over manner was employed, which may be different than some of these patients are used to when performing stair ascent and descent activities.

Conclusion

In summary, dissatisfied TKR patients do show different knee biomechanics than satisfied TKR patients and healthy controls as well as between their replaced and non-replaced limbs. Reduced gait speed, increased pain levels, and asymmetrical joint loading were evident in the dissatisfied group. Future research should examine ways to improve the loading symmetry and to alleviate the pain levels experienced by the dissatisfied patients in stair climbing related tasks. This may help to improve the ability of the dissatisfied patients to handle increased knee joint loads and restore functional abilities.

Chapter IV Appendix: Tables and Figures

Table 4. GRF and Knee Kinematics/Kinetics during Ascent

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
1st Peak VGRF#	0.93±0.07	1.01±0.04	0.99±0.04	1.01±0.07	1.02±0.11	1.04±0.08	0.3075
2nd Peak VGRF#*	1.03±0.09^ABC	1.12±0.09^C	1.16±0.07^A	1.22±0.11^C	1.14±0.11	1.14±0.11	**0.0338**
Extension ROM	53.4±4.9	57.0±5.4	55.3±5.3	56.3±4.5	57.3±4.3	57.1±4.8	0.3572
Loading-response Extension Moment#*	0.75±0.31^ABC	1.11±0.26	1.08±0.26^A	1.23±0.23	1.23±0.24	1.19±0.27	**0.0003**
Abduction ROM#	-11.8±7.4	-12.2±6.7	-15.9±4.9^A	-9.3±5.3	-13.9±9.1	-12.5±8.0	**0.0296**
Loading-response Abduction Moment#	-0.36±0.16	-0.48±0.14	-0.35±0.15	-0.40±0.17	-0.39±0.20	-0.50±0.15	0.6838
Push-off Abduction Moment#	-0.33±0.20	-0.35±0.20	-0.27±0.18	-0.44±0.24	-0.18±0.13	-0.44±0.16	0.1561
Internal Rotation ROM	6.2±5.2	5.4±4.4	2.3±4.2	4.7±3.9	2.0±3.5	3.1±4.8	0.2916
Loading-response Internal Rotation Moment#	0.23±0.16	0.30±0.22^C	0.24±0.17^A	0.38±0.18	0.13±0.10	0.46±0.13	**0.0176**

^A Significantly different from contralateral leg of same TKR group, ^B Significantly different from same leg of satisfied TKR group, ^C Significantly different from same leg of healthy group, #Limb main effect, *Group main effect.

Table 5. GRF and Knee Kinematics/Kinetics during Descent

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
1st Peak VGRF*	1.24±0.25[B]	1.34±0.19[B]	1.52±0.19	1.59±0.19	1.44±0.09	1.43±0.09	0.2213
2nd Peak VGRF#	0.91±0.05	0.97±0.09	0.87±0.05	0.93±0.07	0.89±0.10	0.88±0.09	0.0600
Flexion ROM	-82.5±3.7	-83.2±3.3	-78.8±5.7	-80.5±5.9	-80.8±5.6	-79.8±5.6	0.1576
Loading-response Extension Moment*	0.39±0.22[ABC]	0.69±0.34	0.74±0.23	0.83±0.29	0.85±0.31	0.72±0.26	**0.0079**
Push-off Extension Moment#	0.78±0.17[AC]	1.09±0.27	0.88±0.26[A]	1.05±0.23	0.96±0.18	0.93±0.16	**0.0022**
Adduction ROM#	11.2±6.9	8.6±3.4	10.4±5.3	6.8±2.8	8.5±3.4	7.6±2.5	0.4620
Loading-response Abduction Moment	-0.40±0.17[BC]	-0.56±0.13	-0.61±0.21	-0.55±0.23	-0.70±0.19	-0.37±0.14	**0.0002**
Push-off Abduction Moment	-0.35±0.19[C]	-0.48±0.18[C]	-0.41±0.18	-0.36±0.14	-0.51±0.11	-0.26±0.11	**0.0002**
Internal Rotation ROM#*	9.5±2.1[AB]	13.1±2.5[BC]	6.6±2.9	8.2±3.8	8.3±3.5	8.2±2.8	**0.0186**
Loading-Response Internal Rotation Moment#	0.10±0.04	0.13±0.10	0.13±0.06	0.17±0.08	0.08±0.05	0.15±0.05	0.4313
Push-off Internal Rotation Moment#	0.14±0.07	0.20±0.10	0.18±0.08	0.20±0.07	0.12±0.05	0.20±0.06	0.2498

[A] Significantly different from contralateral leg of same TKR group, [B] Significantly different from same leg of satisfied TKR group, [C] Significantly different from same leg of healthy group, #Limb main effect, *Group main effect.

Table 6. Symmetry Index for knee kinematics and kinetics during stair ascent

	Dissatisfied	Satisfied	Healthy	p-value
1st Peak VGRF (Ascent)	-8.74±6.66	-2.39±8.66	-2.74±13.56	0.3132
2nd Peak VGRF (Ascent)	-8.27±5.82[B]	-5.37±8.30	-0.24±6.51	0.0274
Loading-Response Extension Moment (Ascent)	-48.13±43.68[AB]	-14.10±23.86	3.74±13.74	0.0002
1st Peak VGRF (Descent)	-8.61±14.91	-4.95±13.92	0.96±7.03	0.1554
2nd Peak VGRF (Descent)	-5.67±10.29	-6.45±7.88	0.19±7.52	0.0816
Loading-Response Extension Moment (Descent)	-55.24±39.16[B]	-9.35±58.74	16.35±24.79	0.0029
Push-off Extension Moment (Descent)	-33.13±22.20[B]	-17.75±32.03	2.73±14.52	0.0036

[A] Different from satisfied group, [B] Different from healthy group

Figure 1. The staircase with the instrumented steps (steps 1-3) and non-instrumented steps (steps 4-5) for continuous motion with a landing platform.

CHAPTER V

STRENGTH AND BALANCE DEFICITS AFFECTING PATIENT SATISFACTION FOR TOTAL KNEE REPLACEMENTS

Abstract

Knee strength is a common part of the total knee replacement (TKR) rehabilitation process as an increase in knee strength is crucial for an increase in functional abilities. In addition to strength, balance is an additional measure of TKR operation success. However, it is unknown how dissatisfied TKR patients differ from satisfied TKR patients with respect to strength and balance abilities. Therefore, the purpose of this study was to examine how knee flexor and extensor strength, balance abilities, and deep knee flexion biomechanics differ for dissatisfied TKR patients compared to satisfied patients and healthy controls. Nine dissatisfied and fifteen satisfied TKR patients and fifteen healthy controls participated in this study, performing isokinetic knee flexion and extension tests at 60°/s and 180°/s, bilateral and unilateral static and dynamic balance trials, bilateral deep knee flexions, stair ascend/descend tests, and a chair rise test. Dissatisfied patients showed reduced peak extension (180°/s) and flexion (60°/s) torque compared to satisfied patients. No balance differences were evident, although an increased percentage of dissatisfied patients were unable to complete the static and dynamic unilateral balance tests. Reduced knee extension moments were evident in the replaced limb of the dissatisfied group compared to their non-replaced limb and both satisfied and healthy groups. Stair ascent and descent times and pain levels were increased in the dissatisfied group compared to both other groups. An increase in strength may provide a more symmetrical movement pattern and therefore better function. Future research should further examine the improvements in strength and its subsequent effect on function and improving patient satisfaction.

Keywords: total knee replacement, arthroplasty, isokinetic strength, balance, deep knee flexion

Introduction

Current research on the dissatisfied patients who undergo a total knee replacement (TKR) has largely focused on survey data and limited on testing of physical functions and capacities (16-18). Survey data has shown increased difficulty in certain activities for dissatisfied TKR populations (223) but has failed to provide additional insight into the magnitude as well as the mechanisms of why these activities are more difficult for the dissatisfied population. For example, stair climbing has been suggested as a difficult activity for patients with knee problems (33), however the physical mechanisms causing difficulty are unknown. Increased strength and balance abilities are needed in order to successfully perform more demanding daily activities such as navigating stairs and therefore information about strength and balance for dissatisfied TKR populations may provide insight into the difficulties experienced by dissatisfied TKR patients. Some more challenging daily activities require higher levels of knee flexion and increased internal knee extension moments, which is often difficult for TKR patients (11, 230).

An increase in in knee strength levels following a TKR operation is crucial for a return to more normal function levels. Quadriceps strength is the most commonly assessed strength variable for TKR patients: however, the hamstrings are also important for stabilizing the knee, warranting their examination as well. Significant reductions in quadriceps and hamstrings strength are evident early (one-month post-operatively) in the rehabilitation process, with upwards of 60% deficits observed compared to pre-operative levels (44). By six months post-operation, both muscle groups show significant increases in strength (45). However, TKR patients do not normally achieve strength levels equal to those of healthy controls, with deficits still present 12 months after surgery in the replaced limb but no difference in the non-replaced limb compared to healthy controls (46). While most studies examine strength levels within one year post-operatively, one study has shown reduced peak quadriceps and hamstrings torques at 180°/s at an average of 98 months post-operative (36), suggesting that reduced strength still persists over time. Multiple studies involving isokinetic strength testing for this patient group has commonly employed testing speeds of 60°/s and 180°/s (36, 142, 146). There is a lack of research on strength with respect to TKR patient dissatisfaction. Strength deficits post-operatively may be more pronounced in dissatisfied patients, which may impair functional ability.

Balance is an additional measure of success for TKR operations and return to normal daily activities as falls can be detrimental to the TKR patients (47). TKR patients have been shown to have decreased stability after surgery compared to healthy controls (48). Improvements in balance have been associated with improvements in functional capacities commonly tested in stair climb, 30 second chair rise, timed-up-and-go, and improvements in gait speed (49). Strength and balance have been often measured together as a means of using strength gains to explain changes in balance abilities. Increased knee extensor strength coupled with an increased gait speed has led to increased anteroposterior (AP) balance (measured through the range of the AP trajectory of center of pressure (COP)), but increased knee extensor strength with a reduced gait speed led to a reduced AP balance (50). However, it was shown that peak torque did not predict single leg static balance performance (51). As with strength data, there is a lack of balance data with respect to patient dissatisfaction.

To our knowledge, no studies have been conducted on the strength and balance abilities as it relates to dissatisfied TKR patients. Therefore, the purpose of this study was to examine how the knee concentric muscle strength, balance abilities, and deep knee flexion of both the replaced and non-replaced limbs for dissatisfied TKR patients compared to satisfied TKR patients and healthy controls. It was hypothesized that dissatisfied TKR patients would show deficits of knee extensor and flexor strength, balance abilities, and internal knee extension moment and ROM of deep knee flexion in their replaced limb compared to their non-replaced limbs and compared to satisfied TKR patients and healthy controls.

Materials and Methods

Participants

Nine dissatisfied TKR participants (34.6±14.3 months from surgery), fifteen satisfied TKR participants (29.3±12.8 months from surgery), and fifteen healthy participants participated in this study (Table 7). TKR participants were recruited from a local orthopaedic clinic. The inclusion criteria for TKR patients were the presence of a unilateral total knee replacement performed by a single surgeon, at least 12 months but less than 60 months removed from surgery, and between ages of 50 and 75. Exclusion criteria were any additional lower extremity joint replacements, any additional diagnosed osteoarthritis of hip, knee, or ankle, BMI greater than 38, or neurological diseases. TKR patients were asked, "How satisfied are you with your total knee replacement?" The available responses were "very dissatisfied, dissatisfied, neutral, satisfied, or very satisfied." Neutral were excluded. "Very dissatisfied" or "dissatisfied" responses were placed into the Dissatisfied group and "satisfied" or "very satisfied" were placed into the Satisfied group. A healthy control group was included with the same exclusion criteria as the TKR groups.

Instrumentation

A twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) and two force platforms (1200 Hz, BP600600, American Mechanical Technology Inc., Watertown, MA, USA) were used to obtain three-dimensional (3D) kinematics and GRFs during deep knee flexion trials. All participants wore standardized running shoes (Noveto, Adidas, Herzogenaurach, Germany). A cluster of four retroreflective markers was placed on the lateral aspects of both shanks and thighs, and on the posterior aspect of the pelvis and the thoracic cage, attached via an elastic neoprene wrap with hooks and loops of Velcro. Four individual tracking markers were placed on the heel counter of the shoe. Anatomical retroreflective markers were placed bilaterally on the acromion processes, iliac crests, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads, and 2nd toe. Anatomical and tracking markers were kept on for the static trials and anatomical markers were removed prior to testing trials.

Postural stability tests were performed using a balance system (Biodex Balance System SD, Biodex Medical Systems, Shirley, New York), sampling at a rate of 20 Hz. The visual feedback of center of pressure (COP) traces was provided to participants during practice and test trials.

Concentric knee extension and flexion muscle strength tests were performed using an isokinetic dynamometer (System 4, Biodex Medical Systems, Shirley, New York), speeds of 60°/s and 180°/s.

Experimental Procedures

At the beginning of the first testing session, all participants completed a Western Ontario and McMaster University survey (WOMAC) for both knees (178). TKR participants then completed a Forgotten Joint Score (FJS) (158). Following completion of all forms and surveys, participants performed a five-minute walking warm up on a treadmill at a self-selected speed. Passive knee range of motion (ROM) was then measured on both knees while participant was lying supine on a treatment table. Participants were then fitted with the previously described retroreflective marker set. Participants then performed five deep knee flexions in which they were instructed to squat down as low as they comfortably could without fear of losing balance. One leg was positioned on each force platform. No additional instruction was given with respect to foot placement. The deep knee flexion trials were collected at the end of the first day as part of a larger study with other motions not reported here.

On the second day, participants completed another five minute walking warm up on a treadmill at a self-selected speed. Participants then completed two trials of a stair ascent/descent test using an 11-step staircase and a chair rise test, with best times being reported. After the completion of the functional tests, participants performed six test conditions of bilateral and unilateral postural static and dynamic (at level 11 setting, with 1 being the most difficult and 12 being the least difficult) stability tests. Participant's feet were placed according to the instruction of the balance system. The participants performed three trials of 20 seconds per condition. One practice trial per condition was given and a rest period of 30 seconds were given between trials. A trial was repeated if the participant grabbed the handrail or required the investigator to catch them from falling. All balance test conditions were tested in a randomized order. After the completion of balance tests, participants completed isokinetic strength tests of the knee flexors and extensors. Strength tests were performed last to minimize the effect of fatigue from maximum effort muscle action on the other tests. Following a practice trial of two sub-maximum and one maximum effort trials, participants performed three maximum effort trials of knee flexion and extension, at two different speeds (60°/s and 180°/s). Knee flexion and extension repetitions were tested in succession at each speed for each leg. A rest period of two minutes were given between conditions. The speed conditions were randomized. A 0-10 numerical pain visual analog scale (VAS) was used to assess pain level after the tests in both knees for TKR participants and healthy participants for all conditions and tests.

Data Analyses

Visual3D biomechanical analysis software suite (C-Motion, Inc., Germantown, MD, USA) was used for 3D kinematic and kinetic variable computations for deep knee flexion data. A Cardan rotational sequence (X-y-z) was used for 3D angular kinematics computations and the conventions of the angular kinematic and kinetic variables were defined using the right-hand rule. Positive values indicate knee extension, adduction, and internal rotation angles and joint moments (computed as internal moments). Kinematic and GRF data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 8Hz before kinematics and joint moment calculations. Raw GRF were filtered separately using a fourth-order low-pass Butterworth filter with a cut-off frequency of 50 Hz to calculate GRF variables. Critical events and values, including peak VGRF, knee extension, abduction, and internal rotation moments, loading-response knee flexion, adduction, and external rotation ROM, and sagittal plane hip and ankle ROM and moments, were chosen using customized computer programs (VB_V3D and VB_Table, MS Visual Basic 6.0, USA). Joint moments represent internally applied moments, were reported in the proximal reference system and were normalized to body mass (Nm/kg). GRF variables were normalized to body weight (BW). Averages across the five trials of selected variables for every condition for each participant were used in statistical analyses.

Overall, medial-lateral, and anteroposterior stability indices were calculated. Based on the center of balance point defined as (0,0) of the X and Y coordinate of the system, X and Y coordinates values were recorded at each sampling point (20 Hz). During the dynamic trials of different levels of difficulty (level 11 was the dynamic level utilized in this testing), X and Y coordinate data were scaled at 1/100th degrees, up to 20 degrees of the test platform's tilt. The X and Y coordinates effectively represent mediolateral (X) and anteroposterior (Y) deviations from the center of the balance surface. The Overall Stability Index (OSI) was computed as:

$$OSI = \sqrt{\frac{\Sigma(X)^2 - \Sigma(Y)^2}{N}}$$

where X is the mediolateral coordinate, Y is the anteroposterior coordinate, and N is the number of data points sampled. The Mediolateral stability index (MLSI) was calculated through the following equation:

$$MLSI = \sqrt{\frac{\Sigma(X)^2}{N}}$$

The anteroposterior stability index (APSI) was calculated through the following equation:

$$APSI = \sqrt{\frac{\Sigma(Y)^2}{N}}$$

A customized Matlab script (MathWorks, Natick, MA, USA) was created to calculate strength related variables, including peak torque and loading rate. Loading rate was calculated by dividing the peak torque by its time (from onset of the movement).

Statistical Analyses

A 2 x 3 (limb x group) mixed model analysis of variance (ANOVA, p<0.05) using SAS (Version 9.4, Cary, NC, USA) was performed to detect differences between limbs and groups for selected variables of deep knee flexion, balance, strength variables, and WOMAC. A one-way ANOVA (p<0.05) was performed on demographic, survey, bilateral balance, and functional test data to test for differences between the three groups. When the ANOVA results revealed a significant interaction or main effect, pairwise t-tests were used to compare means with adjusted p values of 0.00625 for 2x3 ANOVA significant interactions and 0.0167 for 1x3 ANOVA comparisons. Post hoc comparisons were only made between the TKR replaced and healthy dominant limbs and TKR non-replaced limbs against the healthy non-dominant limbs. This was performed under the assumption that any differences between the dominant and non-dominant limb are random and small when present in the healthy population.

Results

Post hoc tests revealed for the functional tests, the dissatisfied group had increased stair ascent ($p=0.0148$) and descent ($p=0.0031$) times compared to both the satisfied and healthy groups (Table 7). Significant interactions were present for pain levels during chair rise, stair ascent, and stair descent tests ; and the dissatisfied group reported increased pain in their replaced limb compared to other groups and respective limbs during all three tests ($p<0.0148$ for all tests, Table 12). Significant interactions revealed the dissatisfied group had a decreased passive knee ROM in the replaced limb compared to their non-replaced limb and the healthy group ($p<0.0015$ for both tests) but no difference from the replaced limb of the satisfied group (Table 8). Significant interactions were present for all WOMAC subscales and total scores (Table 8). The dissatisfied group reported increased total WOMAC and subscale scores in their replaced limb compared to their non-replaced limb and satisfied and healthy groups. The satisfied group reported increased WOMAC total and physical function scores for both limbs as well as increased stiffness in their replaced limb, compared to the healthy group.

Significant interactions were present for peak torque of isokinetic knee extension strength at 180°/s and flexion at both 60°/s and 180°/s (Table 9). The post hoc comparisons showed that the dissatisfied replaced limb had lower peak extension torque at 180°/s than the non-replaced limb of the dissatisfied group, and both satisfied and healthy groups ($p<0.0051$ for all tests). Peak torque during the 60°/s flexion test was reduced in the replaced-limb of the dissatisfied group compared to that of the satisfied group (p=0.0168). Additionally, there was a limb main effect for the 60°/s extension test, with the replaced limbs having lower peak torque than the non-replaced. However, there were no differences in loading rate for any of the tested speeds. Significant interactions revealed that the dissatisfied group reported increased knee pain in their replaced limb during the 60 (p=0.0018) and 180°/s (p=0.0011) strength tests compared to their non-replaced limb and satisfied and healthy groups. (Table 12). A group main effect was present during the non-replaced 60°/s test, with the dissatisfied group showing increased pain compared to the satisfied and healthy groups.

There were no interactions for any of the balance variables (Table 10). There was a limb main effect for the ML Stability index during the static condition, with replaced limbs having increased ML sway during unilateral stance. It is of interest to note, approximately 33% of dissatisfied participants were unable to complete unilateral static balance trials on either limb while 13% of the satisfied group were unable to do so on their replaced limb and 20% on their non-replaced limb. During the dynamic unilateral tests, these numbers increased to 56% of dissatisfied participants and 27% of satisfied participants on both limbs. All healthy participants were able to complete the test on the non-dominant limb but 13% could not on their dominant limb. The dissatisfied group reported increased knee pain in their replaced knees compared to their non-replaced knee and satisfied and healthy groups during all balance tests (except for unilateral balance on the non-replaced static trials, Table 12).

During active knee flexion, there were significant interactions for peak knee extension moment, peak knee abduction moment, and knee internal rotation ROM (Table 11). The replaced limb of the dissatisfied group showed a decreased peak knee extension moment compared to their non-replaced limb, the replaced limb of the satisfied, and the healthy groups, while the satisfied group only showed a decreased peak knee extension moment in their replaced limb compared to the non-replaced limb. For peak knee abduction moment, post hoc analysis revealed no significant differences. The replaced limb of the satisfied group showed a reduced knee internal rotation ROM compared to the healthy group. There was a limb main effect for knee adduction ROM, with the non-replaced limb of TKR groups or non-dominant limb of healthy group being lower than the replaced or the dominant limb (Table 11). There was a group main effect for knee pain during the active flexion, with the dissatisfied group reporting increased pain levels in both knees compared to the other groups (Table 12).

Discussion

The purpose of this study was to examine differences in strength, balance, and deep knee flexion between dissatisfied and satisfied TKR patients. Our hypothesis related to reductions in knee extension strength for the replaced limbs of the dissatisfied group was partially confirmed as the dissatisfied group showed reductions in peak knee extension torque at 180°/s of the replaced limbs compared to their non-replaced limbs, those of the satisfied and healthy groups. The limb main effect for knee extension during the 60°/s test showed reduced extension strength for the replaced limbs compared to the non-replaced limbs, offering partial support for our hypothesis. Additionally, the decreased peak flexion torque in the dissatisfied replaced limb at 60°/s compared to the satisfied group also provided partial confirmation of our hypothesis. Post-operative increases in knee extensor and flexor strength have been related to improvements in balance and restoration of functional abilities (240-242). It has been suggested that knee extensor strengthening exercises should continue long-term to improve patient satisfaction and restore functional abilities (243). Decreased concentric strength in the knee extensors has been linked to decreased stair climbing abilities (240), which is in partial agreement with the results of this study. The dissatisfied group showed reduced stair ascent and descent times compared to the satisfied and healthy groups while having reduced knee extensor strength at 180°/s in their replaced limb. The replaced limbs showed lower peak torque compared to the non-replaced limbs during knee extension at 60°/s. This imbalance in the dissatisfied group (30% strength increase in the non-replaced limb compared to the replaced limb) is substantially larger than that in the satisfied group (12% strength increase in non-replaced limb) which could render the given task of stair climbing more difficult (with only a 4% difference between dominant and non-dominant limbs for the healthy group). Our results of knee extensor and flexor peak torque differences at both 180°/s and 60°/s are in partial agreement with previous research which has shown peak torque reductions in TKR patients compared to healthy controls for both knee extensors and flexors at 180°/s but not 60°/s (36). While not all results were statistically significant, it is worth noting that average peak torque values across the groups and limbs were always lower in the dissatisfied group compared to the satisfied and healthy groups, for both the replaced and non-replaced limbs. It can be generally concluded that reduced strength is present in the dissatisfied TKR population.

The reductions in strength levels may be in part related to the increased pain levels present in the replaced limb of the dissatisfied group. Pain relief and subsequent restoration of activity abilities have been highly correlated with increasing patient satisfaction (241). Daily activities with increased difficulty often require increased knee flexion and extension movements, which often require increased quadriceps and hamstring strength (242). This can be further confounded when asymmetries exist. Limb loading asymmetries have been present early after surgery and have been shown to contribute to increased stair climbing times (244). These reductions in functional abilities have been speculated as being related to pain and quadriceps weakness, both of which are present in our dissatisfied patient population. Quadriceps weakness is often a point of interest during the rehabilitation process, and an increase in the strength levels with a subsequent increase in knee ROM have been evident with increased patient satisfaction, although this same study did not show any differences in WOMAC pain and function scores associated with the strength and ROM gains (245). It should be noted that this previous study did not group the patients based on their satisfaction as has been done in the current study. The current study showed reductions in passive knee ROM for the dissatisfied group in their replaced limb compared to all other groups and respective limbs, except for the replaced limb of the satisfied group. In addition, the increased WOMAC total and sub-scale scores showed increased deterioration of the replaced limb of the dissatisfied group.

A goal of TKR implants is to increase maximum knee flexion of TKR patients, with the idea that increased flexion leads to improved patient outcomes (246). During weight-bearing flexion related activities, over 85% of TKR patients achieve flexion ROM over 100° (247) but this was not the case in the deep knee flexion test for either TKR group in this study. Participants in this study were instructed to squat as low as possible in the deep knee flexion test, and neither TKR group achieved mean flexion ROM above 100°, although during this activity, no statistically significant flexion ROM differences were present. However, asymmetries were present in peak knee extension moments for the dissatisfied TKR group. Additionally, the dissatisfied group had a reduced peak knee extension moment in their replaced limb compared to the satisfied and healthy groups, likely due to the increased pain levels experienced during the activity. What is of interest though is that they also experienced increased pain in their non-replaced limb during the activity, likely due to the increased joint loading experienced by compensating with their non-replaced limb. This increased pain level on both sides can make the task increasingly more difficult to achieve. It may ultimately lead to an avoidance to this type of high flexion task, further increasing their dissatisfaction with the replaced knee. It is paramount during the rehabilitation process to promote achievement of these higher levels of deep knee flexion in order to increase long-term outcomes. An inability to do so may be a good identification of patients at-risk of poor long-term outcomes (248). Deep knee flexion is a difficult task and it has been speculated that a return to normal function during difficult activities such as deep knee flexion is not truly possible for TKR patients (249). TKR patients may be able to achieve a shallower knee flexion compared to healthy individuals, possibly due to the pain experienced during the activity. However, alleviating the pain may allow for more symmetrical function and allow for task completion. It has been reported that 75-86% of TKR patients have knee symptoms during squatting, as 42-59% have moderate to severe difficulty during squatting, and 25% are unable to squat at all (11, 230). This is in agreement with the current results showing the asymmetry in deep knee flexion as well as the presence of pain for the dissatisfied group.

No significant differences were present in both the static and dynamic balance levels and limbs, aside from slight increases in ML stability in the replaced limb compared to the non-replaced limb. This was not in agreement with our hypothesis. Additionally, this is of interest due to the significant number of patients who could not complete the balance trials. During the unilateral static balance test, 33% of dissatisfied patients were unable to complete the tests on both their replaced and non-replaced limbs, which is an increase over the 13% and 20% of the satisfied group on their replaced and non-replaced limbs, respectively. As the difficulty increased to the dynamic unilateral stability test, these numbers elevated to 56% of dissatisfied and 27% of satisfied patients. This may be in part related to replacement design types received by our patients in the study. Most of the participants had cruciate retaining TKR designs, which do not contain a cam-post mechanism. Longer cam-post designs aid frontal plane stability to the replaced knee joint (250). Without this added stability, the replaced knees are left to be controlled by musculature and ligaments, some of which (knee musculature) has been shown as reduced in the dissatisfied patients. Further research is warranted to examine the effects of different TKR design types on patient balance ability. With these reduced numbers of patients who were unable to complete the tests, our sample sizes for the statistical analysis were greatly reduced, which may have skewed results of the balance tests as no differences were reported when the patient was able to complete the trials. A completion rate of less than 50% for the dissatisfied patients is quite low, although the difficulty level was set at the lowest level (level 11) in the unilateral dynamic balance test. The inability to perform the balance tests may have also contributed to the patient dissatisfaction. Additionally, pain levels were increased for the replaced limb of the dissatisfied participants compared to the satisfied and healthy groups. Improvements in balance have been associated with improvements in gait speed, chair rise tests, and stair climb tests (49). The presence of pain may not be enough to impact the balance abilities at the difficulty levels tested here when patients were able to complete the test. However, the subsequent improvements in stair climbing were not evident in this research. Strength and balance are frequently connected since strength is necessary to maintain balance. Increased knee extensor strength coupled with an increased gait speed has led to increased anteroposterior balance, but increased knee extensor strength with a reduced gait speed led to a reduced anteroposterior balance (50). This was not evident with the dissatisfied group as no AP differences were evident. Other research has shown that peak torque did not predict single-limb balance (51), which does agree with the results of this research since strength differences were evident but balance differences were not.

The consistent issue with the dissatisfied patients is the presence of pain, which subsequently seems to impact certain physical abilities. Increased patient dissatisfaction has been associated with increased pain during activities, lower knee function post-operatively, and depressive symptoms or somatization dysfunction (251). Treating the psychological factors associated with the surgery may help to improve outcomes. Patients with somatization dysfunction have a two-fold increase in risk for dissatisfaction with their TKR (251). This may suggest one of two options. First, pre-operative psychological screening may help with the rehabilitation of TKR patients as certain psychological needs can be addressed in conjunction with the physical needs. Second, psychological tools to deal with pain management may help to improve functional ability. Multivariate logistic and linear regression models have suggested that dissatisfaction is largely associated with the pain reductions and functional improvements experienced during the first three months post-operatively, suggesting that the decision to have surgery should be based on functional limitations, not high pain scores (252). However, given that pain is present and may continuously impair functional abilities, it should be addressed during rehabilitation processes. Tools such as guided imagery may help to lower pain and anxiety experienced post-operatively (232). A reduction in pain experienced by dissatisfied patients may help improve their functional abilities and subsequently increase their satisfaction levels. Given the physical and time-based investment in an operation such as a TKR, it is beneficial to address all issues which may improve outcomes.

This study has some limitations. First, given the large amount of variables and comparisons in our statistical analyses, type I error is a potential issue. Some of these differences detected in this study may be by pure chances. Second, the classification of the patient satisfaction and dissatisfaction is subjective in nature which is likely a multifaceted response based on factors such as personal experience, bias, and perception, none of which were captured in this study. It is simply a question posed to the patients about their perception of their replaced limb without qualifying whether the satisfaction is based on pain, functional ability, or any other characteristics. As mentioned earlier, the balance results are to be interpreted with caution given the small sample sizes due to the inability of some dissatisfied patients to complete the test. Finally, while patients were asked to perform isokinetic tests with maximum effort, there may have been some reduced performances due to the presence of pain. With the presence of pain, these results appeared to be their maximum efforts, it may not reflect the true muscular abilities of the patients.

Conclusion

Patient dissatisfaction is a complex construct that is evidently multifaceted. Throughout all tests, pain was evident, regardless of changes in function. Strength deficits were evident for the dissatisfied patients in both the knee flexors and extensors. Balance abilities were also reduced through an inability to successfully balance on one limb, although when possible, no differences were evident between groups who were able to complete the unilateral balance tests. Self-reported increased difficulty with certain activities for dissatisfied patients was evident through a structural imbalance during deep knee flexion tests, whereby dissatisfied patients exhibited an increased dependence on their non-replaced limb. An increase in strength may provide a more symmetrical movement pattern and therefore better function. This may improve patient satisfaction. More research needs to further determine the mechanisms contributing to patient dissatisfaction and subsequent ways to improve them. This may be achieved through longitudinal tracking of patient satisfaction in an attempt to identify both the physical and psychological factors as they occur over time.

Chapter V Appendix: Tables and Figures

Table 7. Descriptive statistics, functional tests, and survey data.

	Dissatisfied	Satisfied	Healthy	p value
Age (years)	68.0±4.2[A]	66.6±6.3[A]	60.7±9.2	**0.0034**
Height	1.69±0.07	1.76±0.10	1.75±0.09	0.1280
Weight	80.99±18.59	90.19±16.98	77.74±11.75	0.0944
BMI (kg/m^2)	28.13±4.61	28.85±4.26	25.33±3.34	0.0563
Months from surgery	34.6±14.3	29.3±12.8	NA	0.3598
FJS (replaced limb)	21.53±16.04[B]	67.78±27.76	NA	**0.0002**
Chair Rise (s)	18.43±7.26	16.84±5.45	15.01±4.21	0.3327
Stair Ascent (s)	5.50±1.93[AB]	4.30±0.79	4.06±0.68	**0.0117**
Stair Descent (s)	5.93±2.91[AB]	3.98±0.60	3.68±0.50	**0.0021**

[A] Different from Healthy group, [B] Different from Satisfied group.

Table 8. WOMAC Scores (100mm VAS) and Passive Knee ROM (°).

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
WOMAC Total[#*]	794.9±484.2[ABC]	67.2±64.5	251.2±179.2[C]	196.5±175.8[C]	29.9±73.5	18.5±40.2	**<0.0001**
WOMAC Physical Function[#*]	525.2±323.9[ABC]	38.3±30.3	179.2±141.3[C]	144.5±131.1[C]	16.1±39.3	12.5±26.8	**<0.0001**
WOMAC Stiffness[#*]	76.1±58.3[ABC]	8.2±8.6	38.1±41.8[C]	26.8±44.4	6.5±18.3	2.9±6.3	**0.0007**
WOMAC Pain[#*]	193.7±138.6[ABC]	20.7±34.0	33.9±30.1	25.1±22.8	7.3±17.3	3.1±7.6	**<0.0001**
Passive Knee ROM[#]	118.3±7.4[AC]	131.0±10.4	122.9±10.5[AC]	134.4±9.3	134.3±13.5	135.4±13.4	**0.0001**

[A] Significantly different from contralateral leg of same TKR group, [B] Significantly different from same leg of satisfied TKR group, [C] Significantly different from same leg of healthy group, [#]Limb main effect, [*]Group main effect.

Table 9. Peak Isokinetic Knee Extension and Flexion Torque (Nm) and Extension and Flexion Loading Rate (LR; Nm/s).

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
Extension @ 60°/s #	85.2±30.9	110.5±41.1	118.3±39.1	132.5±41.3	117.6±36.4	122.1±39.3	0.0664
Extension @ 180°/s#	58.3±22.7[ABC]	72.9±26.9	83.0±24.9[A]	95.4±27.0	80.8±29.3	76.4±25.8	**0.0081**
Flexion @ 60°/s	48.0±15.9[B]	52.4±19.8	64.3±21.1	67.1±21.0	63.2±13.0	58.0±17.1	**0.0168**
Flexion @ 180°/s*	34.4±13.7	33.7±15.3[B]	48.5±19.0[A]	57.0±21.4	47.7±14.8	45.8±12.7	**0.0020**
Extension LR @ 60°/s	151.0±114.0	139.2±68.9	169.1±95.9	189.4±73.4	164.8±76.2	158.3±61.9	0.6898
Extension LR @ 180°/s	244.2±92.3	261.8±103.8	343.5±160.5	342.1±162.6	274.9±132.1	243.3±104.6	0.7562
Flexion LR @ 60°/s	135.3±81.6	190.2±207.5	202.2±150.1	163.6±86.9	195.8±246.4	223.9±329.5	0.6871
Flexion LR @ 180°/s	185.0±84.0	171.0±111.1	288.7±184.2	320.2±224.0	295.5±213.9	224.9±203.2	0.2566

[A] Significantly different from contralateral leg of same TKR group, [B] Significantly different from same leg of satisfied TKR group, [C] Significantly different from same leg of healthy group, #Limb main effect, *Group main effect.

Table 10. Unilateral overall stability index (OSI), mediolateral stability index (MLSI) and anteroposterior stability index (APSI) and bilateral OSI, MLSI, and APSI stability indices (one-way ANOVA).

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
Static OSI	2.68±1.17	3.20±1.35	3.05±1.59	2.21±1.46	3.08±1.52	1.71±0.81	0.1314
Dynamic OSI	2.23±0.57	2.60±0.47	2.55±0.81	2.56±0.92	2.38±0.52	2.41±0.84	0.8397
Static APSI	1.55±0.90	2.40±1.20	1.72±1.36	1.38±1.16	1.50±1.26	1.14±0.63	0.2484
Dynamic APSI	1.65±0.95	2.38±0.39	1.45±0.73	1.61±0.85	1.73±0.81	1.49±0.80	0.1316
Static MLSI#	1.95±1.04	1.80±0.95	2.20±1.20	1.39±1.14	2.35±1.28	1.03±0.55	0.2598
Dynamic MLSI	0.90±0.88	0.93±0.28	1.64±1.12	1.50±1.18	1.27±0.51	1.57±0.85	0.7045
Static OSI Bilateral	1.36±1.86		0.90±0.86		1.40±1.36		0.5498
Dynamic OSI Bilateral	1.69±0.53		1.56±0.75		1.79±0.65		0.6511
Static APSI Bilateral	1.13±1.89		0.70±0.85		1.06±1.20		0.6518
Dynamic APSI Bilateral	1.24±0.54		1.21±0.79		1.39±0.74		0.7786
Static MLSI Bilateral	0.39±0.43		0.35±0.36		0.65±0.84		0.3504
Dynamic MLSI Bilateral	0.90±0.43		0.73±0.35		0.85±0.27		0.4439

[A] Significantly different from contralateral leg of same TKR group, [B] Significantly different from same leg of satisfied TKR group, [C] Significantly different from same leg of healthy group, #Limb main effect, *Group main effect.

Table 11. Deep knee flexion kinematics and kinetics.

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
VGRF (BW)	0.56±0.07	0.61±0.05	0.60±0.08	0.64±0.08	0.63±0.08	0.62±0.08	0.0895
Knee Flex ROM (°)	-86.2±19.6	-88.4±21.7	-94.9±13.3	-95.7±12.9	-100.5±23.4	-100.4±21.6	0.6972
Knee Add ROM (°) #	19.0±12.2	19.5±7.8	19.2±7.0	13.2±6.9	19.9±8.3	13.2±7.5	0.2252
Knee Int Rot ROM (°)	14.5±11.0	13.0±9.2	9.7±8.0 C	12.0±6.9	20.3±13.2	13.1±9.5	**0.0312**
Knee Ext Mom (Nm/kg)*	0.75±0.14 ABC	0.89±0.16	0.98±0.24 A	1.09±0.23	1.05±0.24	1.00±0.29	**0.0417**
Knee Abd Mom (Nm/kg)	-0.29±0.22	-0.32±0.12	-0.33±0.16	-0.29±0.18	-0.41±0.25	-0.29±0.15	**0.0292**
Knee Ext Rot Mom (Nm/kg)	-0.13±0.06	-0.12±0.08	-0.18±0.08	-0.16±0.09	-0.24±0.12	-0.18±0.08	0.3769

A Significantly different from contralateral leg of same TKR group, B Significantly different from same leg of satisfied TKR group, C Significantly different from same leg of healthy group, #Limb main effect, *Group main effect.

Table 12. Pain for individual tests (0-10 Likert).

	Dissatisfied Replaced	Dissatisfied Non-Replaced	Satisfied Replaced	Satisfied Non-Replaced	Healthy Dominant	Healthy Non-Dominant	Interaction p value
Chair Rise#*	1.44±2.00 ABC	0.00±0.00	0.13±0.52	0.13±0.52	0.00±0.00	0.00±0.00	**0.0013**
Stair Ascend#*	1.56±1.94 ABC	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0001**
Stair Descend#*	1.78±2.44 ABC	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0006**
Bilateral Static Balance#*	1.33±2.06 ABC	0.22±0.67	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0033**
Bilateral Dynamic Balance#*	0.78±1.56 ABC	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0257**
Unilateral Replaced static#*	1.56±2.46 ABC	0.22±0.67	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0064**
Unilateral Replaced Dynamic#*	0.78±1.56 ABC	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0257**
Unilateral Non-replaced static	0.33±1.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.07±0.26	0.1508
Unilateral Non-replaced Dynamic#*	0.78±1.56 ABC	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0257**
Replaced 60°/s#*	1.67±2.5 ABC	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0018**
Replaced 180°/s#*	1.56±2.24 ABC	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	**0.0011**
Non-replaced 60°/s *	0.78±1.56	0.11±0.33	0.00±0.00	0.00±0.00	0.00±0.00	0.10±0.39	0.0615
Non-replaced 180°/s	0.78±1.56 ABC	0.00±0.00	0.00±0.00	0.07±0.26	0.00±0.00	0.07±0.26	**0.0197**
Deep Knee Flexion*	1.39±1.69	1.83±2.89	0.07±0.26	0.27±0.59	0.07±0.26	0.07±0.26	0.7632

A Significantly different from contralateral leg of same TKR group, B Significantly different from same leg of satisfied TKR group, C Significantly different from same leg of healthy group, #Limb main effect, *Group main effect.

CHAPTER VI

LOGISTIC REGRESSION ANALYSES REGARDING PATIENT DISSATISFACTION WITH TOTAL KNEE REPLACEMENT OUTCOMES

Abstract

Current research on patient satisfaction after a total knee replacement (TKR) lacks an examination of objective assessments with respect to gait biomechanics, strength, and balance abilities. Therefore, the purpose of this research was to examine associations between patient satisfaction and the gait biomechanics, strength, balance, functional capacities, and survey data. Twenty four TKR patients participated in overground walking, stair ascent and descent, isokinetic strength, static and dynamic balance, and functional tests. Nine patients were in the dissatisfied group and fifteen in the satisfied group. Logistic regression analyses were performed to identify four models of satisfaction prediction: one for walking biomechanics, stair ascent biomechanics, stair descent biomechanics, and functional/survey data. The functional model was inclusive of WOMAC total scores, stair ascent and chair rise times, and peak knee extension torque. The walking model included 1st and 2nd peak VGRF, knee extension moment, and the forgotten joint score. The stair ascent model included 2nd peak VGRF, knee extension moment, preferred gait speed, and peak extension torque. The stair descent model included knee extension moment, preferred gait speed, peak extension torque, and the forgotten joint score. The biomechanical models included both VGRF and knee extension moments, indicating their relevance to patient satisfaction. Pain was not included in any models (as in previous prediction models) due to a complete separation of data points.

Keywords: logistic regression, total knee replacement, satisfaction, arthroplasty

Introduction

Patient dissatisfaction is a complicated and multi-faceted construct involving both subjective and objective information (16). Many of the subjective survey tools utilized in the total knee replacement (TKR) population examine patients' desires and abilities to return to performing more advanced activities (111, 210). This suggests that there is an expectation that the surgery will help the patient to return to these activities. The desired outcomes are not always evident though as some patients have difficulty with function and lingering pain in the replaced knee joint. Overall, most TKR operations are considered successful as there are often reductions in pain levels and improvements in ROM in the replaced knee (6-9). However, patient satisfaction rates for the procedure have been reported between 81-97% (10, 11). This leaves a significant portion of the TKR population as being dissatisfied with the outcomes of their replaced knees. Post-operative pain (12) and functional limitations (13) are commonly reported by dissatisfied patients. Reduced pain and increased functional ability are often seen as a defining point for "success" of the operation as they are deemed to determine the restoration of function for the replaced joint. However, these test results do not sufficiently explain why the TKR patients are dissatisfied with the TKR outcomes, thereby suggesting that additional research into the mechanisms of dissatisfaction is needed. Current literature is lacking on the biomechanical studies related to patient dissatisfaction and the variables which most contribute to dissatisfaction.

Current research on the dissatisfied population has primarily focused on survey data and minimally on biomechanical testing (16-18). Lab-based biomechanical studies focusing on level walking, stair negotiation, strength, and balance can provide detailed and quantifiable insights into the movement profiles of the dissatisfied TKR population. For example, one study has shown no difference in functional test scores while showing reduced loading-response knee extension moments and increased push-off knee abduction moments in the replaced limb of TKR patients compared to the non-replaced limbs and healthy controls during stair ascent (19). Despite similarities in functional tests, the biomechanical analysis was able to show deficits in the movement patterns, providing valuable and detailed gait biomechanics in movement recovery, which would not be detectable. Prior to the collection of the data set employed in this research, there was a lack of three-dimensional kinematic and kinetic research specifically on the dissatisfied TKR patient population. Through this data set, kinematic, kinetic, strength, and balance deficits in the dissatisfied patient population have been identified, including reduced knee extensor moments during level walking, stair ascent, and stair descent, reduced gait speed in all three activities, reduced stair ascent/descent performance tests, reduced knee extensor/flexor strength, and differences in survey data compared to the satisfied patient population.

The research on patient satisfaction currently lacks an examination of objective and numerical assessments with respect to gait biomechanics, strength, and balance abilities. This presents a unique opportunity to identify the physical differences which may help to improve TKR patient satisfaction rates. The purpose of this research was, therefore, to examine associations between TKR patient dissatisfaction and gait biomechanics, strength, balance, functional capacities, and survey data (measuring joint awareness, pain, stiffness, and functional ability) using a logistic regression analyses. Four subsequent models were created to reflect data traditionally associated with patient satisfaction (survey and functional test data) and three additional models for overground walking, stair ascent, and stair descent data. It was hypothesized that reduced knee extensor moments, reduced quadriceps strength, reduced gait speed, and increased pain would contribute to increased dissatisfaction in TKR patients in the biomechanical models.

Materials and Methods

Participants

There were 24 TKR participants recruited from a local orthopaedic clinic. The inclusion criteria for TKR patients was the presence of a unilateral total knee replacement performed by a single surgeon, at least 12 months but less than 60 months removed from surgery, and between the ages of 50 and 75. Potential participants were excluded if they had any additional lower extremity joint replacements, any additional diagnosed osteoarthritis of the hip, knee, or ankle, BMI greater than 38 or neurologic diseases. TKR patients were then asked, "How satisfied are you with your total knee replacement?" The available responses were "very dissatisfied, dissatisfied, neutral, satisfied, or very satisfied" using a 1-5 Likert scale. Participants who responded neutral were excluded, thus shifting the scale to a 1-4 scale for the "very dissatisfied, dissatisfied, satisfied, or very satisfied" responses, respectively. Participants were subsequently categorized into two groups based on their responses to the satisfaction question: "very dissatisfied" and "dissatisfied" were grouped together as were "satisfied" and "very satisfied" responses. Nine TKR patients (68.0±4.2 years, 1.69±0.07m, 80.99±18.59 kg, 34.6±14.3 months post-surgery) were grouped as dissatisfied patients and fifteen TKR patients (66.6±6.3 years, 1.76±0.10m, 90.19±16.98 kg, 29.3±12.8 months post-surgery) were grouped as satisfied.

Experimental Procedures

On day one, all participants signed an informed consent form, completed a physical activity readiness survey (PAR-Q) to assess cardiovascular risks to exercise, and completed a Western Ontario and McMaster University survey (WOMAC) for both knees (178) and the

Forgotten Joint Score (FJS (158)). Following completion of the surveys, all participants completed a five-minute warm up on a treadmill, walking at a self-selected speed. Participants were then fitted with retroreflective discrete anatomical and clustered tracking markers affixed to their thoracic cage, pelvis, thighs, shanks and feet. Three-dimensional kinematics and kinetics were obtained using a twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK), two force platforms (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA), and an instrumented 3-step stair case (FP-Stairs, American Mechanical Technology Inc., Watertown, MA, USA). Participants performed five trials of stair ascent and five trials of descent with their replaced limb on the second step of the five step stair case, using a step-over manner. Following completion of stair trials, five overground walking trials were performed, with the replaced limb coming into contact with the force platform.

On day two, participants completed a five-minute warm up walking on a treadmill at a self-selected speed. Passive knee range of motion (ROM) was then measured on both knees while participant was lying supine on a table. Two trials of a stair ascent/descent test using an 11-step stair case and a chair rise test were performed, with average times being reported. After the completion of the functional tests, participants performed bilateral and unilateral postural stability tests in a static position and at level 11 on a Biodex Balance System SD (Biodex medical Systems, Shirley, NY, USA). Participant's feet were placed according to the instruction of the balance system. The participants performed three trials per condition, with each trial lasting 20 seconds. If the participant was unable to complete a condition, no score was given. All balance test conditions were tested in a randomized order. After the completion of balance tests, participants completed isokinetic strength tests of the knee flexors and extensors. Strength tests were performed last to minimize the effect of fatigue. Following a practice trial of two sub-maximum and one maximum effort practice trials, participants performed three maximum effort trials at two different speeds (60°/s and 180°/s), testing the concentric strength of the knee flexors and extensors. A rest period of two minutes was given between conditions. The speed conditions were randomized. A visual analogue pain scale was used to assess pain in both knees for all conditions and tests.

Data Analyses

Visual3D biomechanical analysis software suite (version 5.0, C-Motion, Inc., Germantown, MD, USA) was used for 3D kinematic and kinetic variable computations. A Cardan rotational sequence (X-y-z) was used for 3D angular kinematics computations and the conventions of the angular kinematic and kinetic variables were defined using the right-hand rule. Marker coordinate and GRF data were filtered using a fourth-order low-pass Butterworth filter with cut-off frequency of 8 Hz for joint angle and moment computations. For GRF variables, raw GRF data were filtered again using a fourth-order low-pass Butterworth filter with cut-off frequency of 50 Hz. Joint moments were normalized to participant mass (Nm/kg) and GRF variables were normalized to body weight (BW). Averages of selected variables across the five trials for every condition for each participant were used in statistical analyses.

Using the Biodex Balance System SD software, overall, medial-lateral, and anterior-posterior stability indices were calculated. Based on the center of balance point defined as [0,0] of the X and Y coordinate of the system, X and Y coordinates values were recorded at each sampling point (20 Hz). The X and Y coordinates effectively represent medial-lateral (X) and anterior-posterior (Y) deviations from the center of balance. The Overall Stability Index (OSI) was defined as:

$$OSI = \sqrt{\frac{\Sigma(X)^2 - \Sigma(Y)^2}{N}}$$

where X is the medial-lateral coordinate, Y is the anterior-posterior coordinate, and N is the number of data points sampled. The Medial-lateral Stability Index (MLSI) was calculated through the following equation:

$$MLSI = \sqrt{\frac{\Sigma(X)^2}{N}}$$

where X is the medial-lateral coordinate and N is the number of data points sampled. The Anterior-posterior Stability Index (APSI) was calculated as:

$$APSI = \sqrt{\frac{\Sigma(Y)^2}{N}}$$

where Y is the anterior-posterior coordinate, and N is the number of data points sampled.

A customized Matlab script (MathWorks, Natick, MA, USA) was created to calculate strength related variables, including peak torque, angle of occurrence for peak torque, and loading rate. Loading rate was calculated by dividing the peak torque by its time (from onset of the movement).

Statistical Analyses

A correlation matrix was computed on all available variables to identify potential variables for the regression model. If high correlations ($r \geq 0.7$) existed, variables were selected based on biomechanical and functional importance identified through review of literature concerning TKR patients. Selected kinematic, kinetic, strength, and balance variables along with functional test and survey data scores were input into a logistic regression analysis using SAS (Version 9.4, Cary, NC, USA). Variables for inclusion in regression models were selected based on three steps. First, a χ^2 analysis was performed to determine the highest values of all variables. Second, variables were chosen based on their biomechanical and clinical relevance and current literature. Third, a correlation matrix was performed to reduce number of highly correlated variables for redundancy, with the more relevant variable being selected for inclusion. Models were evaluated using Akaike's Information Criterion (AIC) values, comparing the nonnested models of the same sample. The AIC value was calculated as:

$$AIC = -2LogL + 2x$$

where *x* is the number of parameters in the model and calculated as:

$$x = r(e + 1)$$

where *r* is the total number of response levels and *e* is the number of explanatory effects. The AIC uses a maximum log likelihood to add to the model parameters, calculated as:

$$-2 \; Log \; L = -2 \sum_{j} \frac{w_j}{\sigma^2} f_j \log(\hat{\pi} j)$$

where *w* and *f* are weight and frequency values for the *j*th observation, and σ^2 is the dispersion parameter (253).

Goodness of fit is detailed with AIC and R^2 values, taking model accuracy and complexity into account. The model with the lowest AIC value was selected as the best model. Significance levels were assessed using the Likelihood Ratio given the small sample size, with a *p* level of 0.05. Using the Analysis of Maximum Likelihood Estimates, individual variable and intercept slopes and standard errors were calculated. Odds ratios for the model variables were calculated through the logistic regression, with the 95% Wald Confidence Limits. Models were placed through two passes of the data, one without cross validation and then an additional test with cross validation. This is performed by fitting the model to the entire data set. The model was then used to predict probability for an observation by ignoring the selected observation and fitting the model to the remainder of the observations to obtain a predicted probability for the ignored observation. The data was not split into training and validation sets due to the small sample size. Four main models were selected for further analysis. One for the more traditionally assessed information with respect to patient satisfaction (survey, functional test, and strength data) and three additional models: one for walking, stair ascent, and stair descent data (Table 13).

Results

The first model was inclusive of WOMAC total scores, stair ascent and chair rise times, peak extension torque, and the Quadriceps/Hamstrings peak torque ratio, achieving the highest R-square (0.87) and lowest AIC values (19.51, Table 13). Dissatisfied patients showed increased WOMAC total scores, stair ascend times, and chair rise times and decreased peak knee extension torques and quadriceps/hamstrings ratios. Individual variable and intercept slopes, standard errors, odds ratios and confidence intervals are presented in Tables 14-17. None of the individual variables showed significance for predictive ability in the model, despite the goodness of fit.

The model on walking data achieved an R^2 of 0.75 and an AIC of 21.34 (p=0.0015, Table 13). This model included 1st peak VGRF, 2nd peak VGRF, loading-response internal rotation moments, and the FJS. Dissatisfied patients showed decreased 1st and 2nd peak VGRF values in their replaced limb and peak loading-response internal rotation moments and increased FJS. A second walking model was performed with the loading-response knee extension moment in place of the internal rotation moment given that knee extension moments are more frequently discussed with respect to TKR patients than internal rotation moments. The loading-response internal rotation moment and knee extension moment were highly correlated (r=0.80) and the internal rotation moment had a reduced χ^2 value, resulting in the knee extension moment initially being chosen for inclusion. However, upon further examination, when the internal rotation moment was included in the model, the R-square increased by 0.06 and the AIC decreased by

1.40, resulting in a better model fit (both models were significant). Both walking models were included for ease of literature comparison. No significant individual predictors were present ($p>0.05$, Table 15).

The model on stair ascent data included 2nd peak VGRF, loading-response knee extension moment, preferred ascent gait speed, and peak extension torque (180°/s), achieving an R^2 of 0.72 and an AIC of 23.85 ($p=0.0013$). Dissatisfied patients showed reductions in all four variables, with no significant individual predictors ($p>0.05$, Table 16). The model on stair descent data included loading-response knee extension moments, preferred descent gait speed, peak knee extension torque (180°/s), and FJS ($R^2=0.80$, AIC=20.47, $p=0.0003$). Dissatisfied patients showed reduced knee extension moments, preferred gait speed, and peak torque, with increased FJS scores. No individual variables were significant predictors of patient dissatisfaction ($p>0.05$, Table 17).

Discussion

The purpose of this research was to examine associations between different physical characteristics and patient dissatisfaction after TKR operations in order to create four different satisfaction regression models. In an examination of the different models, the model of best fit contained survey, functional test, and strength data, achieving an R^2 of 0.87 and an AIC value of 19.51 (Table 1). This model includes WOMAC total score, stair ascent and chair rise times, peak knee extension torque, and the quadriceps to hamstring ratio. A prediction model for patient dissatisfaction post TKR operation also included WOMAC total scores at one year post-operation as a predictive variable (210). However, it should be noted that our research contains more stringent inclusion and exclusion criteria, which may have altered the dissatisfaction predictors. Dissatisfied patients reported higher WOMAC total scores in this data set, with increased scores for pain, stiffness, and functional disability. While this model does not split the WOMAC subsets, reduced functional abilities are evident in the model, as represented by the increased stair ascent and chair rise times. Knee strength related measures have not been previously included in predictive models for dissatisfied TKR patients prior to this research, where reduced peak knee extension torques were evident for the dissatisfied patient population. TKR patients exhibited a 331. Nm decrease in peak isokinetic knee extension torque compared to healthy controls in the current study. This reduction in strength may have contributed to the reduced functional ability of the dissatisfied patients. Lower knee extension power during isokinetic testing (which is a product of torque and velocity) has been shown to be predictive of slower stair ascent and descent tests (141). While power and torque are not directly related, peak torque reductions were evident with reduced stair ascent times, both of which were included in this model, suggesting the reduced functional ability being related to the reduced strength.

It was hypothesized that reduced knee extensor moments, reduced isokinetic quadriceps strength, reduced gait speed, and increased pain would contribute to increased dissatisfaction in TKR patients, which was partially confirmed by the walking, stair ascent, and stair descent models. Reduced knee extension moments were present in the models for all three activities and reduced quadriceps strength and preferred gait speed were evident in both stair ascent and descent models. The two walking models were similar with respect to the variables entered into them, however, the one with the higher R^2 and lower AIC value included the peak loading-response knee internal rotation moment. The model with slightly reduced fit statistics replaced the internal rotation moment with the eventually chosen model with the peak loading-response knee extension moment. The knee extension moment is a more important variable biomechanically in gait and more frequently examined with respect to TKR patients (20, 24-26).

The dissatisfied patients exhibited reduced peak loading-response knee extension moments compared to the satisfied patients. The dissatisfied patients showed reduced knee extension strength in their replaced limb compared to their non-replaced limb and the satisfied patients. It has been suggested that the reduced knee extension moment can be related to a quadriceps avoidance gait pattern (25). By increasing the quadriceps strength and reducing the pain, the dissatisfied patients may be able to increase knee loading. Additionally, both 1^{st} and 2^{nd} peak VGRF levels were reduced in the dissatisfied group compared to the satisfied group. VGRF is an indication of overall body loading but can also impact the joint moments, especially knee extension moment, as is evidenced by simultaneous reductions in the knee extension moment and VGRF levels for the dissatisfied patients. The final variable in this model was the FJS score, with the dissatisfied patients showing increased scores on the FJS compared to satisfied patients. The FJS was designed to examine the patient's awareness of the replaced joint during different activities, with the ability to forget about the replaced joint during activities of daily living as the ultimate measure of satisfaction (158). This is a point not as evident in survey tools such as the WOMAC. The increased scores for the dissatisfied patients indicate an increased awareness of the joint and an inability for the joint to feel natural during movement. This may subsequently reduce the functional abilities of the dissatisfied patients and increase the pain levels, both of which are evident in the dissatisfied patients in this research as well as past research (219, 228).

The stair ascent model had two similar variables to the walking model, 2^{nd} peak VGRF and peak loading-response knee extension moment. Additionally, it was inclusive of preferred ascent gait speed and peak knee extension torque at 180°/s. Reductions in all four variables were present in the dissatisfied group compared to the satisfied group. Reductions in VGRF have been seen in TKR patients compared to healthy controls during stair ascent at preferred gait speed (235), but this was further compounded by the dissatisfied patients being lower than both satisfied patients and healthy controls in 2nd peak VGRF and preferred gait speed. Knee extension moments have mixed results in comparing TKR patients to healthy controls as reduced knee extension moments have been reported by some studies (24, 39-41) while others have reported no differences (22, 36, 42). As mentioned previously, reduced knee extension moments are often due to weaker quadriceps muscles, leading to a quadriceps avoidance gait as a means of avoiding knee joint loading (24, 129). This point is further accentuated by the reduced knee extension strength and extension moments in the same predictive model. Satisfied TKR patients had increased levels of all the included variables, suggesting that an increase in strength, moments, and speed increases patient satisfaction.

The stair descent model was similar to the stair ascent model, with the inclusion of the loading-response knee extension moment, preferred descent gait speed, and peak extension torque (180°/s). The 2nd peak VGRF was replaced with the FJS. Dissatisfied patients showed reduced knee extension moments, preferred gait speeds, and extension torque, while reporting increased FJS scores. Research is mixed with respect to knee extension moments during stair descent with one study showing reduced values in TKR patients compared to healthy controls (22) while other studies have shown no differences (36, 40, 127). Reduced knee extension moments have accompanied reduced gait velocity for TKR patients during stair descent (24, 39-41). As with the stair ascent model, the reduction in quadriceps strength has also been linked to knee extension moments and joint loading. Similar to the walking model, the presence of the increased FJS score indicates an inability for dissatisfied patients to have reduced awareness of the replaced joint. An increased awareness of the replaced joint may impact the patient's ability to perform daily activities using the joint.

In other investigations into satisfaction for TKR patients, pain has been consistently reported as a factor for satisfaction prediction (18, 210, 254). None of the models presented in this paper included specific VAS pain scores (aside from the WOMAC total score which has a pain component to it). Pain was assessed after every test the TKR patients performed through VAS, with the dissatisfied patients consistently reporting higher pain than the satisfied patients. Based on initial analysis, pain would have been included in the models prior to WOMAC and some additional variables as it had the higher Chi square values, therefore, based on the high correlation of pain with the WOMAC, pain would have been input first. However when pain levels were entered into any of the models, the model came back with an error message indicating a complete separation of the data points. This essentially indicates that the presence of pain in the dissatisfied patients is a universal truth, therefore the inclusion of pain in any model is a perfect fit. While pain was not included in any model because of this, it is important to highlight the effect pain has on the models and what its subsequent relationship to patient dissatisfaction is.

This study has a few limitations worth mentioning. Most notably, the sample size is much smaller than what traditional logistic regressions require. We only have nine dissatisfied patients and fifteen satisfied patients. Despite this, to our knowledge, this is the first logistic regression to analyze TKR patient dissatisfaction based on kinematic and kinetic variables. Future research would benefit from a larger sample size of dissatisfied patients in order to add to the power of the regression models, and confirm and strengthen these models. Additionally, none of the included independent variables showed significance within the model, likely due to the small sample size. Aside from this, model fit statistics were still significant and showed good fit for the reported models. Finally, balance data was collected on this patient population, however, due to an inability of many TKR patients to complete the unilateral balance tests, we were unable to include the data in the model analyses. During static unilateral balance trials, approximately 33% of the dissatisfied patients were unable to complete the trials and 13% of the satisfied patients failed to do so. As for the dynamic unilateral balance trials, 56% of dissatisfied patients could not complete the trials compared to 27% of the satisfied patients. This indicates a reduced ability of the dissatisfied patients to complete balance trials, yet it means an inability of the model to include the data due to lack of observations. In order to preserve the already small sample size, we decided not to include the balance data. Future research would benefit from the increased sample size for increased observations which may allow for inclusion of the balance information.

Conclusion

As evidenced, patient satisfaction is a complicated construct. Through the use of kinematic, kinetic, and strength data, a few variables were evident in creating models for dissatisfaction prediction. Knee extension moments, VGRF, and knee isokinetic extension strength were frequently evident for their contribution to patient dissatisfaction. Increasing the patient's ability to handle increases in these independent variables may help to improve their satisfaction levels. Additionally, the presence of pain is the most important factor, despite not being included in any of the models. Future research may benefit from examining improvements in these independent variables and how that improves patient satisfaction rates.

Chapter VI Appendix: Tables and Figures

Table 13. Logistic regression models for TKR patient satisfaction with respect to survey data, strength, and 3D kinematics and kinetics for over ground walking, stair ascent, and stair descent.

Model	R^2	AIC	P value
WOMAC Total Score, Stair Ascend Time, Chair Rise Time, Peak Extension Torque (60°/s), Quad/Hamstring Ratio (60°/s)	0.87	19.51	0.0002
Walking 1st Peak VGRF, Walking 2nd Peak VGRF, Walking Knee Internal Rotation Moment, FJS	0.75	21.34	0.0015
Walking 1st Peak VGRF, Walking 2nd Peak VGRF, Walking Knee Extension Moment, FJS	0.69	22.73	0.0026
Stair Ascend 2nd Peak VGRF, Ascend Loading Knee Extension Moment, Preferred Ascend gait speed, Peak Extension torque (180°/s)	0.72	23.85	0.0013
Stair Descend Loading-response Knee Extension Moment, Preferred Descend gait speed, Peak Extension Torque (180°/s), FJS	0.80	20.47	0.0003

Table 14. Slope (B), standard error (SE), Odds ratio (OR), and 95% confidence intervals (95% CI) for predictive variables for top model of strength, functional test, and survey data.

Variable	B	SE	P value	OR	95% CI
WOMAC Total Score	-0.06	0.04	0.1977	0.95	0.87 - 1.03
Stair Ascend Time	-9.43	7.31	0.1970	<0.001	<0.001 to 133.75
Chair Rise Time	2.69	2.19	0.2186	14.72	0.20 to >999.99
Peak Extension Torque (60°/s)	0.01	0.05	0.8379	1.01	0.91 to 1.13
Quad/Hamstring Ratio (60°/s)	12.80	11.02	0.2454	>999.99	<0.001 to >999.99
Constant (Intercept)	-1.28	8.13	0.8749	NA	NA

Table 15. Slope (B), standard error (SE), Odds ratio (OR), and 95% confidence intervals (95% CI) for predictive variables for top model of walking data.

Variable	B	SE	P value	OR	95% CI
1st Peak VGRF	-30.65	41.56	0.4608	<0.001	<0.001 to >999.99
2nd Peak VGRF	43.56	48.94	0.3735	>999.99	<0.001 to >999.99
Loading-response Knee Extension Moment	10.92	10.48	0.2978	>999.99	<0.001 to >999.99
FJS	0.05	0.04	0.1743	1.05	0.98 to 1.13
Constant (Intercept)	-18.89	17.03	0.2674	NA	NA

Table 16. Slope (B), standard error (SE), Odds ratio (OR), and 95% confidence intervals (95% CI) for predictive variables for top model of stair ascent data.

Variable	B	SE	P value	OR	95% CI
2nd Peak VGRF	17.74	10.93	0.1046	>999.99	0.025 to >999.99
Loading-response Knee Extension Moment	0.97	3.48	0.7801	2.64	0.003 to >999.99
Preferred Ascend Gait Speed	10.19	7.06	0.1491	>999.99	0.026 to >999.99
Peak Extension Torque (180°/s)	0.03	0.04	0.4162	1.03	0.96 to 1.10
Constant (Intercept)	-28.60	13.21	0.0303	NA	NA

Table 17. Slope (B), standard error (SE), Odds ratio (OR), and 95% confidence intervals (95% CI) for predictive variables for top model of stair descent data.

Variable	B	SE	P value	OR	95% CI
Loading-response Knee Extension Moment	-2.48	5.40	0.6461	0.08	<0.001 to >999.99
Preferred Descend Gait Speed	13.52	11.19	0.2272	>999.99	<0.001 to >999.99
Peak Extension Torque (180°/s)	0.09	0.06	0.1234	1.10	0.98 to 1.24
FJS	0.10	0.06	0.0756	1.10	0.99 to 1.23
Constant (Intercept)	-16.20	9.10	0.0750	NA	NA

CHAPTER VII

CONCLUSION

The purpose of this dissertation was to examine the strength, balance abilities, functional abilities, and lower extremity biomechanics during level ground walking, stair ascent, and stair descent of dissatisfied TKR patients. In study one, the analysis of overground walking biomechanics showed that dissatisfied patients have altered level ground gait mechanics, with the presence of increased knee joint pain and decreased preferred gait speed. Dissatisfied patients exhibited reduced 1st and 2nd peak VGRF values, reduced knee flexion ROM, and knee extension moments. The dissatisfied patients walk in such a manner that the knee joint experiences reduced extension loads, likely as a means of alleviating the experienced pain and joint loading. In study two, this was further evidenced during both stair ascent and descent activities. The dissatisfied patients had reduced knee extension moments and abduction moments, reduced preferred gait speed, and increased knee pain during ascent and descent activities. Stair climbing is a more demanding activity compared to level ground walking, as is evidenced by the amplified gait mechanics differences during these activities. The increased changes may be the result of increasing levels of pain and thus a desire to unload the affected joint.

In study three, the dissatisfied patients showed a reduced ability during functional exams and reduced passive knee ROM, common assessments used during the rehabilitation process. Reduced abilities were further evidenced by reduced strength levels and a more frequent inability to complete single limb balance trials. Dissatisfied patients showed reduced knee extensor and flexor strength, both of which are associated with deficits in gait mechanics. It is worth noting, however, that when the ability to balance was present, there was no difference between satisfied and dissatisfied TKR patients. In study four, a logistic regression analysis examined four different models based on the data collected in this study, which reported good measures of fit in prediction of patient dissatisfaction. These models often showed similarities in prediction variables, such as the knee extension moment during overground walking, stair ascent, and stair descent or one of the VGRF peaks (a measure of whole body loading).

The findings of this dissertation highlight that there are significant physical differences in the dissatisfied TKR patients compared to satisfied TKR patients and healthy controls. With the knee extension moment and knee extensor strength consistently being a source of significant difference between satisfied and dissatisfied patients, it becomes evident that rehabilitation and post-operative training should address this. Gait retraining may be an asset in order to teach dissatisfied patients how to more appropriately handle the joint load. This may be further aided through additional strength training as evidenced by the dissatisfied patients reduced strength. Increased strength of the knee joint muscles may aid in dissatisfied patients ability to handle the increased knee loading and potentially improve the satisfaction rates of TKR patients.

With every test performed, the dissatisfied patients reported increased levels of pain in their replaced knee. When pain was entered into any of the regression models, a complete separation of the data points existed, essentially implying that pain in the dissatisfied patients is a truism. The presence of the knee pain is likely impairing knee mechanics, as there is a desire to unload the joint when pain is present. As such, addressing pain is an additional pertinent issue which may help to subsequently improve the mechanical factors of the knee joint. A goal of TKR surgery is to alleviate joint pain experienced during osteoarthritis, however, in the case of the dissatisfied patients, this goal was not met. From a physical standpoint, the pain should have dissipated with the removal of the bone on bone contact present during end-stage osteoarthritis.

Given the continued presence of pain well over two years after surgery, these patients may benefit from psychological training techniques which have been shown to help with pain reduction, such as guided imagery, deep breathing, or relaxation techniques. These characteristics all collectively illustrate the patient satisfaction is a multifaceted construct. Many potential factors were not taken into consideration with this research (such as quality of life, support, and other factors unrelated to their physical experiences). What this research does highlight is that additional physical training during the rehabilitation process may be beneficial, including mental skills training to help deal with the psychological aspects of increased joint demands and pain. If the patients are unsure of the replaced knee's ability to perform, it may additionally lead to joint avoidance. Future research should examine a more holistic approach to the rehabilitation process to examine the effects on patient satisfaction.

REFERENCES

1. Hootman, J.M. and C.G. Helmick, *Projections of US prevalence of arthritis and associated activity limitations.* Arthritis and Rheumatism, 2006. **54**(1): p. 226-229.
2. Statistics, N.C.f.H., *Cost of hospital discharges with common hospital operating room procedures in non-federal community hospitals, by age and selected principal procedure: United States, selected years 2000-2011.* 2013, Center for Disease Control and Prevention: http://www.cdc.gov/nchs/hus/contents2012.htm.
3. Kurtz, S., et al., *Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030.* Journal of Bone and Joint Surgery-American Volume, 2007. **89a**(4): p. 780-785.
4. Ravi, B., et al., *The changing demographics of total joint arthroplasty recipients in the United States and Ontario from 2001 to 2007.* Best Practice & Research in Clinical Rheumatology, 2012. **26**(5): p. 637-647.
5. Scuderi, G.R., et al., *The New Knee Society Knee Scoring System.* Clinical Orthopaedics and Related Research, 2012. **470**(1): p. 3-19.
6. Bruyere, O., et al., *Health-related quality of life after total knee or hip replacement for osteoarthritis: a 7-year prospective study.* Archives of Orthopaedic and Trauma Surgery, 2012. **132**(11): p. 1583-1587.
7. Hawker, G., et al., *Health-related quality of life after knee replacement - Results of the Knee Replacement Patient Outcomes Research Team Study.* Journal of Bone and Joint Surgery-American Volume, 1998. **80a**(2): p. 163-173.
8. Ko, Y., et al., *Health-Related Quality of Life after Total Knee Replacement or Unicompartmental Knee Arthroplasty in an Urban Asian Population.* Value in Health, 2011. **14**(2): p. 322-328.
9. Kim, T.K., et al., *Causes and Predictors of Patient's Dissatisfaction After Uncomplicated Total Knee Arthroplasty.* Journal of Arthroplasty, 2009. **24**(2): p. 263-271.
10. Felts, E., et al., *Function and quality of life following medial unicompartmental knee arthroplasty in patients 60 years of age or younger.* Orthop Traumatol Surg Res, 2010. **96**(8): p. 861-7.
11. Weiss, J.M., et al., *What functional activities are important to patients with knee replacements?* Clin Orthop Relat Res, 2002(404): p. 172-88.
12. Beswick, A.D., et al., *What proportion of patients report long-term pain after total hip or knee replacement for osteoarthritis? A systematic review of prospective studies in unselected patients.* BMJ Open, 2012. **2**(1): p. e000435.
13. Noble, P.C., et al., *Does total knee replacement restore normal knee function?* Clin Orthop Relat Res, 2005(431): p. 157-65.
14. Boonstra, M.C., M.C. De Waal Malefijt, and N. Verdonschot, *How to quantify knee function after total knee arthroplasty?* Knee, 2008. **15**(5): p. 390-5.
15. Ouellet, D. and H. Moffet, *Locomotor deficits before and two months after knee arthroplasty.* Arthritis Rheum, 2002. **47**(5): p. 484-93.
16. Ali, A., et al., *Dissatisfied patients after total knee arthroplasty: a registry study involving 114 patients with 8-13 years of followup.* Acta Orthop, 2014. **85**(3): p. 229-33.
17. Anderson, J.G., et al., *Functional outcome and patient satisfaction in total knee patients over the age of 75.* Journal of Arthroplasty, 1996. **11**(7): p. 831-840.
18. Baker, P.N., et al., *The role of pain and function in determining patient satisfaction after total knee replacement - Data from the National Joint Registry for England and Wales.* Journal of Bone and Joint Surgery-British Volume, 2007. **89b**(7): p. 893-900.

19. Standifird, T.W., et al., *Influence of Total Knee Arthroplasty on Gait Mechanics of the Replaced and Non-Replaced Limb During Stair Negotiation.* J Arthroplasty, 2016. **31**(1): p. 278-83.
20. Benedetti, M.G., et al., *Muscle activation pattern and gait biomechanics after total knee replacement.* Clin Biomech (Bristol, Avon), 2003. **18**(9): p. 871-6.
21. Metcalfe, A., et al., *Abnormal loading of the major joints in knee osteoarthritis and the response to knee replacement.* Gait Posture, 2013. **37**(1): p. 32-6.
22. Wilson, S.A., et al., *Comprehensive gait analysis in posterior-stabilized knee arthroplasty.* J Arthroplasty, 1996. **11**(4): p. 359-67.
23. McClelland, J.A., et al., *Knee kinematics during walking at different speeds in people who have undergone total knee replacement.* Knee, 2011. **18**(3): p. 151-5.
24. Mandeville, D., L.R. Osternig, and L.S. Chou, *The effect of total knee replacement on dynamic support of the body during walking and stair ascent.* Clin Biomech (Bristol, Avon), 2007. **22**(7): p. 787-94.
25. Levinger, P., et al., *Lower limb biomechanics in individuals with knee osteoarthritis before and after total knee arthroplasty surgery.* J Arthroplasty, 2013. **28**(6): p. 994-9.
26. Smith, A.J., D.G. Lloyd, and D.J. Wood, *A kinematic and kinetic analysis of walking after total knee arthroplasty with and without patellar resurfacing.* Clin Biomech (Bristol, Avon), 2006. **21**(4): p. 379-86.
27. Orishimo, K.F., et al., *Does total knee arthroplasty change frontal plane knee biomechanics during gait?* Clin Orthop Relat Res, 2012. **470**(4): p. 1171-6.
28. Mandeville, D., et al., *The effect of total knee replacement on the knee varus angle and moment during walking and stair ascent.* Clin Biomech (Bristol, Avon), 2008. **23**(8): p. 1053-8.
29. Nadeau, S., B.J. McFadyen, and F. Malouin, *Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking?* Clin Biomech (Bristol, Avon), 2003. **18**(10): p. 950-9.
30. Paquette, M.R., et al., *Effects of increased step width on frontal plane knee biomechanics in healthy older adults during stair descent.* Knee, 2014. **21**(4): p. 821-826.
31. Startzell, J.K., et al., *Stair negotiation in older people: a review.* J Am Geriatr Soc, 2000. **48**(5): p. 567-80.
32. Williamson, J.D. and L.P. Fried, *Characterization of older adults who attribute functional decrements to "old age".* J Am Geriatr Soc, 1996. **44**(12): p. 1429-34.
33. Costigan, P.A., K.J. Deluzio, and U.P. Wyss, *Knee and hip kinetics during normal stair climbing.* Gait Posture, 2002. **16**(1): p. 31-7.
34. Dawson, J., et al., *Questionnaire on the perceptions of patients about total knee replacement.* J Bone Joint Surg Br, 1998. **80**(1): p. 63-9.
35. Insall, J.N., et al., *Rationale of the Knee Society clinical rating system.* Clin Orthop Relat Res, 1989(248): p. 13-4.
36. Bolanos, A.A., et al., *A comparison of isokinetic strength testing and gait analysis in patients with posterior cruciate-retaining and substituting knee arthroplasties.* J Arthroplasty, 1998. **13**(8): p. 906-15.
37. Kelman, G.J., et al., *Gait laboratory analysis of a posterior cruciate-sparing total knee arthroplasty in stair ascent and descent.* Clin Orthop Relat Res, 1989(248): p. 21-5; discussion 25-6.

38. Alnahdi, A.H., J.A. Zeni, and L. Snyder-Mackler, *Gait after unilateral total knee arthroplasty: frontal plane analysis.* J Orthop Res, 2011. **29**(5): p. 647-52.
39. Berti, L., et al., *Clinical and biomechanical assessment of patella resurfacing in total knee arthroplasty.* Clin Biomech (Bristol, Avon), 2006. **21**(6): p. 610-6.
40. Catani, F., et al., *Mobile and fixed bearing total knee prosthesis functional comparison during stair climbing.* Clin Biomech (Bristol, Avon), 2003. **18**(5): p. 410-8.
41. Fantozzi, S., et al., *Fluoroscopic and gait analysis of the functional performance in stair ascent of two total knee replacement designs.* Gait Posture, 2003. **17**(3): p. 225-34.
42. Saari, T., et al., *Total knee replacement influences both knee and hip joint kinematics during stair climbing.* Int Orthop, 2004. **28**(2): p. 82-6.
43. Mizner, R.L., et al., *Preoperative quadriceps strength predicts functional ability one year after total knee arthroplasty.* J Rheumatol, 2005. **32**(8): p. 1533-9.
44. Judd, D.L., D.G. Eckhoff, and J.E. Stevens-Lapsley, *Muscle strength loss in the lower limb after total knee arthroplasty.* Am J Phys Med Rehabil, 2012. **91**(3): p. 220-6; quiz 227-30.
45. Schroer, W.C., et al., *Isokinetic strength testing of minimally invasive total knee arthroplasty recovery.* J Arthroplasty, 2010. **25**(2): p. 274-9.
46. Yoshida, Y., et al., *Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time.* Clin Biomech (Bristol, Avon), 2008. **23**(3): p. 320-8.
47. Swinkels, A., J.H. Newman, and T.J. Allain, *A prospective observational study of falling before and after knee replacement surgery.* Age Ageing, 2009. **38**(2): p. 175-81.
48. Gauchard, G.C., et al., *On the role of knee joint in balance control and postural strategies: effects of total knee replacement in elderly subjects with knee osteoarthritis.* Gait Posture, 2010. **32**(2): p. 155-60.
49. Liao, C.D., et al., *Functional outcomes of outpatient balance training following total knee replacement in patients with knee osteoarthritis: a randomized controlled trial.* Clin Rehabil, 2015. **29**(9): p. 855-67.
50. Pua, Y.H., et al., *Associations of knee extensor strength and standing balance with physical function in knee osteoarthritis.* Arthritis Care Res (Hoboken), 2011. **63**(12): p. 1706-14.
51. Cho, S.D. and C.H. Hwang, *Improved single-limb balance after total knee arthroplasty.* Knee Surg Sports Traumatol Arthrosc, 2013. **21**(12): p. 2744-50.
52. Stensdotter, A.K., J. Bjerke, and M. Djupsjobacka, *Postural sway in single-limb and bilateral quiet standing after unilateral total knee arthroplasty.* Gait Posture, 2015. **41**(3): p. 769-73.
53. Hatfield, G.L., et al., *The effect of total knee arthroplasty on knee joint kinematics and kinetics during gait.* J Arthroplasty, 2011. **26**(2): p. 309-18.
54. Mandeville, D., L.R. Osternig, and L.S. Chou, *The effect of total knee replacement surgery on gait stability.* Gait Posture, 2008. **27**(1): p. 103-9.
55. White, R., et al., *The variability of force platform data in normal and cerebral palsy gait.* Clin Biomech (Bristol, Avon), 1999. **14**(3): p. 185-92.
56. Sigal, L., A.O. Balan, and M.J. Black, *HUMANEVA: Synchronized Video and Motion Capture Dataset and Baseline Algorithm for Evaluation of Articulated Human Motion.* International Journal of Computer Vision, 2010. **87**: p. 4-27.

57. Winter, D.A., *Biomechanics and motor control of human movement*. 2009: John Wiley & Sons.
58. Plankers, R. and P. Fua, *Tracking and modeling people in video sequences.* Computer Vision and Image Understanding, 2001. **81**: p. 285-302.
59. Liu, J. and T.E. Lockhart, *Comparison of 3D joint moments using local and global inverse dynamics approaches among three different age groups.* Gait Posture, 2006. **23**(4): p. 480-5.
60. Akbarshahi, M., et al., *Non-invasive assessment of soft-tissue artifact and its effect on knee joint kinematics during functional activity*. J Biomech, 2010. **43**(7): p. 1292-301.
61. Kuo, M.Y., et al., *Influence of soft tissue artifacts on the calculated kinematics and kinetics of total knee replacements during sit-to-stand.* Gait Posture, 2011. **33**(3): p. 379-84.
62. Alkjaer, T., E.B. Simonsen, and P. Dyhre-Poulsen, *Comparison of inverse dynamics calculated by two- and three-dimensional models during walking.* Gait Posture, 2001. **13**(2): p. 73-7.
63. Davis, R.B., *Clinical gait analysis.* IEEE Eng Med Biol Mag, 1988. **7**(3): p. 35-40.
64. Collins, T.D., et al., *A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set.* Gait Posture, 2009. **30**(2): p. 173-80.
65. Schwartz, M.H., J.P. Trost, and R.A. Wervey, *Measurement and management of errors in quantitative gait data.* Gait Posture, 2004. **20**(2): p. 196-203.
66. Moeslund, T.B. and E. Granum, *A survey of computer vision-based human motion capture.* Computer Vision and Image Understanding, 2001. **81**: p. 231-268.
67. Weinhandl, J.T., et al., *Validation of a single camera three-dimensional motion tracking system.* J Biomech, 2010. **43**(7): p. 1437-40.
68. Miro, F., et al., *2D versus 3D in the kinematic analysis of the horse at the trot.* Vet Res Commun, 2009. **33**(6): p. 507-13.
69. Kadaba, M.P., H.K. Ramakrishnan, and M.E. Wootten, *Measurement of lower extremity kinematics during level walking.* J Orthop Res, 1990. **8**(3): p. 383-92.
70. Cappozzo, A., *Gait Analysis Methodology.* Human Movement Science, 1984. **3**(1-2): p. 27-50.
71. Alexander, E.J. and T.P. Andriacchi, *Correcting for deformation in skin-based marker systems.* J Biomech, 2001. **34**(3): p. 355-61.
72. Andersen, M.S., et al., *Do kinematic models reduce the effects of soft tissue artefacts in skin marker-based motion analysis? An in vivo study of knee kinematics.* J Biomech, 2010. **43**(2): p. 268-73.
73. Benoit, D.L., et al., *Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo.* Gait Posture, 2006. **24**(2): p. 152-64.
74. Holden, J.P., et al., *Surface movement errors in shank kinematics and knee kinetics during gait.* Gait Posture, 1997. **5**: p. 217-227.
75. Manal, K., et al., *Knee moment profiles during walking: errors due to soft tissue movement of the shank and the influence of the reference coordinate system.* Gait Posture, 2002. **15**(1): p. 10-7.
76. Ramsey, D.K., et al., *Methodological concerns using intra-cortical pins to measure tibiofemoral kinematics.* Knee Surg Sports Traumatol Arthrosc, 2003. **11**(5): p. 344-9.
77. Reinschmidt, C., et al., *Tibiofemoral and tibiocalcaneal motion during walking: external vs. skeletal markers.* Gait Posture, 1997. **6**: p. 98-109.

78. Ryu, T., H.S. Choi, and M.K. Chung, *Soft tissue artifact compensation using displacement dependency between anatomical landmarks and skin markers--a preliminary study.* International Journal of Industrial Ergonomics, 2009. **39**: p. 152-158.
79. Della Croce, U., et al., *Human movement analysis using stereophotogrammetry: Part 4: assessment of anatomical landmark misplacement and its effects on joint kinematics.* Gait Posture, 2005. **21**(2): p. 226-237.
80. Manal, K., et al., *Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: an in vivo study.* Gait Posture, 2000. **11**(1): p. 38-45.
81. Ferrari, A., et al., *Quantitative comparison of five current protocols in gait analysis.* Gait Posture, 2008. **28**(2): p. 207-16.
82. Gao, B. and N.N. Zheng, *Investigation of soft tissue movement during level walking: translations and rotations of skin markers.* J Biomech, 2008. **41**(15): p. 3189-95.
83. Miranda, D.L., et al., *Kinematic differences between optical motion capture and biplanar videoradiography during a jump-cut maneuver.* J Biomech, 2013. **46**(3): p. 567-73.
84. Stagni, R., et al., *Quantification of soft tissue artefact in motion analysis by combining 3D fluoroscopy and stereophotogrammetry: a study on two subjects.* Clin Biomech (Bristol, Avon), 2005. **20**(3): p. 320-9.
85. Tsai, T.Y., et al., *Effects of soft tissue artifacts on the calculated kinematics and kinetics of the knee during stair-ascent.* J Biomech, 2011. **44**(6): p. 1182-8.
86. Cappozzo, A., et al., *Position and orientation in space of bones during movement: experimental artefacts.* Clin Biomech (Bristol, Avon), 1996. **11**(2): p. 90-100.
87. Cappello, A., et al., *Multiple anatomical landmark calibration for optimal bone pose estimation.* Human Movement Science, 1997. **16**: p. 259-274.
88. Andriacchi, T.P., et al., *A point cluster method for in vivo motion analysis: applied to a study of knee kinematics.* J Biomech Eng, 1998. **120**(6): p. 743-9.
89. Perry, J. and J.R. Davids, *Gait analysis: normal and pathological function.* Journal of Pediatric Orthopaedics, 1992. **12**(6): p. 815.
90. Gorton, G.E., 3rd, D.A. Hebert, and M.E. Gannotti, *Assessment of the kinematic variability among 12 motion analysis laboratories.* Gait Posture, 2009. **29**(3): p. 398-402.
91. McGinley, J.L., et al., *The reliability of three-dimensional kinematic gait measurements: a systematic review.* Gait Posture, 2009. **29**(3): p. 360-9.
92. Corazza, S., et al., *A markerless motion capture system to study musculoskeletal biomechanics: visual hull and simulated annealing approach.* Ann Biomed Eng, 2006. **34**(6): p. 1019-29.
93. Chao, E.Y., et al., *Normative data of knee joint motion and ground reaction forces in adult level walking.* J Biomech, 1983. **16**(3): p. 219-33.
94. Soderkvist, I. and P.A. Wedin, *Determining the movements of the skeleton using well-configured markers.* J Biomech, 1993. **26**(12): p. 1473-7.
95. Grood, E.S. and W.J. Suntay, *A joint coordinate system for the clinical description of three-dimensional motions: application to the knee.* J Biomech Eng, 1983. **105**(2): p. 136-44.
96. Wu, G., et al., *ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. International Society of Biomechanics.* J Biomech, 2002. **35**(4): p. 543-8.

97. Schache, A.G., R. Baker, and C.L. Vaughan, *Differences in lower limb transverse plane joint moments during gait when expressed in two alternative reference frames.* J Biomech, 2007. **40**(1): p. 9-19.
98. Kristianslund, E., et al., *Expressing the joint moments of drop jumps and sidestep cutting in different reference frames--does it matter?* J Biomech, 2014. **47**(1): p. 193-9.
99. Woltring, H.J., *Representation and Calculation of 3-D Joint Movement.* Human Movement Science, 1991. **10**(5): p. 603-616.
100. Cole, G.K., et al., *Application of the Joint Coordinate System to 3-Dimensional Joint Attitude and Movement Representation - a Standardization Proposal.* Journal of Biomechanical Engineering-Transactions of the Asme, 1993. **115**(4): p. 344-349.
101. Lees, A., G. Barton, and M. Robinson, *The influence of Cardan rotation sequence on angular orientation data for the lower limb in the soccer kick.* Journal of Sports Sciences, 2010. **28**(4): p. 445-450.
102. Senk, M. and L. Cheze, *Rotation sequence as an important factor in shoulder kinematics.* Clinical Biomechanics, 2006. **21**: p. S3-S8.
103. Cappozzo, A., et al., *Human movement analysis using stereophotogrammetry - Part 1: theoretical background.* Gait & Posture, 2005. **21**(2): p. 186-196.
104. Choisne, J., et al., *Influence of kinematic analysis methods on detecting ankle and subtalar joint instability.* Journal of Biomechanics, 2012. **45**(1): p. 46-52.
105. Schache, A.G. and R. Baker, *On the expression of joint moments during gait.* Gait Posture, 2007. **25**(3): p. 440-52.
106. Schache, A.G., R. Baker, and L.W. Lamoreux, *Defining the knee joint flexion-extension axis for purposes of quantitative gait analysis: an evaluation of methods.* Gait Posture, 2006. **24**(1): p. 100-9.
107. Barbour, K., et al., *Prevalence of doctor-diagnosed arthritis and arthritis-attributable activity limitation--United States, 2010-2012.* Morbidity and Mortality Weekly Report, 2013. **62**(44): p. 869-873.
108. Mehrotra, C., et al., *Trends in total knee replacement surgeries and implications for public health, 1990-2000.* Public Health Reports, 2005. **120**(3): p. 278-282.
109. Paquette, M.R., et al., *Does increasing step width alter knee biomechanics in medial compartment knee osteoarthritis patients during stair descent?* Knee, 2014. **21**(3): p. 676-82.
110. Tekin, B., B. Unver, and V. Karatosun, *Expectations in patients with total knee arthroplasty.* Acta Orthop Traumatol Turc, 2012. **46**(3): p. 174-80.
111. Noble, P.C., et al., *The John Insall Award: Patient expectations affect satisfaction with total knee arthroplasty.* Clin Orthop Relat Res, 2006. **452**: p. 35-43.
112. Parvizi, J., et al., *High level of residual symptoms in young patients after total knee arthroplasty.* Clin Orthop Relat Res, 2014. **472**(1): p. 133-7.
113. Kramers-de Quervain, I.A., et al., *Prospective study of gait function before and 2 years after total knee arthroplasty.* Knee, 2012. **19**(5): p. 622-7.
114. Milner, C.E. and M.E. O'Bryan, *Bilateral frontal plane mechanics after unilateral total knee arthroplasty.* Arch Phys Med Rehabil, 2008. **89**(10): p. 1965-9.
115. Ainsworth, B.E., et al., *2011 Compendium of Physical Activities: a second update of codes and MET values.* Med Sci Sports Exerc, 2011. **43**(8): p. 1575-81.
116. Turcot, K., et al., *How gait and clinical outcomes contribute to patients' satisfaction three months following a total knee arthroplasty.* J Arthroplasty, 2013. **28**(8): p. 1297-300.

117. Protopapadaki, A., et al., *Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals.* Clin Biomech (Bristol, Avon), 2007. **22**(2): p. 203-10.
118. McMahon, M. and J.A. Block, *The risk of contralateral total knee arthroplasty after knee replacement for osteoarthritis.* J Rheumatol, 2003. **30**(8): p. 1822-4.
119. Hamel, K.A., et al., *A comparison of foot/ground interaction during stair negotiation and level walking in young and older women.* Ergonomics, 2005. **48**(8): p. 1047-56.
120. Standifird, T.W., *Lower Extremity Biomechanics during Stair Ascent in Healthy and Total Knee Replacement Older Adults,* in *Kinesiology, Recreation, and Sports Studies*. 2015, University of Tennessee Knoxville: Trace: Tennessee Research and Creative Exchange. p. 231.
121. Morrison, J.B., *Function of the knee joint in various activities.* Biomed Eng, 1969. **4**(12): p. 573-80.
122. Rasnick, R., et al., *Knee Joint Loads and Surrounding Muscle Forces during Stair Ascent in Patients with Total Knee Replacement.* PLoS One, 2016. **11**(6): p. e0156282.
123. Luepongsak, N., et al., *The contribution of type of daily activity to loading across the hip and knee joints in the elderly*. Osteoarthritis Cartilage, 2002. **10**(5): p. 353-9.
124. Milner, C.E., *Is gait normal after total knee arthroplasty? Systematic review of the literature*. J Orthop Sci, 2009. **14**(1): p. 114-20.
125. Jevsevar, D.S., et al., *Knee kinematics and kinetics during locomotor activities of daily living in subjects with knee arthroplasty and in healthy control subjects.* Phys Ther, 1993. **73**(4): p. 229-39; discussion 240-2.
126. Pollo, F.E., et al., *Walking, chair rising, and stair climbing after total knee arthroplasty: patellar resurfacing versus nonresurfacing.* Am J Knee Surg, 2000. **13**(2): p. 103-8; discussion 108-9.
127. Joglekar, S., et al., *Gait analysis comparison of cruciate retaining and substituting TKA following PCL sacrifice*. Knee, 2012. **19**(4): p. 279-85.
128. McClelland, J.A., K.E. Webster, and J.A. Feller, *Variability of walking and other daily activities in patients with total knee replacement.* Gait Posture, 2009. **30**(3): p. 288-95.
129. Andriacchi, T.P., J.O. Galante, and R.W. Fermier, *The influence of total knee-replacement design on walking and stair-climbing.* J Bone Joint Surg Am, 1982. **64**(9): p. 1328-35.
130. Milner, C.E., *Interlimb asymmetry during walking following unilateral total knee arthroplasty*. Gait Posture, 2008. **28**(1): p. 69-73.
131. Andriacchi, T.P., et al., *A study of lower-limb mechanics during stair-climbing.* J Bone Joint Surg Am, 1980. **62**(5): p. 749-57.
132. Standifird, T.W., H.E. Cates, and S. Zhang, *Stair ambulation biomechanics following total knee arthroplasty: a systematic review*. J Arthroplasty, 2014. **29**(9): p. 1857-62.
133. Zhao, D., et al., *Correlation between the knee adduction torque and medial contact force for a variety of gait patterns.* J Orthop Res, 2007. **25**(6): p. 789-97.
134. Baliunas, A.J., et al., *Increased knee joint loads during walking are present in subjects with knee osteoarthritis.* Osteoarthritis Cartilage, 2002. **10**(7): p. 573-9.
135. Hurwitz, D.E., et al., *The knee adduction moment during gait in subjects with knee osteoarthritis is more closely correlated with static alignment than radiographic disease severity, toe out angle and pain.* J Orthop Res, 2002. **20**(1): p. 101-7.

136. Miyazaki, T., et al., *Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis.* Ann Rheum Dis, 2002. **61**(7): p. 617-22.
137. Bennett, H.J., *Static Frontal Plane Tibiofemoral Alignments and Their Effects on Knee Biomechanics During Level Walking and Stair Ascent Tasks*, in *Kinesiology, Recreation, and Sports Studies*. 2016, University of Tennessee Knoxville: Trace: Tennessee Research and Creative Exchange. p. 194.
138. Debbi, E.M., et al., *Frontal plane biomechanics of the operated and non-operated knees before and after unilateral total knee arthroplasty.* Clin Biomech (Bristol, Avon), 2015. **30**(9): p. 889-94.
139. Vahtrik, D., et al., *Postural stability in relation to anthropometric and functional characteristics in women with knee osteoarthritis following total knee arthroplasty.* Arch Orthop Trauma Surg, 2014. **134**(5): p. 685-92.
140. Huang, C.H., et al., *Muscle strength after successful total knee replacement: a 6- to 13-year followup.* Clin Orthop Relat Res, 1996(328): p. 147-54.
141. Valtonen, A., et al., *Muscle deficits persist after unilateral knee replacement and have implications for rehabilitation.* Phys Ther, 2009. **89**(10): p. 1072-9.
142. Rossi, M.D., et al., *Comparison of knee extensor strength between limbs in individuals with bilateral total knee replacement.* Arch Phys Med Rehabil, 2002. **83**(4): p. 523-6.
143. Vandekerckhove, P.J., et al., *Does cruciate retention primary total knee arthroplasty affect proprioception, strength and clinical outcome?* Knee Surg Sports Traumatol Arthrosc, 2015. **23**(6): p. 1644-52.
144. Franklin, P.D., W. Li, and D.C. Ayers, *The Chitranjan Ranawat Award: functional outcome after total knee replacement varies with patient attributes.* Clin Orthop Relat Res, 2008. **466**(11): p. 2597-604.
145. Topp, R., et al., *The effect of prehabilitation exercise on strength and functioning after total knee arthroplasty.* PM R, 2009. **1**(8): p. 729-35.
146. Rodgers, J.A., et al., *Preoperative physical therapy in primary total knee arthroplasty.* J Arthroplasty, 1998. **13**(4): p. 414-21.
147. Rahmann, A.E., S.G. Brauer, and J.C. Nitz, *A specific inpatient aquatic physiotherapy program improves strength after total hip or knee replacement surgery: a randomized controlled trial.* Arch Phys Med Rehabil, 2009. **90**(5): p. 745-55.
148. Lorentzen, J.S., et al., *Early changes in muscle strength after total knee arthroplasty. A 6-month follow-up of 30 knees.* Acta Orthop Scand, 1999. **70**(2): p. 176-9.
149. Gstoettner, M., et al., *Preoperative proprioceptive training in patients with total knee arthroplasty.* Knee, 2011. **18**(4): p. 265-70.
150. Doyle, T.L., R.U. Newton, and A.F. Burnett, *Reliability of traditional and fractal dimension measures of quiet stance center of pressure in young, healthy people.* Arch Phys Med Rehabil, 2005. **86**(10): p. 2034-40.
151. Alviar, M.J., et al., *Do Patient-Reported Outcome Measures in Hip and Knee Arthroplasty Rehabilitation Have Robust Measurement Attributes? A Systematic Review.* Journal of Rehabilitation Medicine, 2011. **43**(7): p. 572-583.
152. Bellamy, N. and W.W. Buchanan, *A preliminary evaluation of the dimensionality and clinical importance of pain and disability in osteoarthritis of the hip and knee.* Clin Rheumatol, 1986. **5**(2): p. 231-41.

153. Dawson, J., et al., *Comparison of measures to assess outcomes in total hip replacement surgery.* Qual Health Care, 1996. **5**(2): p. 81-8.
154. Ware, J.E., Jr. and C.D. Sherbourne, *The MOS 36-item short-form health survey (SF-36). I. Conceptual framework and item selection.* Med Care, 1992. **30**(6): p. 473-83.
155. Terwee, C.B., et al., *Quality criteria were proposed for measurement properties of health status questionnaires.* J Clin Epidemiol, 2007. **60**(1): p. 34-42.
156. Streiner, D.L. and G.R. Norman, *Health measurement scales: a practical guide to their development and use*. 1995, Oxford: Oxford University Press.
157. Dunbar, M.J., et al., *Appropriate questionnaires for knee arthroplasty. Results of a survey of 3600 patients from The Swedish Knee Arthroplasty Registry.* J Bone Joint Surg Br, 2001. **83**(3): p. 339-44.
158. Behrend, H., et al., *The "forgotten joint" as the ultimate goal in joint arthroplasty: validation of a new patient-reported outcome measure.* J Arthroplasty, 2012. **27**(3): p. 430-436 e1.
159. Nunnally, J.C., *Psychometric theory*. 1978, New York: McGraw-Hill Inc.
160. de Vet, H.C., et al., *Are factor analytical techniques used appropriately in the validation of health status questionnaires? A systematic review on the quality of factor analysis of the SF-36.* Qual Life Res, 2005. **14**(5): p. 1203-18; dicussion 1219-21, 1223-4.
161. Charoencholvanich, K. and B. Pongcharoen, *Oxford knee score and SF-36: translation & reliability for use with total knee arthroscopy patients in Thailand.* J Med Assoc Thai, 2005. **88**(9): p. 1194-202.
162. Brazier, J.E., et al., *Generic and condition-specific outcome measures for people with osteoarthritis of the knee.* Rheumatology (Oxford), 1999. **38**(9): p. 870-7.
163. Gabr, A., R. Tansey, and F.S. Haddad, *Outcome Measures in Total Knee Arthroplasty*. 2015, Switzerland: Springer International Publishing. 79-87.
164. de Vet, H.C., et al., *Reproducibility and responsiveness of evaluative outcome measures. Theoretical considerations illustrated by an empirical example.* Int J Technol Assess Health Care, 2001. **17**(4): p. 479-87.
165. Norman, G.R., J.A. Sloan, and K.W. Wyrwich, *Interpretation of changes in health-related quality of life: the remarkable universality of half a standard deviation.* Med Care, 2003. **41**(5): p. 582-92.
166. Angst, F., et al., *Responsiveness of the WOMAC osteoarthritis index as compared with the SF-36 in patients with osteoarthritis of the legs undergoing a comprehensive rehabilitation intervention.* Ann Rheum Dis, 2001. **60**(9): p. 834-40.
167. de Vet, H.C., et al., *When to use agreement versus reliability measures.* J Clin Epidemiol, 2006. **59**(10): p. 1033-9.
168. Bland, J.M. and D.G. Altman, *Statistical methods for assessing agreement between two methods of clinical measurement.* Lancet, 1986. **1**(8476): p. 307-10.
169. Terwee, C.B., et al., *On assessing responsiveness of health-related quality of life instruments: guidelines for instrument evaluation.* Qual Life Res, 2003. **12**(4): p. 349-62.
170. Osoba, D., et al., *Interpreting the significance of changes in health-related quality-of-life scores.* J Clin Oncol, 1998. **16**(1): p. 139-44.
171. Jaeschke, R., J. Singer, and G.H. Guyatt, *Measurement of health status. Ascertaining the minimal clinically important difference.* Control Clin Trials, 1989. **10**(4): p. 407-15.
172. Blanchard, C., et al., *Is the Health Utilities Index responsive in total hip arthroplasty patients?* J Clin Epidemiol, 2003. **56**(11): p. 1046-54.

173. Crosby, R.D., R.L. Kolotkin, and G.R. Williams, *Defining clinically meaningful change in health-related quality of life.* J Clin Epidemiol, 2003. **56**(5): p. 395-407.
174. Dunbar, M.J., et al., *Translation and validation of the Oxford-12 item knee score for use in Sweden.* Acta Orthop Scand, 2000. **71**(3): p. 268-74.
175. Wright, R.W., *Knee injury outcomes measures.* J Am Acad Orthop Surg, 2009. **17**(1): p. 31-9.
176. McConnell, S., P. Kolopack, and A.M. Davis, *The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC): a review of its utility and measurement properties.* Arthritis Rheum, 2001. **45**(5): p. 453-61.
177. Bellamy, N., et al., *Validation study of WOMAC: a health status instrument for measuring clinically important patient-relevant outcomes following total hip or knee arthroplasty in osteoarthritis.* J Orthop Rheumatol, 1988. **1**: p. 95-108.
178. Bellamy, N., et al., *Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee.* J Rheumatol, 1988. **15**(12): p. 1833-40.
179. Ostendorf, M., et al., *Patient-reported outcome in total hip replacement. A comparison of five instruments of health status.* J Bone Joint Surg Br, 2004. **86**(6): p. 801-8.
180. Soderman, P. and H. Malchau, *Validity and reliability of Swedish WOMAC osteoarthritis index: a self-administered disease-specific questionnaire (WOMAC) versus generic instruments (SF-36 and NHP).* Acta Orthop Scand, 2000. **71**(1): p. 39-46.
181. Xie, F., et al., *Validation of Chinese Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) in patients scheduled for total knee replacement.* Qual Life Res, 2008. **17**(4): p. 595-601.
182. Kennedy, D., et al., *Exploring the factorial validity and clinical interpretability of the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC).* Physiother Can, 2003. **55**: p. 160-168.
183. Roorda, L.D., et al., *Satisfactory cross cultural equivalence of the Dutch WOMAC in patients with hip osteoarthritis waiting for arthroplasty.* Ann Rheum Dis, 2004. **63**(1): p. 36-42.
184. Stratford, P.W., et al., *Measurement properties of the WOMAC LK 3.1 pain scale.* Osteoarthritis Cartilage, 2007. **15**(3): p. 266-72.
185. Chesworth, B.M., et al., *Willingness to go through surgery again validated the WOMAC clinically important difference from THR/TKR surgery.* J Clin Epidemiol, 2008. **61**(9): p. 907-18.
186. Escobar, A., et al., *Responsiveness and clinically important differences for the WOMAC and SF-36 after total knee replacement.* Osteoarthritis Cartilage, 2007. **15**(3): p. 273-80.
187. Quintana, J.M., et al., *Responsiveness and clinically important differences for the WOMAC and SF-36 after hip joint replacement.* Osteoarthritis Cartilage, 2005. **13**(12): p. 1076-83.
188. Bachmeier, C.J., et al., *A comparison of outcomes in osteoarthritis patients undergoing total hip and knee replacement surgery.* Osteoarthritis Cartilage, 2001. **9**(2): p. 137-46.
189. Haverkamp, D., et al., *Translation and validation of the Dutch version of the Oxford 12-item knee questionnaire for knee arthroplasty.* Acta Orthop, 2005. **76**(3): p. 347-52.
190. Matsumoto, M., et al., *Validation study of the Forgotten Joint Score-12 as a universal patient-reported outcome measure.* Eur J Orthop Surg Traumatol, 2015. **25**(7): p. 1141-5.

191. Thienpont, E., et al., *Joint awareness in different types of knee arthroplasty evaluated with the Forgotten Joint score.* J Arthroplasty, 2014. **29**(1): p. 48-51.
192. Hamilton, D.F., et al., *What determines patient satisfaction with surgery? A prospective cohort study of 4709 patients following total joint replacement.* Bmj Open, 2013. **3**(4).
193. Impellizzeri, F.M., et al., *Comparison of the Reliability, Responsiveness, and Construct Validity of 4 Different Questionnaires for Evaluating Outcomes after Total Knee Arthroplasty.* Journal of Arthroplasty, 2011. **26**(6): p. 861-869.
194. Robertsson, O. and M.J. Dunbar, *Patient satisfaction compared with general health and disease-specific questionnaires in knee arthroplasty patients.* J Arthroplasty, 2001. **16**(4): p. 476-82.
195. Wylde, V., et al., *Patient-reported outcomes after total hip and knee arthroplasty: comparison of midterm results.* J Arthroplasty, 2009. **24**(2): p. 210-6.
196. Xie, F., et al., *Cross-cultural adaptation and validation of Singapore English and Chinese Versions of the Oxford Knee Score (OKS) in knee osteoarthritis patients undergoing total knee replacement.* Osteoarthritis Cartilage, 2007. **15**(9): p. 1019-24.
197. Roos, E.M., et al., *Knee Injury and Osteoarthritis Outcome Score (KOOS)--development of a self-administered outcome measure.* J Orthop Sports Phys Ther, 1998. **28**(2): p. 88-96.
198. Roos, E.M. and S. Toksvig-Larsen, *Knee injury and Osteoarthritis Outcome Score (KOOS) - validation and comparison to the WOMAC in total knee replacement.* Health Qual Life Outcomes, 2003. **1**: p. 17.
199. Davis, A.M., et al., *Comparative, validity and responsiveness of the HOOS-PS and KOOS-PS to the WOMAC physical function subscale in total joint replacement for osteoarthritis.* Osteoarthritis Cartilage, 2009. **17**(7): p. 843-7.
200. de Groot, I.B., et al., *The Dutch version of the Knee Injury and Osteoarthritis Outcome Score: a validation study.* Health Qual Life Outcomes, 2008. **6**: p. 16.
201. Bombardier, C., et al., *Comparison of a generic and a disease-specific measure of pain and physical function after knee replacement surgery.* Med Care, 1995. **33**(4 Suppl): p. AS131-44.
202. Becker, R., et al., *Expectation, satisfaction and clinical outcome of patients after total knee arthroplasty.* Knee Surg Sports Traumatol Arthrosc, 2011. **19**(9): p. 1433-41.
203. Conditt, M.A., et al., *The PCL significantly affects the functional outcome of total knee arthroplasty.* J Arthroplasty, 2004. **19**(7 Suppl 2): p. 107-12.
204. Ware, J.E., Jr., et al., *Comparison of methods for the scoring and statistical analysis of SF-36 health profile and summary measures: summary of results from the Medical Outcomes Study.* Med Care, 1995. **33**(4 Suppl): p. AS264-79.
205. Ware, J., Jr., M. Kosinski, and S.D. Keller, *A 12-Item Short-Form Health Survey: construction of scales and preliminary tests of reliability and validity.* Med Care, 1996. **34**(3): p. 220-33.
206. Stucki, G., et al., *The Short Form-36 is preferable to the SIP as a generic health status measure in patients undergoing elective total hip arthroplasty.* Arthritis Care Res, 1995. **8**(3): p. 174-81.
207. Busija, L., et al., *Magnitude and meaningfulness of change in SF-36 scores in four types of orthopedic surgery.* Health Qual Life Outcomes, 2008. **6**: p. 55.
208. Hossain, F.S., et al., *A performance based patient outcome score for active patients following total knee arthroplasty.* Osteoarthritis Cartilage, 2013. **21**(1): p. 51-9.

209. Noble, P.C., et al., *Development of a new Knee Society scoring system.* Clin Orthop Relat Res, 2012. **470**(1): p. 20-32.
210. Bourne, R.B., et al., *Patient Satisfaction after Total Knee Arthroplasty Who is Satisfied and Who is Not?* Clinical Orthopaedics and Related Research, 2010. **468**(1): p. 57-63.
211. Bullens, P.H.J., et al., *Patient satisfaction after total knee arthroplasty - A comparison between subjective and objective outcome assessments.* Journal of Arthroplasty, 2001. **16**(6): p. 740-747.
212. Dahm, D.L., et al., *Patient-reported activity level after total knee arthroplasty.* Journal of Arthroplasty, 2008. **23**(3): p. 401-407.
213. Giesinger, J.M., et al., *Association of psychological status and patient-reported physical outcome measures in joint arthroplasty: a lack of divergent validity.* Health Qual Life Outcomes, 2013. **11**: p. 64.
214. Tracey, J., *Inside the clinic: health professionals' role in their clients' psychological rehabilitation.* J Sport Rehabil, 2008. **17**(4): p. 413-31.
215. Clement, D., M.D. Granquist, and M.M. Arvinen-Barrow, *Psychosocial aspects of athletic injuries as perceived by athletic trainers.* J Athl Train, 2013. **48**(4): p. 512-21.
216. Mahomed, N., et al., *The self-administered patient satisfaction scale for primary hip and knee arthroplasty.* Arthritis, 2011. **2011**: p. 591253.
217. Jones, C.A. and S. Pohar, *Health-related quality of life after total joint arthroplasty: a scoping review.* Clin Geriatr Med, 2012. **28**(3): p. 395-429.
218. Engh, G.A., N.L. Parks, and C.E. Whitney, *A prospective randomized study of bicompartmental vs. total knee arthroplasty with functional testing and short term outcome.* J Arthroplasty, 2014. **29**(9): p. 1790-4.
219. Vissers, M.M., et al., *Functional capacity and actual daily activity do not contribute to patient satisfaction after total knee arthroplasty.* BMC Musculoskelet Disord, 2010. **11**: p. 121.
220. Von Keudell, A., et al., *Patient satisfaction after primary total and unicompartmental knee arthroplasty: an age-dependent analysis.* Knee, 2014. **21**(1): p. 180-4.
221. Lau, R.L., et al., *Patient satisfaction after total knee and hip arthroplasty.* Clin Geriatr Med, 2012. **28**(3): p. 349-65.
222. Chan, E.Y., et al., *Acute postoperative pain following hospital discharge after total knee arthroplasty.* Osteoarthritis Cartilage, 2013. **21**(9): p. 1257-63.
223. Kim, T.K., et al., *Functional disabilities and satisfaction after total knee arthroplasty in female Asian patients.* J Arthroplasty, 2010. **25**(3): p. 458-464 e1-2.
224. Kim, S.J., et al., *Patients still wish for key improvements after total knee arthroplasty.* Knee Surg Relat Res, 2015. **27**(1): p. 24-33.
225. Nyland, J., et al., *Total knee arthroplasty in motivated patients with knee osteoarthritis and athletic activity approach type goals: a conceptual decision-making model.* Disabil Rehabil, 2011. **33**(17-18): p. 1683-92.
226. Devers, B.N., et al., *Does greater knee flexion increase patient function and satisfaction after total knee arthroplasty?* J Arthroplasty, 2011. **26**(2): p. 178-86.
227. Christen, M., E. Aghayev, and B. Christen, *Short-term functional versus patient-reported outcome of the bicruciate stabilized total knee arthroplasty: prospective consecutive case series.* BMC Musculoskelet Disord, 2014. **15**: p. 435.
228. Mannion, A.F., et al., *The role of patient expectations in predicting outcome after total knee arthroplasty.* Arthritis Res Ther, 2009. **11**(5): p. R139.

229. Pua, Y.H., et al., *Development of a Prediction Model to Estimate the Risk of Walking Limitations in Patients with Total Knee Arthroplasty.* J Rheumatol, 2016. **43**(2): p. 419-26.
230. Hepinstall, M.S., et al., *Factors that impact expectations before total knee arthroplasty.* J Arthroplasty, 2011. **26**(6): p. 870-6.
231. Su, E.P., et al., *A prospective, multi-center, randomised trial to evaluate the efficacy of a cryopneumatic device on total knee arthroplasty recovery.* J Bone Joint Surg Br, 2012. **94**(11 Suppl A): p. 153-6.
232. Thomas, K.M. and K.A. Sethares, *Is guided imagery effective in reducing pain and anxiety in the postoperative total joint arthroplasty patient?* Orthop Nurs, 2010. **29**(6): p. 393-9.
233. Sayeed, S.A., et al., *The Risk of Subsequent Joint Arthroplasty after Primary Unilateral Total Knee Arthroplasty, a 10-Year Study*. Journal of Arthroplasty, 2011. **26**(6): p. 842-846.
234. Llikavainio, T., et al., *Loading and gait symmetry during level and stair walking in asymptomatic subjects with knee osteoarthritis: Importance of quadriceps femoris in reducing impact force during heel strike?* Knee, 2007. **14**(3): p. 231-238.
235. Wiik, A., *Gait Analysis Using an Instrumented Treadmill*, in *Department of Surgery and Cancer*. 2016, Imperial College London. p. 129.
236. Robinson, R.O., W. Herzog, and B.M. Nigg, *Use of Force Platform Variables to Quantify the Effects of Chiropractic Manipulation on Gait Symmetry.* Journal of Manipulative and Physiological Therapeutics, 1987. **10**(4): p. 172-176.
237. Shao, Y.C., et al., *The Fate of the Remaining Knee(s) or Hip(s) in Osteoarthritic Patients Undergoing a Primary TKA or THA.* Journal of Arthroplasty, 2013. **28**(10): p. 1842-1845.
238. Pozzi, F., L. Snyder-Mackler, and J. Zeni, *Relationship between biomechanical asymmetries during a step up and over task and stair climbing after total knee arthroplasty.* Clinical Biomechanics, 2015. **30**(1): p. 78-85.
239. Yu, B., et al., *Reproducibility of the kinematics and kinetics of the lower extremity during normal stair-climbing.* Journal of Orthopaedic Research, 1997. **15**(3): p. 348-352.
240. Bade, M.J., W.M. Kohrt, and J.E. Stevens-Lapsley, *Outcomes before and after total knee arthroplasty compared to healthy adults.* J Orthop Sports Phys Ther, 2010. **40**(9): p. 559-67.
241. Furu, M., et al., *Quadriceps strength affects patient satisfaction after total knee arthroplasty.* J Orthop Sci, 2016. **21**(1): p. 38-43.
242. Ward, T.R., et al., *Bicruciate-stabilised total knee replacements produce more normal sagittal plane kinematics than posterior-stabilised designs.* J Bone Joint Surg Br, 2011. **93**(7): p. 907-13.
243. Ishii, Y., et al., *Quadriceps strength impairment in the mid- to long-term follow-up period after total knee arthroplasty.* Knee Surg Sports Traumatol Arthrosc, 2016.
244. Christiansen, C.L., et al., *Weight-bearing asymmetry during sit-stand transitions related to impairment and functional mobility after total knee arthroplasty.* Arch Phys Med Rehabil, 2011. **92**(10): p. 1624-9.
245. Collados-Maestre, I., et al., *Better functional outcome after single-radius TKA compared with multi-radius TKA.* Knee Surg Sports Traumatol Arthrosc, 2016.

246. Morra, E.A., et al., *The influence of contemporary knee design on high flexion: a kinematic comparison with the normal knee.* J Bone Joint Surg Am, 2008. **90 Suppl 4**: p. 195-201.
247. Victor, J., et al., *In vivo kinematics after a cruciate-substituting TKA.* Clin Orthop Relat Res, 2010. **468**(3): p. 807-14.
248. Ebert, J.R., C. Munsie, and B. Joss, *Guidelines for the early restoration of active knee flexion after total knee arthroplasty: implications for rehabilitation and early intervention.* Arch Phys Med Rehabil, 2014. **95**(6): p. 1135-40.
249. Tolk, J.J., et al., *Total Knee Arthroplasty: What to Expect? A Survey of the Members of the Dutch Knee Society on Long-Term Recovery after Total Knee Arthroplasty.* J Knee Surg, 2016.
250. Williams, D.H., D.S. Garbuz, and B.A. Marsi, *Total knee arthroplasty: Techniques and results.* BC Medical Journal, 2010. **52**(9): p. 447-454.
251. Bierke, S., M. Haner, and W. Petersen, *Influence of somatization and depressive symptoms on the course of pain within the first year after uncomplicated total knee replacement: a prospective study.* Int Orthop, 2016. **40**(7): p. 1353-60.
252. Huijbregts, H.J., et al., *Prosthetic alignment after total knee replacement is not associated with dissatisfaction or change in Oxford Knee Score: A multivariable regression analysis.* Knee, 2016. **23**(3): p. 535-9.
253. Akaike, H., *New Look at Statistical-Model Identification.* Ieee Transactions on Automatic Control, 1974. **Ac19**(6): p. 716-723.
254. Lundblad, H., A. Kreicbergs, and K.A. Jansson, *Prediction of persistent pain after total knee replacement for osteoarthritis.* Journal of Bone and Joint Surgery-British Volume, 2008. **90b**(2): p. 166-171.

APPENDICES

Appendix A: Forgotten Joint Score

FJS-12 score

The following 12 questions refer to how aware you are of your artificial hip/knee joint in everyday life. Please tick one answer from each question.

Are you aware of your artificial joint...

1. ... in bed at night?
O never O almost never O seldom O sometimes O mostly

2. ... when you are sitting on a chair for more than 1 hour?
O never O almost never O seldom O sometimes O mostly

3. ... when you are walking for more than 15 minutes?
O never O almost never O seldom O sometimes O mostly

4. ... when you are taking a bath/shower?
O never O almost never O seldom O sometimes O mostly

5. ... when you are traveling in a car?
O never O almost never O seldom O sometimes O mostly

6. ... when you are climbing stairs?
O never O almost never O seldom O sometimes O mostly

7. ... when you are walking on uneven ground?
O never O almost never O seldom O sometimes O mostly

8. ... when you are standing up from a low-sitting position?
O never O almost never O seldom O sometimes O mostly

9. ... when you are standing for long periods of time?
O never O almost never O seldom O sometimes O mostly

10. ... when you are doing housework or gardening?
O never O almost never O seldom O sometimes O mostly

11. ... when you are taking a walk/hiking?
O never O almost never O seldom O sometimes O mostly

12. ... when you are doing your favorite sport?
O never O almost never O seldom O sometimes O mostly

Scoring: For scoring the FJS-12, all responses are summed (never, 0 points; almost never, 1 point; seldom, 2 points; sometimes, 3 points; mostly, 4 points) and then divided by the number of completed items. This mean value is subsequently multiplied by 25 to obtain a total score range of 0 to 100. Finally, the score is subtracted from 100, to change the direction of the final score in a way that high scores indicate a high degree of "forgetting" the artificial joint, that is, a low degree of awareness.

If more than 4 responses are missing, the total score should not be used.

Appendix B: Informed Consents

Informed Consent Form for TKR Subjects

INFORMED CONSENT FORM

Influence of Patient Satisfaction of Total knee Replacement Patients on Gait Mechanics during Stair Negotiation and Walking

Principal Investigators: Songning Zhang, PhD.
Address: 340 HPER
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: (865) 974-4716

Kevin Valenzuela
Address: 136 HPER
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: (865) 974-2091

Introduction

You are invited to participate in this research study because you had a total knee replacement (TKR) and are between 50 and 75 years old. The purpose of this research is to learn the differences in how the knee works in people with total knee replacements (TKR). Before agreeing to participate in this study, please read this form. It will tell you about the research. Please ask us to explain anything you do not understand.

Testing Protocol

If you agree to be in this study, you will attend two study visits at the Biomechanics/Sports Medicine Lab on the UT campus. Each visit will last about 1.5 – 2 hours. You can park on campus for free. You will fill out a few surveys (WOMAC, Forgotten Joint Score, and Knee Society Score) about your knee and any problems you have. You will need to wear shorts and t-shirt for the study procedures. Your shorts should be close-fitting so we can see how your body moves during the study procedures. If you do not have close-fitting shorts, we will provide paper laboratory shorts.

On the first visit, we will measure your weight and height. You will walk on the treadmill for 3 minutes to get ready for the exercises. At different times during the study visit, we will ask about your knee pain.

For the next tests, reflective markers will be placed on both sides of your feet, ankles, legs, knees, thighs, pelvis and trunk. This is so a motion camera can follow your movements. You will walk across the floor 3-5 times and climb up and down stairs 3-5 times. Each time you will be asked to perform these movements at different speeds. You can take a rest between each time. You can stop at any time. Data collected during the phone interview will also be used for this study.

On the second day, you will do some exercises such as:

- get out of a chair, walk about 9 feet, and walk back to the chair),
- walk up and down a flight of stairs,
- walk for 6 minutes,

- stand up and sit down 10 times.

We will also perform some tests. Some of these tests will measure the activity of your muscle. This is called electromyography (EMG). For those tests we will place electrodes on several muscles. Electrodes record the electrical signal produced by the muscles. The electrodes will not shock or hurt you. You will perform:

- balance test,
- strength test,
- knee range of motion test.

Potential Risks

Risks associated with this study are minimal so they are no greater than your daily activities. You can practice the movements to familiarize yourself with walking up and down the staircase before the testing. You may stop anytime if you feel uncomfortable. If an injury occurs during the course of study visit, we will provide standard first aid as necessary. In the unlikely event you are injured during this study, the University of Tennessee does not automatically provide reimbursement for medical care or other compensation. You will be responsible for any medical expenses. If you are injured during the study, or you have questions, please talk to Kevin Valenzuela or Songning Zhang (974-2091).

Every research study involves some risk to your confidentiality. It is possible that other people could find out you were in the study or see your study information. But we will do our best to keep your information confidential, so we think this risk is very low.

Benefits of Participation

You may not benefit from your participation in this study. 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.

Results from this study may help improve future designs, surgical methods and rehabilitation used for TKR. Results may also help us understand why patients may be dissatisfied with TKR and how patient satisfaction might be improved. You will also receive a $60 gift card at the completion of the second testing session.

Confidentiality

Your information will be kept confidential. All research data and records will be stored securely and will be made available only to researchers who work on this study. The motion cameras will not record images of you. Your name will not be on any research data. Instead, a code number will be assigned to all of your data.

Your name will not appear with the study results that will be presented at conferences and published in journals. The research data will be kept indefinitely. These data may be used for future research purposes after the completion of this project. If you withdraw from the study, we will keep your consent form, but all of your other information will be destroyed.

Contact Information

If you have any questions about the study at any time or if you experience problems as a result of participating in this study, you can contact Kevin Valenzuela or Songning Zhang at 1914 Andy Holt Ave. 136 HPER Bldg, The University of Tennessee (974-2091). Questions about your rights as a research participant can be addressed to Compliance Officer in the Office of Research at the University of Tennessee at (865) 974-7697.

Voluntary Participation and Withdrawal

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

Consent Statement

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

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

Investigator's Signature: ______________________________ Date: ___________

Informed Consent Form for Healthy Subjects

INFORMED CONSENT FORM

Influence of Patient Satisfaction of Total knee Replacement Patients on Gait Mechanics during Stair Negotiation and Walking

Principal Investigators: Songning Zhang, PhD.
Address: 340 HPER
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: (865) 974-4716

Kevin Valenzuela
Address: 136 HPER
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: (865) 974-2091

Introduction

You are invited to participate in this research study because you are a healthy adult and are between 50 and 75 years old. The purpose of this research is to learn the differences in how the knee works in people with total knee replacements (TKR) and those who are healthy. Before agreeing to participate in this study, please read this form. It will tell you about the research. Please ask us to explain anything you do not understand.

Testing Protocol

If you agree to be in this study, you will attend two study visits at the Biomechanics/Sports Medicine Lab on the UT campus. Each visit will last about 1.5 – 2 hours. You can park on campus for free. You will fill out a few surveys (WOMAC, Forgotten Joint Score, and Knee Society Score) about your knee and any problems you have. You will need to wear shorts and t-shirt for the study procedures. Your shorts should be close-fitting so we can see how your body moves during the study procedures. If you do not have close-fitting shorts, we will provide paper laboratory shorts**.**

On the first day, we will measure your weight and height. You will walk on the treadmill for 3 minutes to get ready for the exercises. At different times during the study visit, we will ask about your knee pain.

For the next tests, reflective markers will be placed on both sides of your feet, ankles, legs, knees, thighs, pelvis and trunk. This is so a motion camera can follow your movements. You will walk across the floor 3-5 times and climb up and down stairs 3-5 times. Each time you will be asked to perform these movements at different speeds. You can take a rest between each time. You can stop at any time.

On the second day, you will do some exercises such as:

- get out of a chair, walk about 9 feet, and walk back to the chair),
- walk up and down a flight of stairs,
- walk for 6 minutes,

- stand up and sit down 10 times.

We will also perform some tests. Some of these tests will measure the activity of your muscle. This is called electromyography (EMG). For those tests we will place electrodes on several muscles. Electrodes record the electrical signal produced by the muscles. The electrodes will not shock or hurt you. You will perform:

- balance test,
- strength test,
- knee range of motion test.

Potential Risks

Risks associated with this study are minimal so they are no greater than your daily activities. You can practice the movements to familiarize yourself with walking up and down the staircase before the testing. You may stop anytime if you feel uncomfortable. If an injury occurs during the course of study visit, we will provide standard first aid as necessary. In the unlikely event your are injured during this study, the University of Tennessee does not automatically provide reimbursement for medical care or other compensation. You will be responsible for any medical expenses. If you are injured during the study, or you have questions, please talk to Kevin Valenzuela or Songning Zhang (974-2091).

Every research study involves some risk to your confidentiality. It is possible that other people could find out you were in the study or see your study information. But we will do our best to keep your information confidential, so we think this risk is very low.

Benefits of Participation

You may not benefit from your participation in this study. 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.

Results from this study may help improve future designs, surgical methods and rehabilitation used for TKR. Results may also help us understand why patients may be dissatisfied with TKR and how patient satisfaction might be improved. Even though you do not have a TKR, your participation may help to further the understanding of why TKR patients have physical issues. You will also receive a $40 gift card at the completion of the second testing session.

Confidentiality

Your information will be kept confidential. All research data and records will be stored securely and will be made available only to researchers who work on this study. The motion cameras will not record images of you. Your name will not be on any research data. Instead, a code number will be assigned to all of your data.

Your name will not appear with the study results that will be presented at conferences and published in journals. The research data will be kept indefinitely. These data may be used for future research purposes after the completion of this project. If you withdraw from the study, we will keep your consent form, but all of your other information will be destroyed.

Contact Information

If you have any questions about the study at any time or if you experience problems as a result of participating in this study, you can contact Kevin Valenzuela or Songning Zhang at 1914 Andy Holt Ave. 136 HPER Bldg, The University of Tennessee (974-2091). Questions about your rights as a research participant can be addressed to Compliance Officer in the Office of Research at the University of Tennessee at (865) 974-7697.

Voluntary Participation and Withdrawal

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

Consent Statement

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

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

Investigator's Signature: ____________________________ Date: __________

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.

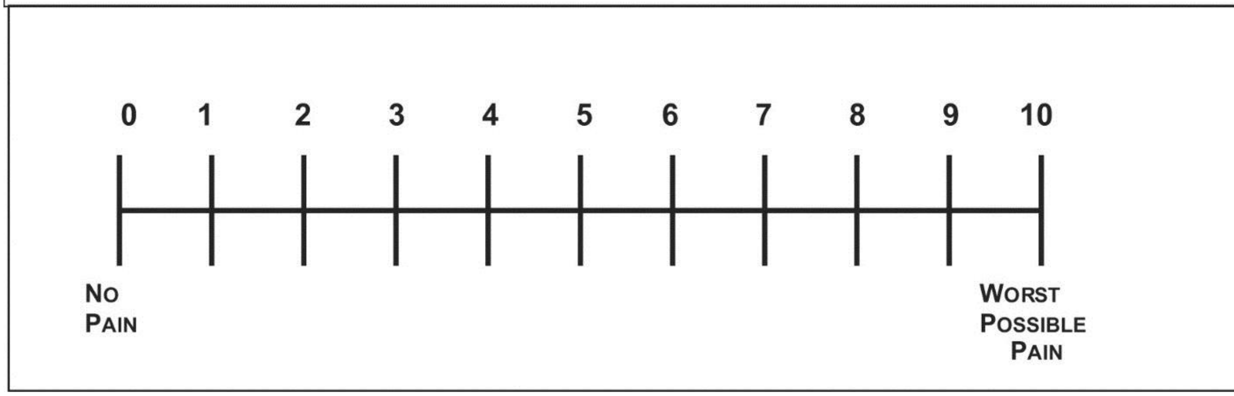
"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____________________

SIGNATURE ____________________ DATE ____________________

Appendix D: Visual Analogue Pain Scale

Visual Analogue pain scale



Appendix E: Demographic Questionnaire

Information Sheet

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

DOB (MM/DD/YY): _____/_____/_______ Shoe Size (US) _______________

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

BMI (answered by PI) ______ Gender (circle one): Female Male

For knee replacement subjects

Knee replacement side (circle one): Right Left

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

Knee replacement type (circle one):

Posterior Stabilized Mobile Bearing Fixed Bearing Other

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

____

Office _________________and doctor who performed surgery _____________________

Rehabilitation clinic and duration: ____________________________

How satisfied are you with your total knee replacement (Circle one)?

Very Dissatisfied Dissatisfied Neutral Satisfied Very Satisfied

Have you had any additional osteoarthritis, systemic arthritis, joint pathologies, or surgeries?

____

Are you able to walk without a walking aid? ___________ Pregnant/Nursing? __________

Neurological conditions? ____

Are you currently taking any pain medications? Frequency? _____________________________

Any reason you should not be participating in exercise? ________________________________

Appendix F: Recruitment Flyers

Total Knee Replacement Recruitment Flyer

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

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

Qualifications to participate in the study include:

- Between the ages of 50 and 75
- A TKR in one knee (Test)
- No TKR in the other knee (Control)
- No other joint replacements or arthritis
- Able to ascend/descend stairs with or without the use of handrail

If you would like to participate or for more information contact Kevin Valenzuela at the UT Biomechanics/Sports Medicine Lab.
Office: 865-974-2091
Cell: 714-612-7845
Email: kvalenzu@vols.utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Healthy Subject Recruitment Flyer

ARE YOU A HEALTHY ADULT? WANT TO HELP ADVANCE THE UNDERSTANDING OF HUMAN MOVEMENT?

A team of researchers from the department of Kinesiology Recreation and Sports Studies at UT are conducting a research study to understand how healthy adults compare to people who have had knee replacements in various activities of daily living. Participants will be required to attend two 1.5 hour testing sessions in the biomechanics/sports medicine lab. **You will be compensated for your time for participating.**

Qualifications to participate in the study include:

- Between the ages of 70 and 75
- No lower limb surgeries
- No diagnosed arthritis issues in the legs
- Able to ascend/descend stairs without the use of handrail

If you would like to participate or for more information contact Kevin Valenzuela at the UT Biomechanics/Sports Medicine Lab.
Office: 865-974-2091
Cell: 714-612-7845
Email: kvalenzu@vols.utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Contact: Kevin V.
P: 974-2091
E: kvalenzu@utk.edu

Appendix G: Subject Demographics

Table 18. Dissatisfied TKR patient characteristics

Subject	Gender	Height (m)	Weight (kg)	BMI (kg/m^2)	Age (years)	Replaced limb	Time from surgery (months)
S4	F	1.70	78.9	27.30	59	R	25
S6	M	1.76	112.28	36.25	70	L	25
S13	F	1.71	73.7	25.35	66	R	24
S18	M	1.71	74.46	25.61	72	L	20
S20	F	1.67	85.83	30.78	72	R	24
S28	F	1.70	75.59	26.31	67	L	34
S30	F	1.52	51.27	22.19	65	L	53
S32	M	1.77	106.32	34.13	71	L	55
S35	F	1.67	70.54	25.29	70	R	51
Mean	-	1.69	80.99	28.13	68.0	-	34.5

Table 19. Satisfied TKR patient characteristics

Subject	**Gender**	**Height (m)**	**Weight (kg)**	**BMI (kg/m^2)**	**Age (years)**	**Replaced limb**	**Time from surgery (months)**
S1	M	1.91	108.26	29.68	73	L	17
S2	M	1.875	114.17	32.48	54	L	21
S3	F	1.68	85.42	30.27	57	R	27
S7	F	1.65	62.39	22.92	60	R	20
S8	M	1.88	106.32	30.08	67	L	40
S9	M	1.795	102.55	31.83	64	R	29
S10	F	1.675	63.4	22.60	68	R	54
S11	M	1.68	107.07	37.94	72	R	12
S12	F	1.715	91.95	31.26	64	R	26
S14	M	1.76	79.85	25.78	75	R	53
S16	M	1.805	92.71	28.46	67	R	45
S17	F	1.63	80.22	30.19	70	L	27
S19	M	1.85	79.61	23.26	74	L	20
S29	M	1.89	104.59	29.28	71	R	22
S36	M	1.67	72.38	25.95	63	R	26
Mean	-	1.76	90.19	28.84	66.6	-	29.3

Table 20. Healthy control participant characteristics

Subject	Gender	Height (m)	Weight (kg)	BMI (kg/m^2)	Age (years)	Dominant limb
S5	F	1.805	81.86	25.13	53	R
S15	M	1.905	79.2	21.82	59	R
S21	M	1.72	83.38	28.18	52	R
S22	F	1.72	58.51	19.78	55	R
S23	M	1.91	75.54	20.71	73	R
S24	F	1.665	66.56	24.01	57	R
S25	M	1.795	94.5	29.33	50	R
S26	F	1.685	71.86	25.31	57	L
S27	M	1.705	83.03	28.56	54	R
S31	F	1.62	63.81	24.31	62	R
S33	F	1.76	99.18	32.02	50	R
S34	M	1.855	92.97	27.02	70	R
S37	F	1.755	77.37	25.12	71	R
S38	M	1.76	70.85	22.87	75	R
S39	F	1.62	67.53	25.73	73	R
Mean	-	1.75	77.74	25.32	60.7	-

Appendix H: Individual Results for Select Variables

Table 21. WOMAC subscales and total scores and passive knee ROM (°) for Dissatisfied TKR patients.

Subject	Limb	Pain	Stiffness	Physical Function	Total	Passive ROM
S4	Replaced	471	172	908.5	1551.5	122
S6	Replaced	169	7	647	823	113
S13	Replaced	45.5	76	100	221.5	112
S18	Replaced	128	96.5	278.5	503	116
S20	Replaced	292.5	154	765	1211.5	122
S28	Replaced	282	91	815	1188	105
S30	Replaced	59	29	89.5	177.5	127
S32	Replaced	77.5	32.5	335.5	445.5	121
S35	Replaced	218.5	27	787.5	1033	127
S4	Non-Replaced	10	5	34.5	49.5	146
S6	Non-Replaced	35	10	53.5	98.5	112
S13	Non-Replaced	13.5	6	53.5	73	130
S18	Non-Replaced	0	0	0	0	135
S20	Non-Replaced	7.5	3	32	42.5	127
S28	Non-Replaced	106.5	16	91	213.5	132
S30	Non-Replaced	14	7	63.5	84.5	137
S32	Non-Replaced	0	0	0	0	120
S35	Non-Replaced	0	27	16.5	43.5	140
Mean	Replaced	193.7	76.1	525.2	794.7	118.3
Mean	Non-Replaced	20.7	8.2	38.3	67.2	131.0

Table 22. WOMAC subscales and total scores and passive knee ROM (°) for Satisfied TKR patients.

Subject	Limb	Pain	Stiffness	Physical Function	Total	Passive ROM
S1	Replaced	63	68	543	674	132
S2	Replaced	17	16	84	117	125
S3	Replaced	18	4.5	99.5	122	125
S7	Replaced	16.5	22	147.5	186	135
S8	Replaced	6.5	150	187	343.5	105
S9	Replaced	16.5	9	78.5	104	124
S10	Replaced	12	8	89.5	109.5	110
S11	Replaced	69.5	6	252.5	328	120
S12	Replaced	20	91.5	69	180.5	107
S14	Replaced	14.5	6.5	51	72	131
S16	Replaced	108	68.5	331.5	508	116
S17	Replaced	6	2	104.5	112.5	130
S19	Replaced	69	27	225	321	140
S29	Replaced	28	53	363.5	444.5	129
S36	Replaced	44	39.5	62	145.5	115
S1	Non-Replaced	47	38	403.5	488.5	150
S2	Non-Replaced	8	11.5	62	81.5	135
S3	Non-Replaced	11	4.5	49.5	65	134
S7	Non-Replaced	12.5	13.5	66	92	141
S8	Non-Replaced	6.5	150	187	343.5	113
S9	Non-Replaced	29	15.5	131.5	176	132
S10	Non-Replaced	12	8	50.5	70.5	136
S11	Non-Replaced	69.5	6	197.5	273	127
S12	Non-Replaced	6	0	0	6	121
S14	Non-Replaced	14.5	6.5	51	72	139
S16	Non-Replaced	7.5	3	42	52.5	131
S17	Non-Replaced	6	2	41	49	135
S19	Non-Replaced	69	27	225	321	147
S29	Non-Replaced	48.5	114	247	409.5	134
S36	Non-Replaced	30	3	0	33	141
Mean	Replaced	33.9	38.1	179.2	251.2	122.9
Mean	Non-Replaced	25.1	26.8	144.5	196.5	134.4

Table 23. WOMAC subscales and total scores and passive knee ROM (°) for healthy controls.

Subject	Limb	Pain	Stiffness	Physical Function	Total	Passive ROM
S5	Dominant	62	69	129.5	260.5	95
S15	Dominant	27	23.5	92.5	143	139
S21	Dominant	0	0	0	0	139
S22	Dominant	0	0	0	0	153
S23	Dominant	0	0	0	0	130
S24	Dominant	0	0	0	0	138
S25	Dominant	20	0	0	20	125
S26	Dominant	0	0	0	0	140
S27	Dominant	0	0	0	0	145
S31	Dominant	0	0	0	0	130
S33	Dominant	0	5.5	11	16.5	132
S34	Dominant	0	0	9	9	124
S37	Dominant	0	0	0	0	139
S38	Dominant	0	0	0	0	148
S39	Dominant	0	0	0	0	137
S5	Non- Dominant	13.5	6	58	77.5	96
S15	Non- Dominant	27	23.5	92.5	143	139
S21	Non- Dominant	0	0	0	0	140
S22	Non- Dominant	0	0	0	0	150
S23	Non- Dominant	0	0	0	0	128
S24	Non- Dominant	0	0	0	0	135
S25	Non- Dominant	0	0	0	0	125
S26	Non- Dominant	6.5	8	17	31.5	145
S27	Non- Dominant	0	0	0	0	147
S31	Non- Dominant	0	0	0	0	140
S33	Non- Dominant	0	5.5	11	16.5	137
S34	Non- Dominant	0	0	9	9	125
S37	Non- Dominant	0	0	0	0	143
S38	Non- Dominant	0	0	0	0	149
S39	Non- Dominant	0	0	0	0	137
Mean	Dominant	7.3	6.5	16.1	29.9	134.3
Mean	Non- Dominant	3.1	2.9	12.5	18.5	135.4

Table 24. Functional testing times and over ground walking, stair ascent, and stair descent velocity for controls and TKR patients.

Subject	Group	Chair Rise (s)	Stair Ascend (s)	Stair Descend (s)	Walking (m/s)	Ascent (m/s)	Descent (m/s)
S4	Dissatisfied	25.11	4.74	4.3	1.35	0.74	0.67
S6	Dissatisfied	11.56	4.47	4.41	1.07	0.49	0.40
S13	Dissatisfied	16.42	4.37	4.04	1.50	0.77	0.59
S18	Dissatisfied	28.99	4.18	4.04	1.13	0.54	0.43
S20	Dissatisfied	18.84	4.84	4.27	1.10	0.51	0.44
S28	Dissatisfied	20.65	6.58	7.71	0.99	0.40	0.37
S30	Dissatisfied	10.01	4.67	4.6	1.18	0.56	0.64
S32	Dissatisfied	12.63	5.42	7.23	1.05	0.48	0.34
S35	Dissatisfied	15.42	10.27	12.74	1.00	0.21	0.15
S5	Healthy	7.26	3.99	3.61	1.39	0.98	0.70
S15	Healthy	13.92	3.28	2.47	1.38	0.67	0.76
S21	Healthy	8.97	3.04	3.53	1.24	0.61	0.54
S22	Healthy	12.89	3.56	3.38	1.60	0.89	0.78
S23	Healthy	21.02	4.29	3.84	1.23	0.58	0.56
S24	Healthy	20.26	2.96	3.38	1.50	0.76	0.63
S25	Healthy	16.8	4.31	3.17	1.31	0.70	0.70
S26	Healthy	16.25	4.16	3.63	1.47	0.77	0.71
S27	Healthy	14.99	4.81	4.2	1.34	0.62	0.63
S31	Healthy	15.29	4.37	4.13	1.13	0.52	0.50
S33	Healthy	24.12	4.61	3.77	1.25	0.68	0.64
S34	Healthy	29.89	4.27	3.69	1.22	0.63	0.66
S37	Healthy	15.66	4.16	4.12	1.36	0.72	0.67
S38	Healthy	18.83	3.58	3.69	1.35	0.64	0.56
S39	Healthy	19.97	5.49	4.59	1.19	0.57	0.50
S1	Satisfied	16.14	5.54	5.05	1.45	0.94	0.75
S2	Satisfied	17.3	4.97	3.83	1.37	0.72	0.73
S3	Satisfied	12.5	4.66	3.87	1.48	0.87	0.78
S7	Satisfied	13.94	4.21	4.08	1.30	0.60	0.57
S8	Satisfied	9.91	5.28	4.83	1.28	0.69	0.49
S9	Satisfied	10.8	3.47	3.29	1.33	0.82	0.66
S10	Satisfied	12.63	4.1	3.23	1.38	0.76	0.70
S11	Satisfied	13	4.27	4.17	1.12	0.60	0.52
S12	Satisfied	22.35	4.55	4.39	1.21	0.68	0.54
S14	Satisfied	15.59	3.86	3.74	1.40	0.78	0.68
S16	Satisfied	25.11	2.94	2.98	1.32	0.70	0.59
S17	Satisfied	11.56	4.18	3.98	1.20	0.76	0.71
S19	Satisfied	16.42	3.38	4.14	1.18	0.82	0.66
S29	Satisfied	28.99	5.48	4.7	1.30	0.78	0.61
S36	Satisfied	18.84	3.58	3.4	1.43	0.64	0.59
Mean	Dissatisfied	18.43	5.50	5.93	1.15	0.52	0.45
Mean	Satisfied	16.84	4.30	3.98	1.32	0.74	0.64
Mean	Healthy	15.01	4.06	3.68	1.33	0.69	0.63

Table 25. 1st and 2nd peak VGRF for Dissatisfied TKR patients.

		1st peak VGRF (BW)			2nd peak VGRF (BW)		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S4	Replaced	1.185±0.023	0.962±0.012	1.583±0.133	1.099±0.014	1.203±0.034	0.867±0.060
S6	Replaced	1.015±0.013	0.883±0.026	1.118±0.101	0.984±0.033	1.035±0.037	0.947±0.012
S13	Replaced	1.033±0.020	0.969±0.006	1.359±0.052	1.056±0.021	0.993±0.036	0.885±0.020
S18	Replaced	1.093±0.031	0.968±0.042	1.064±0.079	0.991±0.016	1.066±0.045	0.890±0.041
S20	Replaced	0.998±0.017	0.809±0.122	1.216±0.070	0.946±0.013	1.049±0.029	0.953±0.021
S28	Replaced	0.978±0.030	0.816±0.014	1.187±0.094	0.998±0.011	0.907±0.014	0.927±0.037
S30	Replaced	1.045±0.036	1.026±0.027	1.680±0.329	1.018±0.013	1.098±0.068	0.839±0.052
S32	Replaced	0.984±0.013	0.937±0.024	1.023±0.052	0.972±0.012	0.995±0.032	0.998±0.030
S35	Replaced	0.946±0.022	0.971±0.057	0.950±0.029	1.002±0.011	0.951±0.084	0.912±0.040
S4	Non-Replaced	1.133±0.057	0.949±0.024	1.345±0.098	1.089±0.029	1.156±0.038	0.771±0.034
S6	Non-Replaced	1.037±0.023	0.999±0.013	1.476±0.061	1.058±0.012	1.106±0.022	0.912±0.027
S13	Non-Replaced	1.179±0.022	1.036±0.011	1.415±0.038	1.132±0.030	1.147±0.025	1.037±0.037
S18	Non-Replaced	1.113±0.040	1.024±0.024	1.026±0.090	1.044±0.031	1.166±0.023	1.088±0.041
S20	Non-Replaced	1.056±0.021	0.938±0.022	1.461±0.156	1.022±0.013	1.219±0.137	0.960±0.029
S28	Non-Replaced	1.005±0.012	1.014±0.041	1.402±0.055	0.992±0.020	0.978±0.010	0.993±0.055
S30	Non-Replaced	1.178±0.056	1.074±0.022	1.613±0.166	1.046±0.012	1.211±0.050	0.939±0.029
S32	Non-Replaced	1.007±0.012	1.018±0.026	1.116±0.063	0.985±0.012	1.121±0.054	0.990±0.022
S35	Non-Replaced	1.053±0.039	1.033±0.022	1.236±0.109	1.003±0.013	0.992±0.031	1.034±0.013
Mean	Replaced	1.03±0.07	0.93±0.07	1.24±0.25	1.01±0.05	1.03±0.09	0.91±0.05
Mean	Non-Replaced	1.08±0.07	1.01±0.04	1.34±0.19	1.04±0.05	1.12±0.09	0.97±0.09

Table 26. 1st and 2nd peak VGRF for Satisfied TKR patients.

		1st peak VGRF (BW)			2nd peak VGRF (BW)		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S1	Replaced	1.100±0.019	0.366±0.022	1.235±0.092	1.004±0.027	1.164±0.051	0.878±0.033
S2	Replaced	1.079±0.017	0.354±0.024	1.322±0.087	1.080±0.010	1.022±0.095	0.861±0.061
S3	Replaced	1.188±0.021	0.357±0.036	1.701±0.066	1.056±0.015	1.247±0.039	0.848±0.076
S7	Replaced	0.985±0.018	0.394±0.021	1.280±0.118	1.050±0.013	1.103±0.037	0.881±0.031
S8	Replaced	0.990±0.012	0.483±0.018	1.401±0.091	1.080±0.034	1.164±0.057	0.976±0.028
S9	Replaced	1.116±0.021	0.404±0.024	1.619±0.088	1.109±0.026	1.186±0.053	0.905±0.031
S10	Replaced	1.035±0.027	0.380±0.008	1.810±0.066	1.096±0.025	1.106±0.061	0.777±0.013
S11	Replaced	1.033±0.031	0.497±0.043	1.640±0.034	0.973±0.024	1.182±0.061	0.887±0.051
S12	Replaced	1.042±0.010	0.419±0.030	1.534±0.056	1.006±0.015	1.165±0.015	0.907±0.031
S14	Replaced	1.146±0.057	0.347±0.018	1.692±0.123	1.105±0.029	1.274±0.030	0.918±0.086
S16	Replaced	1.140±0.028	0.459±0.005	1.404±0.179	1.087±0.039	1.216±0.074	0.898±0.039
S17	Replaced	1.073±0.059	0.365±0.035	1.548±0.105	1.117±0.022	1.122±0.019	0.807±0.043
S19	Replaced	1.033±0.005	0.378±0.011	1.747±0.178	1.017±0.018	1.156±0.041	0.811±0.008
S29	Replaced	1.108±0.012	0.400±0.019	1.556±0.086	1.070±0.009	1.064±0.034	0.816±0.022
S36	Replaced	1.149±0.022	0.422±0.013	1.270±0.086	1.150±0.016	1.201±0.057	0.923±0.018
S1	Non-Replaced	1.259±0.041	1.078±0.050	1.637±0.060	1.076±0.023	1.245±0.031	0.931±0.076
S2	Non-Replaced	1.081±0.032	1.044±0.029	1.378±0.072	1.088±0.009	1.115±0.048	0.941±0.034
S3	Non-Replaced	1.312±0.021	0.935±0.016	1.963±0.071	1.156±0.030	1.210±0.039	0.843±0.105
S7	Non-Replaced	1.145±0.046	1.043±0.019	1.821±0.197	1.124±0.029	1.366±0.078	1.076±0.030
S8	Non-Replaced	1.015±0.024	0.961±0.009	1.319±0.064	1.060±0.007	1.093±0.018	0.912±0.012
S9	Non-Replaced	1.105±0.024	1.026±0.020	1.550±0.051	1.113±0.015	1.105±0.014	0.912±0.037
S10	Non-Replaced	1.104±0.021	1.071±0.038	1.917±0.060	1.143±0.031	1.161±0.060	0.907±0.027
S11	Non-Replaced	1.106±0.021	0.952±0.005	1.658±0.088	0.997±0.019	1.156±0.072	0.913±0.030
S12	Non-Replaced	1.078±0.034	0.997±0.014	1.462±0.065	1.007±0.007	1.248±0.031	0.969±0.049
S14	Non-Replaced	1.094±0.017	1.041±0.021	1.660±0.061	1.141±0.033	1.316±0.015	0.868±0.021
S16	Non-Replaced	1.144±0.038	1.054±0.034	1.599±0.133	1.099±0.011	1.389±0.054	1.028±0.054
S17	Non-Replaced	1.078±0.028	1.063±0.011	1.410±0.045	1.076±0.033	1.162±0.056	0.824±0.083
S19	Non-Replaced	1.065±0.030	0.812±0.268	1.611±0.147	1.055±0.010	1.368±0.264	0.959±0.032
S29	Non-Replaced	1.135±0.050	1.012±0.027	1.406±0.080	1.073±0.023	1.074±0.022	0.887±0.052
S36	Non-Replaced	1.201±0.011	1.107±0.025	1.520±0.106	1.199±0.009	1.366±0.066	1.005±0.036
Mean	Replaced	1.08±0.06	0.99±0.04	1.52±0.19	1.07±0.05	1.16±0.07	0.87±0.05
Mean	Non-Replaced	1.13±0.08	1.01±0.07	1.59±0.19	1.09±0.05	1.22±0.11	0.93±0.07

Table 27. 1st and 2nd peak VGRF for healthy controls.

		1st peak VGRF (BW)			2nd peak VGRF (BW)		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S5	Dominant	1.189±0.020	1.136±0.024	1.403±0.028	0.981±0.033	0.927±0.085	0.791±0.069
S15	Dominant	1.116±0.004	1.017±0.043	1.520±0.114	1.107±0.035	1.025±0.094	0.660±0.061
S21	Dominant	1.180±0.035	1.071±0.007	1.482±0.054	1.114±0.017	1.104±0.036	0.866±0.046
S22	Dominant	1.194±0.033	1.074±0.030	1.537±0.104	1.268±0.020	1.314±0.047	1.040±0.034
S23	Dominant	1.178±0.014	1.052±0.012	1.371±0.068	1.164±0.016	1.044±0.026	0.902±0.022
S24	Dominant	1.197±0.011	1.183±0.011	1.348±0.061	1.256±0.043	1.314±0.021	0.980±0.027
S25	Dominant	1.147±0.038	0.942±0.023	1.335±0.083	1.082±0.009	1.171±0.050	0.892±0.053
S26	Dominant	1.193±0.029	1.010±0.025	1.444±0.064	1.138±0.014	1.157±0.062	0.874±0.055
S27	Dominant	1.227±0.017	0.673±0.141	1.594±0.097	1.055±0.029	1.108±0.038	0.785±0.046
S31	Dominant	1.137±0.021	1.061±0.023	1.484±0.096	1.092±0.019	1.172±0.027	1.034±0.052
S33	Dominant	1.073±0.007	0.953±0.022	1.418±0.027	1.060±0.017	1.117±0.031	0.902±0.024
S34	Dominant	1.209±0.022	1.056±0.034	1.397±0.042	1.029±0.015	0.969±0.050	0.798±0.063
S37	Dominant	1.033±0.022	1.021±0.018	1.358±0.109	1.061±0.044	1.174±0.057	0.908±0.040
S38	Dominant	1.169±0.038	0.993±0.024	1.567±0.067	1.047±0.014	1.199±0.036	0.886±0.024
S39	Dominant	1.052±0.049	1.000±0.024	1.333±0.020	1.014±0.032	1.257±0.021	0.989±0.018
S5	Non- Dominant	1.182±0.033	1.206±0.070	1.505±0.051	1.100±0.006	1.084±0.061	0.769±0.026
S15	Non- Dominant	1.167±0.033	0.980±0.036	1.635±0.190	1.078±0.025	1.010±0.075	0.797±0.063
S21	Non- Dominant	1.129±0.026	0.997±0.022	1.379±0.069	1.074±0.027	1.018±0.029	0.876±0.017
S22	Non- Dominant	1.143±0.022	1.107±0.037	1.566±0.082	1.249±0.014	1.379±0.056	1.018±0.008
S23	Non- Dominant	1.155±0.029	1.101±0.017	1.429±0.054	1.106±0.026	1.052±0.027	0.943±0.016
S24	Non- Dominant	1.192±0.015	1.147±0.015	1.368±0.047	1.218±0.023	1.259±0.026	1.038±0.053
S25	Non- Dominant	1.100±0.021	0.942±0.037	1.376±0.042	1.075±0.026	1.195±0.078	0.942±0.021
S26	Non- Dominant	1.145±0.019	0.997±0.028	1.506±0.066	1.086±0.021	1.186±0.060	0.776±0.024
S27	Non- Dominant	1.280±0.011	1.122±0.018	1.345±0.027	1.118±0.028	1.204±0.055	0.779±0.021
S31	Non- Dominant	1.097±0.022	1.011±0.006	1.508±0.072	1.067±0.015	1.110±0.037	0.912±0.037
S33	Non- Dominant	1.054±0.016	0.942±0.018	1.366±0.026	1.015±0.015	1.059±0.068	0.847±0.014
S34	Non- Dominant	1.122±0.016	1.028±0.028	1.351±0.090	0.981±0.023	0.994±0.031	0.783±0.046
S37	Non- Dominant	1.093±0.011	0.998±0.032	1.385±0.092	1.092±0.016	1.222±0.011	0.902±0.054
S38	Non- Dominant	1.131±0.006	1.002±0.079	1.370±0.163	1.072±0.004	1.121±0.049	0.890±0.016
S39	Non- Dominant	1.064±0.023	1.028±0.024	1.304±0.047	1.038±0.008	1.186±0.049	0.988±0.034
Mean	Dominant	1.15±0.06	1.02±0.11	1.44±0.09	1.10±0.08	1.14±0.11	0.89±0.10
Mean	Non- Dominant	1.14±0.06	1.04±0.08	1.43±0.09	1.09±0.07	1.14±0.11	0.88±0.09

Table 28. Knee Flexion ROM (°) and loading-response knee extension moment (Nm/kg) for Dissatisfied TKR patients.

		Flexion ROM			Loading-response Extension Moment		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S4	Replaced	-9.990±1.196	57.396±1.954	-82.870±2.412	0.532±0.054	1.039±0.076	0.764±0.114
S6	Replaced	-16.467±2.616	49.496±2.869	-79.736±0.807	0.496±0.062	0.815±0.068	0.320±0.096
S13	Replaced	-1.744±0.788	57.186±1.646	-77.057±2.564	0.132±0.029	0.820±0.031	0.614±0.077
S18	Replaced	-18.455±2.265	55.057±2.150	-82.720±2.443	0.691±0.069	1.187±0.086	0.324±0.169
S20	Replaced	-14.268±1.847	44.907±2.711	-82.885±2.540	0.519±0.053	0.626±0.058	0.397±0.092
S28	Replaced	-5.424±1.098	52.999±2.360	-83.714±1.243	0.265±0.090	0.086±0.015	0.776±0.019
S30	Replaced	-17.827±1.675	52.421±3.130	-89.131±2.055	0.361±0.057	0.800±0.085	0.397±0.200
S32	Replaced	-12.168±0.767	50.049±3.033	-78.646±2.128	0.348±0.063	0.819±0.043	0.047±0.073
S35	Replaced	-3.144±0.817	61.311±2.134	-85.607±1.912	-0.034±0.017	0.538±0.031	0.588±0.078
S4	Non-Replaced	-12.288±1.547	63.672±1.062	-83.566±1.612	0.719±0.017	1.184±0.061	1.004±0.057
S6	Non-Replaced	-18.528±1.949	63.002±1.573	-80.337±1.896	0.824±0.067	1.422±0.009	0.834±0.071
S13	Non-Replaced	-14.395±1.895	62.426±0.352	-80.284±0.514	1.155±0.074	1.335±0.057	1.133±0.149
S18	Non-Replaced	-18.207±3.459	54.717±1.693	-82.690±1.741	0.613±0.054	1.319±0.047	0.296±0.159
S20	Non-Replaced	-15.508±1.867	49.512±8.143	-81.620±2.315	0.496±0.032	0.956±0.053	0.608±0.143
S28	Non-Replaced	-8.400±1.792	56.977±2.569	-87.574±1.230	0.069±0.052	0.591±0.120	0.357±0.111
S30	Non-Replaced	-16.025±1.169	58.546±1.880	-89.691±2.623	0.509±0.101	1.147±0.068	0.908±0.214
S32	Non-Replaced	-17.483±1.152	54.052±3.824	-81.210±1.280	0.212±0.058	0.890±0.032	0.176±0.070
S35	Non-Replaced	-17.843±2.788	49.955±4.792	-81.460±0.506	0.486±0.081	1.152±0.100	0.853±0.181
Mean	Replaced	-11.1±6.4	53.4±4.9	-82.5±3.7	0.42±0.18	0.75±0.31	0.39±0.22
Mean	Non-Replaced	-15.4±3.3	57.0±5.4	-83.2±3.3	0.56±0.32	1.11±0.26	0.69±0.34

Table 29. Knee Flexion ROM (°) and loading-response knee extension moment (Nm/kg) for Satisfied TKR patients.

		Flexion ROM			Loading-response Extension Moment		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S1	Replaced	-16.688±2.491	57.161±1.304	-78.017±1.145	0.712±0.049	1.002±0.073	0.775±0.177
S2	Replaced	-13.383±1.910	48.854±1.323	-72.199±3.429	0.516±0.031	1.486±0.052	0.993±0.209
S3	Replaced	-22.634±2.745	57.280±2.674	-85.243±1.932	0.856±0.036	1.108±0.067	0.826±0.160
S7	Replaced	-6.819±1.111	63.833±1.798	-90.844±1.168	0.112±0.014	0.888±0.039	0.629±0.078
S8	Replaced	-17.432±1.169	51.666±1.658	-72.391±1.143	0.559±0.042	1.422±0.042	0.790±0.113
S9	Replaced	-16.363±2.857	42.851±2.447	-79.359±0.260	0.538±0.068	1.203±0.031	0.925±0.171
S10	Replaced	-14.097±1.338	52.127±1.001	-78.754±1.337	0.568±0.043	1.047±0.050	0.947±0.131
S11	Replaced	-11.663±0.758	58.939±1.655	-76.861±1.658	0.606±0.028	0.976±0.028	0.859±0.072
S12	Replaced	-6.046±4.071	57.114±1.135	-83.544±2.295	0.305±0.056	0.670±0.021	0.244±0.106
S14	Replaced	-10.787±2.207	57.931±2.126	-75.023±1.996	0.460±0.056	1.220±0.047	0.912±0.192
S16	Replaced	-13.879±1.874	62.448±8.253	-82.498±3.229	0.869±0.051	1.391±0.131	0.843±0.262
S17	Replaced	-8.989±2.065	51.111±1.553	-69.572±1.615	0.635±0.091	1.114±0.058	0.906±0.116
S19	Replaced	-3.295±0.697	57.233±2.755	-76.338±1.610	.±.	1.075±0.038	0.392±0.196
S29	Replaced	-14.403±0.682	56.418±2.492	-76.624±2.128	0.507±0.045	1.009±0.037	0.610±0.076
S36	Replaced	-13.370±2.162	54.514±2.553	-85.018±1.325	0.410±0.053	0.558±0.056	0.425±0.109
S1	Non-Replaced	-20.404±1.368	52.054±0.830	-71.598±1.837	1.075±0.156	1.498±0.074	1.227±0.227
S2	Non-Replaced	-11.042±1.471	53.177±1.719	-73.581±3.150	0.338±0.038	1.545±0.070	1.004±0.153
S3	Non-Replaced	-25.190±2.345	60.936±3.053	-83.176±3.164	1.259±0.090	1.122±0.072	0.748±0.054
S7	Non-Replaced	-21.408±0.695	48.002±2.963	-90.423±2.292	0.665±0.098	1.361±0.041	1.019±0.092
S8	Non-Replaced	-12.573±1.516	59.403±0.920	-77.041±1.156	0.468±0.068	1.084±0.051	0.470±0.088
S9	Non-Replaced	-23.817±0.605	59.178±1.808	-80.224±2.025	0.720±0.052	1.429±0.052	0.674±0.166
S10	Non-Replaced	-17.877±1.040	59.595±3.278	-85.110±1.698	0.716±0.074	1.124±0.062	1.161±0.168
S11	Non-Replaced	-18.452±1.089	53.137±1.287	-81.966±0.368	0.686±0.059	0.984±0.034	0.884±0.096
S12	Non-Replaced	-14.515±0.468	53.759±1.579	-88.573±1.113	0.577±0.048	1.303±0.033	1.077±0.142
S14	Non-Replaced	-16.745±1.781	65.652±1.764	-82.736±1.187	0.520±0.069	1.146±0.079	0.359±0.352
S16	Non-Replaced	-21.674±2.150	56.926±3.005	-84.115±2.462	0.932±0.058	1.678±0.164	0.983±0.258
S17	Non-Replaced	-10.453±2.124	54.767±3.753	-76.125±2.259	0.436±0.034	1.096±0.061	0.699±0.169
S19	Non-Replaced	-10.210±1.974	53.299±4.063	-74.121±0.465	0.686±0.068	1.065±0.070	1.157±0.102
S29	Non-Replaced	-11.222±1.674	54.374±3.146	-73.938±1.861	0.663±0.082	1.100±0.027	0.310±0.061
S36	Non-Replaced	-19.918±1.411	60.095±2.064	-85.515±0.993	0.727±0.054	0.872±0.052	0.734±0.120
Mean	Replaced	-12.7±5.0	55.3±5.3	-78.8±5.7	0.55±0.20	1.08±0.26	0.74±0.23
Mean	Non-Replaced	-17.0±5.1	56.3±4.5	-80.5±5.9	0.70±0.24	1.23±0.23	0.83±0.29

Table 30. Knee Flexion ROM (°) and loading-response knee extension moment (Nm/kg) for healthy controls.

		Flexion ROM			Loading-response Extension Moment		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S5	Dominant	-13.157±0.768	49.566±1.071	-66.403±1.468	1.085±0.061	1.693±0.068	1.350±0.095
S15	Dominant	-20.972±1.611	55.796±2.821	-78.230±1.427	0.884±0.032	1.400±0.068	1.299±0.215
S21	Dominant	-22.280±2.743	61.178±2.205	-85.547±1.369	0.946±0.063	1.535±0.065	1.393±0.108
S22	Dominant	-18.821±1.704	52.666±0.662	-78.885±1.950	0.887±0.053	1.433±0.051	0.908±0.145
S23	Dominant	-24.237±1.341	58.677±1.717	-80.497±1.770	0.857±0.084	1.281±0.109	0.580±0.205
S24	Dominant	-17.712±2.156	54.717±1.347	-81.838±1.719	0.642±0.046	1.350±0.031	0.576±0.150
S25	Dominant	-19.330±2.113	57.313±1.726	-76.734±0.874	0.855±0.095	0.897±0.034	0.682±0.065
S26	Dominant	-22.473±1.888	58.529±1.685	-84.350±1.134	0.787±0.064	1.116±0.048	0.803±0.069
S27	Dominant	-18.078±1.032	58.058±1.786	-86.126±1.331	0.640±0.053	1.329±0.035	0.848±0.078
S31	Dominant	-20.228±1.792	55.363±0.587	-82.397±1.788	0.591±0.036	1.296±0.046	0.758±0.193
S33	Dominant	-20.333±1.385	59.096±1.422	-79.063±1.357	0.895±0.048	1.175±0.063	1.011±0.089
S34	Dominant	-17.034±0.720	54.272±3.821	-74.355±2.085	0.624±0.043	1.015±0.067	0.805±0.115
S37	Dominant	-14.461±2.056	62.159±1.278	-86.826±4.646	0.408±0.043	1.100±0.061	0.579±0.266
S38	Dominant	-12.054±1.682	67.537±1.903	-88.076±2.817	0.713±0.057	0.928±0.092	0.781±0.252
S39	Dominant	-9.830±1.288	54.883±2.054	-82.451±3.755	0.249±0.006	0.863±0.063	0.311±0.089
S5	Non- Dominant	-17.461±1.175	48.711±0.658	-73.302±0.927	1.111±0.078	1.817±0.051	1.089±0.151
S15	Non- Dominant	-23.921±0.787	53.228±2.057	-78.838±2.731	0.941±0.087	1.163±0.074	1.240±0.150
S21	Non- Dominant	-19.059±2.463	62.149±1.541	-87.911±1.576	0.890±0.047	1.428±0.063	1.043±0.061
S22	Non- Dominant	-18.443±2.470	49.225±0.570	-78.117±1.663	0.922±0.037	1.382±0.037	0.639±0.179
S23	Non- Dominant	-27.551±1.223	60.648±1.386	-76.072±2.041	0.838±0.034	1.509±0.114	0.749±0.177
S24	Non- Dominant	-13.078±0.864	55.960±1.478	-81.712±1.230	0.678±0.014	1.294±0.031	0.747±0.099
S25	Non- Dominant	-17.923±1.306	59.208±1.137	-71.956±2.117	0.744±0.034	1.009±0.069	0.581±0.127
S26	Non- Dominant	-16.370±0.961	60.454±2.041	-86.449±1.529	0.548±0.041	0.984±0.023	0.745±0.057
S27	Non- Dominant	-18.453±1.605	63.649±3.047	-86.532±3.027	0.968±0.068	1.417±0.036	0.750±0.114
S31	Non- Dominant	-19.473±1.470	53.495±1.757	-86.605±1.264	0.619±0.017	0.887±0.062	0.435±0.192
S33	Non- Dominant	-20.511±0.998	60.147±2.855	-79.057±1.499	0.776±0.032	1.081±0.051	0.778±0.149
S34	Non- Dominant	-15.868±1.266	52.726±1.132	-69.314±2.535	0.514±0.095	0.974±0.043	0.569±0.045
S37	Non- Dominant	-14.899±1.870	59.972±2.094	-82.525±1.941	0.551±0.025	1.004±0.034	0.720±0.117
S38	Non- Dominant	-13.420±2.884	61.873±4.320	-80.080±3.014	0.693±0.035	0.880±0.110	0.531±0.104
S39	Non- Dominant	-10.738±1.391	55.803±2.334	-78.919±2.086	0.270±0.052	0.982±0.089	0.207±0.110
Mean	Dominant	-18.1±4.1	57.3±4.3	-80.8±5.6	0.74±0.22	1.23±0.24	0.85±0.31
Mean	Non- Dominant	-17.8±4.2	57.1±4.8	-79.8±5.6	0.74±0.22	1.19±0.27	0.72±0.26

Table 31. Push-off knee extension moment (Nm/kg) and knee adduction ROM (°) for Dissatisfied TKR patients.

		Push-off Extension Moment			Ab/Adduction ROM		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S4	Replaced	0.204±0.022	-	0.882±0.048	4.698±0.714	-17.550±1.558	11.965±1.954
S6	Replaced	0.271±0.027	-	0.826±0.031	2.708±0.339	-2.590±0.384	5.767±0.670
S13	Replaced	0.255±0.017	-	0.847±0.075	2.449±0.307	-5.492±1.303	13.946±0.755
S18	Replaced	0.196±0.014	-	1.126±0.082	0.229±0.053	-12.326±0.577	4.865±0.682
S20	Replaced	0.172±0.019	-	0.565±0.037	3.875±0.279	-18.083±1.474	9.936±2.175
S28	Replaced	0.106±0.038	-	.±.	1.134±0.146	-7.533±1.044	4.611±0.744
S30	Replaced	0.074±0.011	-	0.671±0.079	2.950±0.352	-2.371±0.893	8.128±0.688
S32	Replaced	0.047±0.019	-	0.698±0.012	3.803±0.448	-20.472±0.870	15.808±1.225
S35	Replaced	0.085±0.015	-	.±.	1.474±0.416	-19.666±1.045	26.218±1.007
S4	Non-Replaced	0.318±0.029	-	0.837±0.061	2.920±0.531	-14.458±2.734	4.549±1.756
S6	Non-Replaced	0.295±0.021	-	1.276±0.033	5.111±0.490	-23.779±0.468	12.695±0.829
S13	Non-Replaced	0.347±0.032	-	1.408±0.057	1.578±0.550	-7.290±1.237	12.691±1.168
S18	Non-Replaced	0.190±0.013	-	1.417±0.037	1.710±0.346	-16.059±1.151	8.844±0.337
S20	Non-Replaced	0.189±0.020	-	0.788±0.053	1.850±0.403	-10.302±1.816	3.824±0.928
S28	Non-Replaced	0.201±0.034	-	1.276±0.093	2.283±0.488	-7.890±1.963	11.465±1.227
S30	Non-Replaced	0.106±0.007	-	0.919±0.065	2.124±0.530	-1.220±0.637	6.801±0.978
S32	Non-Replaced	0.028±0.000	-	0.756±0.027	2.478±0.787	-17.884±1.654	10.062±3.514
S35	Non-Replaced	0.170±0.024	-	1.175±0.048	4.111±0.644	-11.093±1.081	6.130±0.811
Mean	Replaced	0.16±0.08	-	0.78±0.17	2.6±1.4	-11.8±7.4	11.2±6.9
Mean	Non-Replaced	0.20±0.10	-	1.09±0.27	2.7±1.2	-12.2±6.7	8.6±3.4

Table 32. Push-off knee extension moment (Nm/kg) and knee adduction ROM (°) for Satisfied TKR patients.

		Push-off Extension Moment			Ab/Adduction ROM		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S1	Replaced	0.213±0.028	-	0.967±0.072	1.956±0.957	-15.123±0.778	1.948±1.029
S2	Replaced	0.359±0.023	-	1.016±0.133	1.974±0.309	-9.633±0.735	7.271±1.005
S3	Replaced	0.299±0.012	-	0.728±0.084	9.459±1.060	-8.760±1.484	7.719±1.341
S7	Replaced	0.227±0.010	-	.±.	1.601±0.227	-14.734±0.977	16.086±1.393
S8	Replaced	0.375±0.034	-	1.306±0.065	0.124±0.376	-10.503±0.547	6.062±1.257
S9	Replaced	0.260±0.014	-	1.082±0.059	3.953±0.788	-22.868±1.030	16.105±1.190
S10	Replaced	0.305±0.017	-	0.819±0.015	2.984±0.908	-10.812±1.145	14.004±1.255
S11	Replaced	0.231±0.017	-	0.881±0.069	3.222±0.530	-21.185±1.945	9.806±0.000
S12	Replaced	0.228±0.010	-	0.410±0.044	2.185±0.506	-23.726±1.386	18.465±0.215
S14	Replaced	0.353±0.018	-	1.134±0.072	-1.634±0.941	-17.455±1.188	3.414±1.135
S16	Replaced	0.392±0.017	-	1.258±0.056	0.925±0.208	-14.814±8.685	14.217±0.829
S17	Replaced	0.184±0.018	-	0.782±0.033	0.663±0.391	-16.041±1.554	9.923±1.077
S19	Replaced	.±.	-	0.747±0.053	2.715±0.311	-16.673±1.173	3.773±0.702
S29	Replaced	0.053±0.006	-	0.719±0.039	2.396±0.681	-13.868±1.347	15.912±1.534
S36	Replaced	0.179±0.027	-	0.530±0.065	2.038±0.318	-22.074±1.064	11.549±1.099
S1	Non-Replaced	0.229±0.014	-	1.142±0.101	0.578±0.394	-9.087±1.468	7.623±1.013
S2	Non-Replaced	0.432±0.015	-	1.155±0.059	1.391±0.222	-8.947±0.665	3.857±0.907
S3	Non-Replaced	0.286±0.021	-	0.758±0.111	2.587±0.702	-6.050±2.924	13.208±0.357
S7	Non-Replaced	0.269±0.012	-	1.243±0.057	-0.242±0.728	-11.249±1.930	9.350±2.548
S8	Non-Replaced	0.234±0.018	-	0.936±0.041	0.481±0.695	-16.807±1.058	10.452±0.838
S9	Non-Replaced	0.302±0.022	-	1.262±0.097	1.220±0.174	-10.462±0.808	5.115±1.252
S10	Non-Replaced	0.316±0.029	-	1.038±0.029	-0.744±0.390	-3.992±1.313	5.142±1.516
S11	Non-Replaced	0.179±0.009	-	0.924±0.056	-0.501±0.435	-0.974±0.547	4.877±3.197
S12	Non-Replaced	0.306±0.028	-	1.134±0.056	2.743±0.241	-13.384±1.449	6.834±2.238
S14	Non-Replaced	0.316±0.035	-	0.871±0.121	2.161±0.249	-18.102±0.449	5.427±1.176
S16	Non-Replaced	0.347±0.010	-	1.610±0.031	-1.361±1.311	-10.976±0.996	2.466±0.666
S17	Non-Replaced	0.169±0.014	-	0.748±0.098	1.014±0.567	-13.016±3.791	9.024±1.660
S19	Non-Replaced	0.209±0.012	-	1.163±0.096	2.075±0.576	-1.775±0.986	6.967±1.081
S29	Non-Replaced	0.124±0.008	-	0.858±0.041	2.410±0.665	-2.808±0.478	6.320±1.157
S36	Non-Replaced	0.249±0.025	-	0.935±0.052	-0.754±0.324	-12.109±0.657	5.758±0.375
Mean	Replaced	0.26±0.09	-	0.88±0.26	2.3±2.4	-15.9±4.9	10.4±5.3
Mean	Non-Replaced	0.26±0.08	-	1.05±0.23	0.9±1.4	-9.3±5.3	6.8±2.8

Table 33. Push-off knee extension moment (Nm/kg) and knee adduction ROM (°) for healthy controls.

		Push-off Extension Moment			Ab/Adduction ROM		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S5	Dominant	0.508±0.049	-	1.157±0.113	1.731±0.079	-6.632±0.419	10.834±1.227
S15	Dominant	0.284±0.023	-	0.846±0.045	.±.	-10.693±1.782	12.258±1.420
S21	Dominant	0.208±0.016	-	1.121±0.129	2.900±0.365	-21.304±0.842	6.721±1.945
S22	Dominant	0.298±0.014	-	1.327±0.081	3.486±0.546	-5.535±2.719	5.433±1.773
S23	Dominant	0.116±0.016	-	0.999±0.045	0.471±0.221	-18.447±1.111	7.468±1.094
S24	Dominant	0.214±0.015	-	0.981±0.050	5.649±0.883	-19.612±8.896	.±.
S25	Dominant	0.099±0.030	-	0.959±0.035	4.452±0.887	-16.893±4.555	5.451±1.112
S26	Dominant	0.124±0.029	-	0.798±0.048	2.078±0.248	-7.900±0.848	5.167±0.396
S27	Dominant	0.187±0.028	-	0.731±0.085	7.439±0.428	-36.092±1.143	1.636±1.138
S31	Dominant	0.126±0.012	-	1.162±0.096	4.564±0.508	-3.598±0.593	9.079±0.987
S33	Dominant	0.207±0.023	-	1.053±0.045	0.178±0.415	-7.389±0.668	9.703±0.776
S34	Dominant	0.095±0.008	-	0.754±0.097	3.004±0.468	-20.576±0.544	10.832±0.937
S37	Dominant	0.169±0.009	-	0.829±0.079	3.174±0.842	-0.720±1.598	12.219±0.957
S38	Dominant	0.102±0.024	-	0.789±0.031	3.321±0.441	-18.209±1.519	8.652±1.026
S39	Dominant	0.274±0.030	-	0.881±0.042	4.355±0.230	-14.889±3.424	13.543±1.914
S5	Non- Dominant	0.513±0.035	-	1.027±0.090	1.230±0.323	-3.537±1.035	4.201±1.339
S15	Non- Dominant	0.279±0.024	-	1.073±0.059	3.831±1.019	-4.837±0.319	10.022±1.376
S21	Non- Dominant	0.244±0.019	-	1.131±0.055	1.339±0.148	-18.072±0.919	4.070±1.772
S22	Non- Dominant	0.286±0.038	-	1.102±0.070	0.531±0.259	-3.461±1.996	6.465±1.464
S23	Non- Dominant	0.119±0.022	-	1.144±0.079	4.131±0.328	-22.472±0.671	7.411±0.991
S24	Non- Dominant	0.190±0.018	-	1.064±0.027	3.622±0.430	-20.602±0.723	.±.
S25	Non- Dominant	0.076±0.006	-	0.982±0.101	2.923±0.311	-18.356±0.734	7.423±0.477
S26	Non- Dominant	0.197±0.011	-	0.638±0.027	5.982±0.403	-14.759±7.493	12.456±2.112
S27	Non- Dominant	0.178±0.032	-	0.784±0.037	0.981±0.220	-28.405±0.851	7.071±1.113
S31	Non- Dominant	0.148±0.010	-	0.935±0.029	1.519±0.515	-3.923±0.767	8.013±1.170
S33	Non- Dominant	0.149±0.062	-	0.868±0.057	1.986±0.154	-6.807±1.515	9.911±1.423
S34	Non- Dominant	.±.	-	0.747±0.092	1.180±0.606	-16.960±0.662	6.935±1.062
S37	Non- Dominant	0.155±0.014	-	0.701±0.044	0.072±0.121	-6.688±0.710	4.428±1.021
S38	Non- Dominant	0.118±0.013	-	0.833±0.112	1.636±0.181	-11.562±1.527	10.275±1.215
S39	Non- Dominant	0.260±0.024	-	0.966±0.042	2.439±0.237	-7.269±0.901	7.648±0.520
Mean	Dominant	0.20±0.11	-	0.96±0.18	3.3±1.9	-13.9±9.1	8.5±3.4
Mean	Non- Dominant	0.21±0.11	-	0.93±0.16	2.2±1.6	-12.5±8.0	7.6±2.5

Table 34. Loading-response and push-off knee abduction moments (Nm/kg) for Dissatisfied TKR patients.

		Loading-response Abduction Moment			Push-off Abduction Moment		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S4	Replaced	-0.567±0.052	-0.323±0.040	-0.613±0.039	-0.425±0.034	-0.209±0.023	-0.546±0.038
S6	Replaced	-0.606±0.036	-0.645±0.048	-0.538±0.037	-0.564±0.027	-0.668±0.052	-0.547±0.042
S13	Replaced	-0.591±0.020	-0.295±0.021	-0.630±0.020	-0.363±0.020	-0.126±0.011	-0.580±0.012
S18	Replaced	-0.531±0.036	-0.542±0.030	-0.328±0.026	-0.370±0.014	-0.559±0.041	-0.189±0.020
S20	Replaced	-0.450±0.011	-0.211±0.042	-0.504±0.022	-0.250±0.015	-0.107±0.052	-0.445±0.073
S28	Replaced	-0.145±0.049	-0.182±0.046	-0.176±0.052	-0.192±0.076	-0.274±0.036	-0.092±0.018
S30	Replaced	-0.344±0.048	-0.384±0.036	-0.275±0.120	-0.140±0.020	-0.296±0.031	-0.094±0.067
S32	Replaced	-0.302±0.010	-0.469±0.022	-0.225±0.030	-0.204±0.020	-0.376±0.029	-0.280±0.030
S35	Replaced	-0.225±0.026	-0.205±0.025	-0.285±0.051	-0.084±0.038	.±.	-0.343±0.024
S4	Non-Replaced	-0.534±0.028	-0.623±0.128	-0.536±0.036	-0.560±0.037	-0.716±0.046	-0.358±0.049
S6	Non-Replaced	-0.459±0.028	-0.591±0.032	-0.781±0.026	-0.416±0.046	-0.237±0.011	-0.677±0.040
S13	Non-Replaced	-0.472±0.024	-0.455±0.045	-0.334±0.045	-0.280±0.056	-0.469±0.030	-0.334±0.052
S18	Non-Replaced	-0.663±0.015	-0.469±0.008	-0.692±0.051	-0.422±0.018	-0.205±0.024	-0.697±0.023
S20	Non-Replaced	-0.367±0.013	-0.515±0.019	-0.434±0.071	-0.257±0.008	-0.443±0.056	-0.302±0.046
S28	Non-Replaced	-0.486±0.045	-0.433±0.024	-0.634±0.056	-0.311±0.050	-0.229±0.061	-0.681±0.039
S30	Non-Replaced	-0.531±0.052	-0.189±0.036	-0.580±0.049	-0.250±0.017	-0.063±0.018	-0.341±0.069
S32	Non-Replaced	-0.415±0.022	-0.363±0.029	-0.507±0.035	-0.278±0.028	-0.232±0.029	-0.608±0.026
S35	Non-Replaced	-0.530±0.053	-0.655±0.069	-0.574±0.030	-0.348±0.011	-0.513±0.026	-0.349±0.019
Mean	Replaced	-0.42±0.17	-0.36±0.16	-0.40±0.17	-0.29±0.15	-0.33±0.20	-0.35±-0.19
Mean	Non-Replaced	-0.50±0.08	-0.48±0.14	-0.56±0.13	-0.35±0.10	-0.35±0.20	-0.48±0.18

Table 35. Loading-response and push-off knee abduction moments (Nm/kg) for Satisfied TKR patients.

		Loading-response Abduction Moment			Push-off Abduction Moment		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S1	Replaced	-0.558±0.009	-0.597±0.050	-0.513±0.023	-0.378±0.043	-0.527±0.050	-0.327±0.039
S2	Replaced	-0.536±0.017	-0.627±0.055	-0.541±0.066	-0.469±0.028	-0.521±0.008	-0.428±0.061
S3	Replaced	-0.779±0.040	-0.435±0.048	-0.937±0.058	-0.376±0.019	-0.414±0.090	-0.649±0.080
S7	Replaced	-0.420±0.024	-0.151±0.038	-0.411±0.046	-0.163±0.030	-0.113±0.045	-0.343±0.062
S8	Replaced	-0.301±0.014	-0.386±0.012	-0.404±0.038	-0.323±0.013	-0.464±0.042	-0.199±0.016
S9	Replaced	-0.552±0.014	-0.443±0.027	-0.787±0.039	-0.356±0.025	-0.139±0.019	-0.608±0.033
S10	Replaced	-0.511±0.027	-0.185±0.037	-0.688±0.063	-0.262±0.019	.±.	-0.317±0.009
S11	Replaced	-0.500±0.028	-0.374±0.041	-0.829±0.042	-0.317±0.027	.±.	-0.617±0.066
S12	Replaced	-0.443±0.017	-0.403±0.017	-0.804±0.045	-0.328±0.014	.±.	-0.512±0.027
S14	Replaced	-0.511±0.027	-0.179±0.032	-0.616±0.019	-0.318±0.044	-0.074±0.071	-0.464±0.024
S16	Replaced	-0.559±0.027	-0.378±0.077	-0.687±0.093	-0.460±0.029	-0.248±0.044	-0.544±0.025
S17	Replaced	-0.241±0.036	-0.350±0.025	-0.247±0.057	-0.228±0.026	-0.305±0.019	-0.118±0.042
S19	Replaced	-0.341±0.013	-0.210±0.055	-0.291±0.041	-0.216±0.027	-0.289±0.028	-0.053±0.016
S29	Replaced	-0.558±0.017	-0.360±0.021	-0.866±0.041	-0.388±0.028	-0.110±0.066	-0.499±0.027
S36	Replaced	-0.506±0.026	-0.191±0.033	-0.539±0.040	-0.359±0.009	-0.041±0.018	-0.402±0.018
S1	Non-Replaced	-0.687±0.051	-0.360±0.057	-0.930±0.023	-0.334±0.030	-0.230±0.016	-0.646±0.062
S2	Non-Replaced	-0.531±0.016	-0.202±0.035	-0.599±0.032	-0.403±0.012	-0.119±0.008	-0.418±0.036
S3	Non-Replaced	-0.391±0.029	-0.494±0.071	-0.473±0.068	-0.392±0.039	-0.738±0.040	-0.306±0.063
S7	Non-Replaced	-0.368±0.051	-0.431±0.048	-0.251±0.091	-0.262±0.022	-0.270±0.018	-0.144±0.064
S8	Non-Replaced	-0.545±0.030	-0.103±0.026	-0.653±0.039	-0.368±0.025	-0.211±0.022	-0.484±0.041
S9	Non-Replaced	-0.507±0.023	-0.545±0.067	-0.535±0.043	-0.515±0.011	-0.676±0.035	-0.275±0.037
S10	Non-Replaced	-0.159±0.025	-0.149±0.036	-0.046±0.064	-0.131±0.028	-0.093±0.023	.±.
S11	Non-Replaced	-0.344±0.011	-0.528±0.024	-0.353±0.040	-0.377±0.037	-0.511±0.039	-0.272±0.031
S12	Non-Replaced	-0.547±0.028	-0.587±0.027	-0.602±0.047	-0.407±0.026	-0.601±0.060	-0.280±0.036
S14	Non-Replaced	-0.541±0.029	-0.603±0.024	-0.528±0.017	-0.379±0.018	-0.582±0.034	-0.368±0.039
S16	Non-Replaced	-0.532±0.022	-0.493±0.050	-0.613±0.051	-0.497±0.015	-0.698±0.023	-0.316±0.035
S17	Non-Replaced	-0.310±0.031	-0.231±0.022	-0.613±0.060	-0.113±0.024	.±.	-0.356±0.077
S19	Non-Replaced	-0.584±0.051	-0.283±0.034	-0.982±0.033	-0.356±0.025	-0.218±0.028	-0.567±0.045
S29	Non-Replaced	-0.630±0.040	-0.624±0.013	-0.625±0.042	-0.603±0.016	-0.637±0.049	-0.356±0.050
S36	Non-Replaced	-0.478±0.035	-0.432±0.014	-0.424±0.072	-0.517±0.021	-0.595±0.018	-0.197±0.047
Mean	Replaced	-0.48±0.13	-0.35±0.15	-0.61±0.21	-0.33±0.09	-0.27±0.18	-0.41±0.18
Mean	Non-Replaced	-0.48±0.14	-0.40±0.17	-0.55±0.23	-0.38±0.13	-0.44±0.24	-0.36±0.14

Table 36. Loading-response and push-off knee abduction moments (Nm/kg) for healthy controls.

		Loading-response Abduction Moment			Push-off Abduction Moment		
Subject	Limb	Walking	Ascent	Descent	Walking	Ascent	Descent
S5	Dominant	-0.370±0.029	-0.152±0.027	-0.540±0.034	-0.249±0.009	.±.	-0.460±0.048
S15	Dominant	-0.648±0.018	-0.357±0.048	-1.117±0.058	-0.562±0.019	-0.151±0.050	-0.502±0.033
S21	Dominant	-0.596±0.018	-0.661±0.039	-0.727±0.017	-0.310±0.028	-0.104±0.014	-0.491±0.043
S22	Dominant	-0.649±0.034	-0.206±0.023	-0.738±0.047	-0.287±0.022	-0.095±0.019	-0.515±0.031
S23	Dominant	-0.357±0.016	-0.202±0.035	-0.598±0.045	-0.308±0.030	.±.	-0.363±0.066
S24	Dominant	-0.707±0.029	-0.656±0.035	-0.635±0.065	-0.487±0.008	.±.	-0.667±0.035
S25	Dominant	-0.599±0.045	-0.369±0.043	-0.611±0.053	-0.327±0.018	-0.167±0.062	-0.524±0.050
S26	Dominant	-0.472±0.012	-0.431±0.057	-0.365±0.071	-0.380±0.017	-0.525±0.024	-0.259±0.040
S27	Dominant	-0.614±0.044	-0.682±0.060	-0.737±0.035	-0.252±0.028	.±.	-0.426±0.037
S31	Dominant	-0.528±0.017	-0.359±0.032	-0.740±0.040	-0.220±0.008	.±.	-0.539±0.037
S33	Dominant	-0.323±0.017	-0.042±0.012	-0.504±0.014	-0.205±0.030	.±.	-0.486±0.032
S34	Dominant	-0.776±0.020	-0.601±0.025	-1.006±0.079	-0.288±0.026	-0.166±0.060	-0.625±0.055
S37	Dominant	-0.575±0.045	-0.435±0.027	-0.794±0.063	-0.366±0.026	-0.127±0.014	-0.651±0.040
S38	Dominant	-0.481±0.034	-0.269±0.037	-0.667±0.025	-0.325±0.011	-0.109±0.003	-0.498±0.064
S39	Dominant	-0.599±0.023	-0.386±0.026	-0.680±0.025	-0.354±0.025	-0.158±0.033	-0.671±0.043
S5	Non- Dominant	-0.440±0.036	-0.404±0.048	-0.273±0.024	-0.253±0.018	-0.326±0.031	-0.090±0.065
S15	Non- Dominant	-0.626±0.034	-0.679±0.037	-0.595±0.082	-0.487±0.023	-0.701±0.059	-0.293±0.038
S21	Non- Dominant	-0.285±0.005	-0.435±0.029	-0.308±0.023	-0.379±0.032	-0.266±0.014	-0.225±0.029
S22	Non- Dominant	-0.380±0.021	-0.301±0.030	-0.308±0.025	-0.198±0.031	-0.383±0.041	-0.184±0.014
S23	Non- Dominant	-0.386±0.010	-0.517±0.021	-0.400±0.030	-0.312±0.025	-0.296±0.029	-0.202±0.026
S24	Non- Dominant	-0.614±0.022	-0.848±0.025	-0.515±0.022	-0.475±0.028	-0.530±0.012	-0.426±0.025
S25	Non- Dominant	-0.426±0.029	-0.720±0.040	-0.488±0.046	-0.372±0.017	-0.647±0.018	-0.427±0.075
S26	Non- Dominant	-0.615±0.019	-0.339±0.016	-0.639±0.026	-0.254±0.020	.±.	-0.459±0.019
S27	Non- Dominant	-0.274±0.016	-0.549±0.037	-0.286±0.032	-0.248±0.035	-0.279±0.018	-0.143±0.025
S31	Non- Dominant	-0.238±0.014	-0.378±0.040	-0.223±0.049	-0.224±0.014	-0.285±0.040	-0.178±0.048
S33	Non- Dominant	-0.352±0.032	-0.388±0.025	-0.148±0.029	-0.200±0.012	-0.285±0.025	-0.211±0.014
S34	Non- Dominant	-0.302±0.032	-0.535±0.040	-0.340±0.027	-0.111±0.020	-0.355±0.028	-0.210±0.030
S37	Non- Dominant	-0.453±0.025	-0.425±0.037	-0.294±0.084	-0.420±0.037	-0.520±0.061	-0.155±0.028
S38	Non- Dominant	-0.425±0.027	-0.480±0.073	-0.288±0.033	-0.380±0.025	-0.585±0.077	-0.279±0.038
S39	Non- Dominant	-0.503±0.030	-0.544±0.049	-0.489±0.036	-0.489±0.035	-0.633±0.014	-0.360±0.042
Mean	Dominant	-0.55±0.13	-0.39±0.20	-0.70±0.19	-0.33±0.10	-0.18±0.13	-0.51±0.11
Mean	Non- Dominant	-0.42±0.13	-0.50±0.15	-0.37±0.14	-0.32±0.12	-0.44±0.16	-0.26±0.11

Table 37. Ankle dorsiflexion ROM (°), loading-response dorsiflexion moment (Nm/kg), and push-off plantarflexion moment during walking for Dissatisfied TKR patients.

Subject	Limb	Dorsiflexion ROM	Dorsiflexion Moment	Plantarflexion Moment
S4	Replaced	25.506±1.201	0.393±0.022	-1.332±0.023
S6	Replaced	22.446±1.250	0.098±0.019	-1.279±0.053
S13	Replaced	27.109±1.143	0.374±0.014	-1.376±0.033
S18	Replaced	22.815±1.541	0.356±0.036	-1.261±0.035
S20	Replaced	25.562±0.663	0.214±0.015	-1.063±0.016
S28	Replaced	20.274±1.259	0.205±0.052	-1.206±0.024
S30	Replaced	22.953±0.908	0.281±0.029	-1.122±0.017
S32	Replaced	24.973±0.840	0.361±0.037	-1.077±0.033
S35	Replaced	23.329±1.353	0.263±0.019	-1.081±0.054
S4	Non-Replaced	21.976±2.316	0.259±0.013	-1.365±0.054
S6	Non-Replaced	23.263±0.335	0.236±0.031	-1.368±0.017
S13	Non-Replaced	13.916±0.879	0.309±0.017	-1.460±0.059
S18	Non-Replaced	15.463±2.438	0.224±0.014	-1.357±0.059
S20	Non-Replaced	22.950±1.590	0.247±0.020	-1.194±0.039
S28	Non-Replaced	24.089±1.316	0.095±0.011	-1.141±0.030
S30	Non-Replaced	19.923±0.382	0.334±0.022	-1.139±0.029
S32	Non-Replaced	21.541±1.284	0.320±0.032	-1.126±0.045
S35	Non-Replaced	25.193±0.422	0.229±0.023	-1.058±0.043
Mean	Replaced	23.9±2.1	0.28±0.10	-1.20±0.12
Mean	Non-Replaced	20.9±3.9	0.25±0.07	-1.25±0.14

Table 38. Ankle dorsiflexion ROM (°), loading-response dorsiflexion moment (Nm/kg), and push-off plantarflexion moment during walking for Satisfied TKR patients.

Subject	Limb	Dorsiflexion ROM	Dorsiflexion Moment	Plantarflexion Moment
S1	Replaced	28.185±0.913	0.487±0.029	-1.513±0.043
S2	Replaced	20.982±1.621	0.255±0.018	-1.480±0.012
S3	Replaced	24.835±1.274	0.455±0.013	-1.188±0.044
S7	Replaced	25.741±0.603	0.359±0.034	-1.202±0.022
S8	Replaced	30.579±1.625	0.176±0.010	-1.607±0.062
S9	Replaced	27.260±1.715	0.382±0.019	-1.487±0.048
S10	Replaced	25.445±1.470	0.264±0.015	-1.450±0.031
S11	Replaced	27.429±1.919	0.253±0.027	-1.132±0.045
S12	Replaced	21.537±0.770	0.264±0.023	-1.181±0.020
S14	Replaced	24.467±1.771	0.496±0.022	-1.457±0.047
S16	Replaced	23.481±1.371	0.295±0.029	-1.288±0.054
S17	Replaced	20.552±0.914	0.222±0.027	-1.452±0.040
S19	Replaced	28.419±0.874	0.399±0.017	-1.312±0.053
S29	Replaced	20.844±0.428	0.298±0.021	-1.434±0.024
S36	Replaced	23.743±1.734	0.428±0.029	-1.419±0.033
S1	Non-Replaced	20.186±3.596	0.475±0.047	-1.597±0.045
S2	Non-Replaced	19.705±1.235	0.253±0.018	-1.466±0.005
S3	Non-Replaced	20.160±0.711	0.387±0.022	-1.465±0.035
S7	Non-Replaced	20.137±0.986	0.293±0.028	-1.415±0.049
S8	Non-Replaced	32.213±0.764	0.311±0.014	-1.541±0.016
S9	Non-Replaced	28.591±1.224	0.292±0.011	-1.497±0.019
S10	Non-Replaced	23.975±0.535	0.239±0.020	-1.564±0.042
S11	Non-Replaced	22.949±0.727	0.195±0.030	-1.224±0.038
S12	Non-Replaced	19.443±1.022	0.277±0.024	-1.256±0.024
S14	Non-Replaced	24.695±0.780	0.393±0.027	-1.669±0.039
S16	Non-Replaced	25.352±1.362	0.249±0.016	-1.477±0.027
S17	Non-Replaced	15.935±1.842	0.192±0.023	-1.362±0.042
S19	Non-Replaced	20.988±0.844	0.370±0.033	-1.291±0.036
S29	Non-Replaced	19.421±1.076	0.306±0.035	-1.400±0.025
S36	Non-Replaced	17.154±1.235	0.404±0.031	-1.494±0.014
Mean	Replaced	24.9±3.1	0.34±0.10	-1.37±0.14
Mean	Non-Replaced	22.1±4.3	0.31±0.08	-1.45±0.13

Table 39. Ankle dorsiflexion ROM (°), loading-response dorsiflexion moment (Nm/kg), and push-off plantarflexion moment during walking for healthy controls.

Subject	Limb	Dorsiflexion ROM	Dorsiflexion Moment	Plantarflexion Moment
S5	Dominant	10.555±0.900	0.228±0.025	-1.165±0.045
S15	Dominant	19.703±1.558	0.273±0.022	-1.589±0.028
S21	Dominant	19.162±0.872	0.334±0.022	-1.334±0.032
S22	Dominant	17.174±1.197	0.476±0.029	-1.419±0.034
S23	Dominant	19.659±0.982	0.253±0.012	-1.553±0.033
S24	Dominant	20.261±2.013	0.390±0.043	-1.575±0.064
S25	Dominant	17.708±0.609	0.411±0.033	-1.517±0.011
S26	Dominant	21.248±0.901	0.392±0.026	-1.550±0.028
S27	Dominant	10.782±2.139	0.282±0.024	-1.265±0.022
S31	Dominant	25.798±0.324	0.169±0.015	-1.323±0.019
S33	Dominant	20.853±1.549	0.246±0.025	-1.327±0.025
S34	Dominant	16.575±1.482	0.402±0.038	-1.383±0.030
S37	Dominant	19.184±0.812	0.340±0.032	-1.276±0.048
S38	Dominant	19.731±1.355	0.388±0.023	-1.364±0.016
S39	Dominant	20.611±1.607	0.276±0.019	-1.209±0.072
S5	Non- Dominant	19.101±0.849	0.323±0.023	-1.542±0.022
S15	Non- Dominant	14.340±2.102	0.316±0.023	-1.490±0.050
S21	Non- Dominant	22.935±0.843	0.331±0.026	-1.342±0.042
S22	Non- Dominant	17.823±0.799	0.361±0.010	-1.624±0.019
S23	Non- Dominant	24.977±0.774	0.263±0.009	-1.444±0.045
S24	Non- Dominant	15.097±1.408	0.441±0.015	-1.529±0.042
S25	Non- Dominant	19.013±0.735	0.337±0.025	-1.552±0.033
S26	Non- Dominant	20.481±0.939	0.398±0.021	-1.345±0.027
S27	Non- Dominant	14.298±0.791	0.251±0.012	-1.419±0.045
S31	Non- Dominant	23.968±0.889	0.182±0.010	-1.323±0.020
S33	Non- Dominant	24.173±1.217	0.231±0.029	-1.253±0.038
S34	Non- Dominant	12.651±1.038	0.259±0.039	-1.425±0.041
S37	Non- Dominant	19.637±1.415	0.308±0.012	-1.328±0.044
S38	Non- Dominant	19.058±0.398	0.352±0.020	-1.426±0.039
S39	Non- Dominant	19.749±0.853	0.246±0.017	-1.325±0.015
Mean	Dominant	18.6±3.9	0.32±0.09	-1.39±0.14
Mean	Non- Dominant	19.2±3.8	0.31±0.07	-1.42±0.11

Table 40. Hip extension ROM (°), loading-response extension moment (Nm/kg), and push-off flexion moment (Nm/kg) during walking for Dissatisfied TKR patients.

Subject	Limb	Extension ROM	Extension Moment	Flexion Moment
S4	Replaced	-40.775±0.854	-0.424±0.027	0.784±0.042
S6	Replaced	-36.056±0.516	-0.398±0.046	0.602±0.054
S13	Replaced	-44.977±0.831	-0.823±0.031	0.828±0.038
S18	Replaced	-26.681±1.293	-0.349±0.025	0.449±0.043
S20	Replaced	-32.993±0.269	-0.467±0.017	0.605±0.021
S28	Replaced	-34.190±0.909	-0.325±0.023	0.258±0.216
S30	Replaced	-32.821±1.049	-0.474±0.044	0.696±0.031
S32	Replaced	-32.044±1.688	-0.533±0.022	0.322±0.045
S35	Replaced	-31.981±1.350	-0.467±0.072	0.535±0.048
S4	Non-Replaced	-43.479±2.476	-0.460±0.047	0.705±0.029
S6	Non-Replaced	-37.235±1.057	-0.627±0.033	0.538±0.019
S13	Non-Replaced	-46.345±1.148	-0.693±0.025	0.910±0.094
S18	Non-Replaced	-43.780±0.688	-0.487±0.051	0.411±0.023
S20	Non-Replaced	-34.384±0.680	-0.423±0.034	0.667±0.016
S28	Non-Replaced	-25.167±0.543	-0.414±0.045	0.547±0.060
S30	Non-Replaced	-27.676±0.447	-0.615±0.018	0.595±0.036
S32	Non-Replaced	-34.097±1.363	-0.615±0.078	0.382±0.037
S35	Non-Replaced	-27.178±1.376	-0.324±0.020	0.534±0.036
Mean	Replaced	-34.7±5.4	-0.47±0.15	0.56±0.20
Mean	Non-Replaced	-35.5±7.9	-0.52±0.12	0.59±0.16

Table 41. Hip extension ROM (°), loading-response extension moment (Nm/kg), and push-off flexion moment (Nm/kg) during walking for Satisfied TKR patients.

Subject	Limb	Extension ROM	Extension Moment	Flexion Moment
S1	Replaced	-36.682±1.593	-0.964±0.089	0.774±0.033
S2	Replaced	-28.065±0.742	-0.705±0.045	0.644±0.025
S3	Replaced	-31.354±1.292	-0.976±0.062	0.549±0.031
S7	Replaced	-36.614±0.825	-0.592±0.049	0.716±0.032
S8	Replaced	-36.472±0.823	-0.636±0.038	0.714±0.044
S9	Replaced	-37.271±1.093	-0.710±0.034	0.759±0.039
S10	Replaced	-35.051±1.235	-0.658±0.040	0.582±0.647
S11	Replaced	-36.591±1.569	-0.413±0.033	0.501±0.039
S12	Replaced	-29.163±1.179	-0.580±0.027	0.517±0.030
S14	Replaced	-28.915±0.770	-0.816±0.043	0.716±0.041
S16	Replaced	-42.706±1.069	-0.893±0.078	0.561±0.041
S17	Replaced	-37.476±0.597	-0.243±0.240	0.740±0.035
S19	Replaced	-29.314±0.634	-0.605±0.040	0.355±0.046
S29	Replaced	-30.734±0.444	-0.586±0.034	0.630±0.013
S36	Replaced	-46.634±0.962	-0.622±0.036	0.961±0.043
S1	Non-Replaced	-34.975±1.998	-0.867±0.068	0.604±0.063
S2	Non-Replaced	-30.985±0.949	-0.662±0.034	0.688±0.025
S3	Non-Replaced	-31.814±1.050	-1.223±0.071	0.419±0.034
S7	Non-Replaced	-34.149±1.475	-0.577±0.045	0.709±0.033
S8	Non-Replaced	-26.497±0.645	-0.854±0.028	0.433±0.037
S9	Non-Replaced	-37.810±0.375	-0.598±0.046	0.665±0.037
S10	Non-Replaced	-31.628±17.688	-0.583±0.081	1.027±0.085
S11	Non-Replaced	-33.652±0.584	-0.304±0.023	0.508±0.027
S12	Non-Replaced	-32.564±0.513	-0.530±0.040	0.580±0.027
S14	Non-Replaced	-38.180±1.852	-0.818±0.031	0.676±0.081
S16	Non-Replaced	-40.654±1.181	-0.842±0.053	0.573±0.034
S17	Non-Replaced	-37.204±0.988	-0.359±0.045	0.839±0.034
S19	Non-Replaced	-37.766±0.458	-0.343±0.041	0.650±0.016
S29	Non-Replaced	-42.666±1.389	-0.630±0.097	0.510±0.045
S36	Non-Replaced	-40.966±0.840	-0.606±0.049	0.904±0.042
Mean	Replaced	-34.9±5.3	-0.67±0.19	0.65±0.15
Mean	Non-Replaced	-35.4±4.4	-0.65±0.24	0.65±0.17

Table 42. Hip extension ROM (°), loading-response extension moment (Nm/kg), and push-off flexion moment (Nm/kg) during walking for healthy controls.

Subject	Limb	Extension ROM	Extension Moment	Flexion Moment
S5	Dominant	-36.070±0.560	-0.763±0.016	0.465±0.027
S15	Dominant	-38.848±1.422	-0.633±0.032	0.708±0.060
S21	Dominant	-41.236±1.251	-0.435±0.050	0.771±0.020
S22	Dominant	-38.244±0.537	-0.878±0.072	1.227±0.031
S23	Dominant	-41.169±1.743	-0.930±0.027	0.609±0.060
S24	Dominant	-33.716±1.535	-0.660±0.078	0.784±0.069
S25	Dominant	-40.627±0.671	-0.425±0.026	0.733±0.064
S26	Dominant	-43.972±1.266	-0.865±0.027	0.627±0.038
S27	Dominant	-38.149±0.501	-0.368±0.044	0.833±0.046
S31	Dominant	-30.848±0.669	-0.389±0.036	0.497±0.032
S33	Dominant	-38.800±0.286	-0.592±0.049	0.544±0.015
S34	Dominant	-37.998±1.020	-0.598±0.069	0.491±0.040
S37	Dominant	-38.567±0.614	-0.682±0.063	0.788±0.074
S38	Dominant	-43.462±0.814	-0.482±0.077	0.797±0.039
S39	Dominant	-30.476±0.803	-0.470±0.027	0.671±0.032
S5	Non- Dominant	-37.434±0.747	-0.461±0.021	0.713±0.048
S15	Non- Dominant	-36.172±0.758	-0.540±0.032	0.788±0.030
S21	Non- Dominant	-39.967±0.741	-0.444±0.033	0.796±0.054
S22	Non- Dominant	-38.625±0.767	-0.970±0.061	1.165±0.095
S23	Non- Dominant	-37.564±1.547	-0.755±0.063	0.727±0.047
S24	Non- Dominant	-46.536±0.085	-0.513±0.037	0.724±0.030
S25	Non- Dominant	-39.372±1.428	-0.516±0.045	0.589±0.024
S26	Non- Dominant	-26.160±0.613	-0.779±0.026	0.644±0.019
S27	Non- Dominant	-38.100±0.389	-0.276±0.068	0.760±0.053
S31	Non- Dominant	-38.635±1.047	-0.365±0.022	0.458±0.023
S33	Non- Dominant	-32.835±0.829	-0.759±0.057	0.407±0.043
S34	Non- Dominant	-31.587±0.902	-0.513±0.045	0.361±0.040
S37	Non- Dominant	-43.953±0.595	-0.591±0.052	0.737±0.031
S38	Non- Dominant	-40.819±1.711	-0.370±0.073	0.717±0.038
S39	Non- Dominant	-41.611±0.919	-0.450±0.022	0.598±0.029
Mean	Dominant	-38.1±4.0	-0.61±0.19	0.70±0.19
Mean	Non- Dominant	-38.0±5.0	-0.55±0.19	0.68±0.19

Table 43. Peak knee extension and flexion torque (Nm) for Dissatisfied TKR patients.

		Peak Extension Torque		Peak Flexion Torque	
Subject	Limb	60°/s	180°/s	60°/s	180°/s
S4	Replaced	94.5	63.6	49.2	34.4
S6	Replaced	119.5	100.5	66.6	41.4
S13	Replaced	72.8	49.4	53.7	42.6
S18	Replaced	112.7	67.3	67.9	43.3
S20	Replaced	77.4	56.3	49	43.4
S28	Replaced	49.4	26.7	17.6	3.5
S30	Replaced	49.5	39.5	32.8	28.2
S32	Replaced	131.7	80.4	54.5	47.1
S35	Replaced	59.5	41	41	25.5
S4	Non-Replaced	96	66.9	35.5	26.8
S6	Non-Replaced	173	105.4	75	45.6
S13	Non-Replaced	120.8	81.9	66.2	44.7
S18	Non-Replaced	144.8	84.3	66.2	36.3
S20	Non-Replaced	91.3	71.5	53.7	31.9
S28	Non-Replaced	49.8	27.7	20.9	6.9
S30	Non-Replaced	66.7	44.1	33	28.1
S32	Non-Replaced	154.7	111.5	75.5	59.8
S35	Non-Replaced	97.8	62.5	45.7	22.8
Mean	Replaced	85.2±30.9	58.3±22.7	48.0±15.9	34.4±13.7
Mean	Non-Replaced	110.5±41.1	72.9±26.9	52.4±19.8	33.7±15.3

Table 44. Peak knee extension and flexion torque (Nm) for Satisfied TKR patients.

		Peak Extension Torque		Peak Flexion Torque	
Subject	Limb	60°/s	180°/s	60°/s	180°/s
S1	Replaced	139.1	88	68.9	47.5
S2	Replaced	177.8	114.2	110	83
S3	Replaced	109.7	67.4	66.7	67
S7	Replaced	57.9	45	35.3	20.9
S8	Replaced	144.3	88.4	69.2	49.1
S9	Replaced	159.3	106.3	71.2	62.5
S10	Replaced	66.9	47.1	27	18.6
S11	Replaced	73.5	67.5	36.1	30.2
S12	Replaced	75.5	56.4	61.6	37.6
S14	Replaced	131.8	102.1	68.9	52.5
S16	Replaced	174.4	124.3	75.1	60.5
S17	Replaced	96.3	62.4	46.6	30.6
S19	Replaced	133.2	103.5	75.9	74.7
S29	Replaced	137.1	98.2	84.1	43.1
S36	Replaced	97.4	74.6	68.5	49.6
S1	Non-Replaced	186.6	140.8	79.9	61.7
S2	Non-Replaced	186	128.3	104.3	102.9
S3	Non-Replaced	135.7	77.3	61.7	66.3
S7	Non-Replaced	79.5	60.9	39.1	27.7
S8	Non-Replaced	107	99.7	84.9	72.8
S9	Non-Replaced	169.5	111.7	74.9	55.2
S10	Non-Replaced	62.8	54.5	24.5	22.4
S11	Non-Replaced	98.7	87.9	52.7	46.5
S12	Non-Replaced	126.4	74.3	65.6	57.8
S14	Non-Replaced	141.2	107.7	81.1	67.1
S16	Non-Replaced	201.5	131.9	85.6	64.4
S17	Non-Replaced	101.2	57.8	41.9	25.9
S19	Non-Replaced	128.8	105.6	73	81.5
S29	Non-Replaced	156.8	101.6	78.2	49.9
S36	Non-Replaced	105	90.4	59.4	52.6
Mean	Replaced	118.3±39.1	83.0±24.9	64.3±21.1	48.5±19.0
Mean	Non-Replaced	132.5±41.3	95.4±27.0	67.1±21.0	57.0±21.4

Table 45. Peak knee extension and flexion torque (Nm) for healthy controls.

		Peak Extension Torque		Peak Flexion Torque	
Subject	Limb	60°/s	180°/s	60°/s	180°/s
S5	Dominant	109.7	78.4	65.2	57.5
S15	Dominant	176.1	118.8	84.1	61
S21	Dominant	158.7	116.2	70	56.1
S22	Dominant	102.4	71.2	59.9	42.2
S23	Dominant	131.1	88.4	62.1	38.1
S24	Dominant	147.5	97.1	76.3	57.2
S25	Dominant	154.3	84.2	82.9	57.9
S26	Dominant	99.1	77.8	73.9	64.1
S27	Dominant	161.6	131	65.4	54.5
S31	Dominant	54.9	35.8	41.6	25.1
S33	Dominant	126.8	81	55.6	40.8
S34	Dominant	91.1	97.1	62.1	69.6
S37	Dominant	96	47.7	55.7	26
S38	Dominant	79.7	55.1	52.2	39.3
S39	Dominant	75.4	32.8	41.6	25.5
S5	Non- Dominant	121.2	84.9	49.8	58.2
S15	Non- Dominant	159.5	105.4	96.5	54.4
S21	Non- Dominant	123.7	87.2	52.5	44.3
S22	Non- Dominant	112.1	73.5	57.9	38
S23	Non- Dominant	165.6	81.9	62	33.8
S24	Non- Dominant	139.1	93.6	79.5	67.5
S25	Non- Dominant	177.2	128.3	75.1	56.8
S26	Non- Dominant	89.4	67.5	60.6	57.1
S27	Non- Dominant	174.2	82	62.1	49.9
S31	Non- Dominant	45.4	21.3	26.7	33.9
S33	Non- Dominant	136.3	80.3	51	40.8
S34	Non- Dominant	137.8	87.6	64	58.3
S37	Non- Dominant	95.5	48.7	49.8	31.3
S38	Non- Dominant	76.7	54.8	40.4	38.9
S39	Non- Dominant	77.6	49.4	42	23.1
Mean	Dominant	117.6±36.4	80.8±29.3	63.2±13.0	47.7±14.8
Mean	Non- Dominant	122.1±39.3	76.4±25.8	58.0±17.1	45.8±12.7

Table 46. Unilateral overall stability index (OSI), mediolateral stability index (MLSI) and anteroposterior stability index (APSI) for Dissatisfied TKR patients.

		Static Unilateral			Dynamic Unilateral		
Subject	Limb	OSI	APSI	MLSI	OSI	APSI	MLSI
S4	Replaced	3.6	1.8	2.9	.	.	.
S6	Replaced	1.4	1.1	0.6	.	.	.
S13	Replaced	3.1	0.8	3	2.5	0.9	2.1
S18	Replaced	1.2	0.7	0.8	1.4	0.8	1
S20	Replaced	.	.	.	.	.	.
S28	Replaced	4.1	3.1	2.5	2.7	2.7	0.2
S30	Replaced	2.7	1.8	1.9	2.3	2.2	0.3
S32	Replaced	.	.	.	.	.	.
S35	Replaced	.	.	.	.	.	.
S4	Non-Replaced	2.3	1.7	1.3	.	.	.
S6	Non-Replaced	1.9	1.2	1.3	.	.	.
S13	Non-Replaced	2.5	2	1.2	3.1	2.7	1.2
S18	Non-Replaced	.	.	.	.	.	.
S20	Non-Replaced	5.1	4.6	1.7	2.8	2.5	1.1
S28	Non-Replaced	2.7	2.1	1.6	2.5	2.5	0.6
S30	Non-Replaced	4.7	2.8	3.7	2	1.8	0.8
S32	Non-Replaced	.	.	.	.	.	.
S35	Non-Replaced	.	.	.	.	.	.
Mean	Replaced	2.68±1.17	1.55±0.90	1.95±1.04	2.23±0.57	1.65±0.95	0.90±0.88
Mean	Non-Replaced	3.20±1.35	2.40±1.20	1.80±0.95	2.60±0.47	2.38±0.39	0.93±0.28

Table 47. Unilateral overall stability index (OSI), mediolateral stability index (MLSI) and anteroposterior stability index (APSI) for Satisfied TKR patients.

		Static Unilateral			Dynamic Unilateral		
Subject	Limb	OSI	APSI	MLSI	OSI	APSI	MLSI
S1	Replaced	1.4	0.6	1.1	.	.	.
S2	Replaced	1.6	1.3	0.7	4.4	0.7	4.3
S3	Replaced	6.3	5.2	3.4	2.7	2.6	0.4
S7	Replaced	3.3	0.7	3.1	2	1.4	1.3
S8	Replaced	1.7	1	1.2	2.4	1.9	1.2
S9	Replaced	4	0.7	3.9	3.1	0.8	2.9
S10	Replaced	5.3	3.3	4	1.8	1.1	1.1
S11	Replaced	.	.	.	.	.	.
S12	Replaced	3.3	1.9	2.5	2.7	1.5	2
S14	Replaced	4.4	3	2.9	3	2.3	1.9
S16	Replaced	.	.	.	.	.	.
S17	Replaced	2.4	1.8	1.2	2.5	2.1	1.1
S19	Replaced	1	0.7	0.6	2	1.4	1.2
S29	Replaced	2.7	1	2.3	.	.	.
S36	Replaced	2.3	1.2	1.7	1.4	0.2	0.6
S1	Non-Replaced	.	.	.	.	.	.
S2	Non-Replaced	5.7	4.8	2.9	.	.	.
S3	Non-Replaced	1.3	1.1	0.6	2.4	1.6	1.8
S7	Non-Replaced	1.4	0.6	1.1	2.5	2.3	0.6
S8	Non-Replaced	1.3	0.5	1.1	3.6	3.1	1.4
S9	Non-Replaced	1.3	0.9	0.8	4.4	0.7	4.3
S10	Non-Replaced	1.6	1.2	0.8	1.8	0.9	1.4
S11	Non-Replaced	.	.	.	.	.	.
S12	Non-Replaced	2.3	2.1	0.6	3	2.8	0.9
S14	Non-Replaced	1.1	0.7	0.6	2.1	2	0.5
S16	Non-Replaced	.	.	.	.	.	.
S17	Non-Replaced	4.6	1.3	4.3	3.2	1.4	2.8
S19	Non-Replaced	2.5	1.3	1.8	2	1.3	1.1
S29	Non-Replaced	1.5	1.2	0.6	2.1	1.1	1.6
S36	Non-Replaced	1.9	0.8	1.5	1.1	0.5	0.1
Mean	Replaced	3.05±1.59	1.72±1.36	2.20±1.20	2.55±0.81	1.45±0.73	1.64±1.12
Mean	Non-Replaced	2.21±1.46	1.38±1.16	1.39±1.14	2.56±0.92	1.61±0.85	1.50±1.18

Table 48. Unilateral overall stability index (OSI), mediolateral stability index (MLSI) and anteroposterior stability index (APSI) for healthy controls.

		Static Unilateral			Dynamic Unilateral		
Subject	Limb	OSI	APSI	MLSI	OSI	APSI	MLSI
S5	Dominant	3.5	1	3.3	2.1	1.3	1.4
S15	Dominant	3.8	2.2	3	2.5	1.4	2
S21	Dominant	4.4	0.9	4.2	2.3	1.1	1.8
S22	Dominant	5	3	3.8	1.8	1.3	1.1
S23	Dominant	2	0.7	1.7	2.4	0.7	2.2
S24	Dominant	3.2	1.2	2.9	2.1	1.5	1.2
S25	Dominant	2.2	0.5	2	1.7	0.8	1.4
S26	Dominant	2.2	0.7	2	3.5	3.1	1.3
S27	Dominant	1.1	0.4	0.9	1.8	1.3	0.9
S31	Dominant	6.2	5.2	3	2.3	2	0.8
S33	Dominant	1.1	0.6	0.7	2.5	2.2	1.1
S34	Dominant	3.4	1.8	2.7	2.9	2.9	0.4
S37	Dominant	1.9	1.4	0.1	.	.	.
S38	Dominant	1.6	1	1	3	2.9	0.8
S39	Dominant	4.6	1.9	4	.	.	.
S5	Non- Dominant	1.9	1	1.5	2.8	0.5	2.7
S15	Non- Dominant	1.1	0.6	0.7	1.4	0.8	1
S21	Non- Dominant	1.6	1.2	0.9	3	0.7	2.9
S22	Non- Dominant	1.4	1.1	0.6	3.3	1.8	2.6
S23	Non- Dominant	0.8	0.5	0.5	1.5	0.9	1
S24	Non- Dominant	2.4	2	1	1.8	1.2	0.8
S25	Non- Dominant	0.8	0.4	0.6	0.9	0.6	0.6
S26	Non- Dominant	2	0.7	1.8	3.5	3.3	0.8
S27	Non- Dominant	0.9	0.6	0.5	1.4	1	0.8
S31	Non- Dominant	3.5	2.3	2.4	2.3	2.2	0.6
S33	Non- Dominant	0.9	0.6	0.5	2.7	1.9	1.8
S34	Non- Dominant	2.2	1.6	1.3	3.5	2.5	2.5
S37	Non- Dominant	1.9	1.4	1	2.8	2.1	1.5
S38	Non- Dominant	1.3	0.9	0.8	2.3	1.4	1.6
S39	Non- Dominant	2.9	2.2	1.3	3	1.4	2.4
Mean	Dominant	3.08±1.52	1.50±1.26	2.35±1.28	2.38±0.52	1.73±0.81	1.27±0.51
Mean	Non- Dominant	1.71±0.81	1.14±0.63	1.03±0.55	2.41±0.84	1.49±0.80	1.57±0.85

Table 49. Bilateral static and dynamic overall stability index (OSI), mediolateral stability index (MLSI) and anteroposterior stability index (APSI) for controls and TKR patients.

Subject	Group	Static OSI	Static APSI	Static MLSI	Dynamic OSI	Dynamic APSI	Dynamic MLSI
S4	Dissatisfied	1	0.8	0.4	1.2	0.9	0.7
S6	Dissatisfied	0.6	0.4	0.2	1.4	1	0.7
S13	Dissatisfied	0.3	0.2	0.2	1.6	1	1.2
S18	Dissatisfied	0.4	0.3	0.2	0.9	0.6	0.6
S20	Dissatisfied	6.1	6.1	0.1	1.5	0.9	1
S28	Dissatisfied	0.4	0.3	0.2	2.2	1.9	0.8
S30	Dissatisfied	2.1	1.3	1.5	2.6	1.8	1.7
S32	Dissatisfied	0.7	0.4	0.4	1.7	1	1.2
S35	Dissatisfied	0.6	0.4	0.3	2.1	2.1	0.2
S5	Healthy	0.6	0.3	0.4	1.7	1.3	1
S15	Healthy	1	0.8	0.5	1.7	0.7	1.5
S21	Healthy	0.4	0.3	0.1	1.5	0.9	0.9
S22	Healthy	3	2.5	1.5	2.7	2.5	0.6
S23	Healthy	0.4	0.3	0.2	1.4	0.8	1
S24	Healthy	2.5	1.8	1.6	2.3	2.2	0.8
S25	Healthy	0.3	0.1	0.2	0.5	0.3	0.4
S26	Healthy	1.2	1.1	0.3	3	2.8	1
S27	Healthy	0.3	0.3	0.2	1.1	0.7	0.6
S31	Healthy	4.6	4.6	0.5	1.6	1.2	0.6
S33	Healthy	0.4	0.3	0.1	1.3	1	0.6
S34	Healthy	1.6	1.6	0.4	2.5	2.2	0.9
S37	Healthy	0.8	0.6	0.4	1.5	1.1	0.8
S38	Healthy	0.4	0.3	0.2	1.9	1.3	1.1
S39	Healthy	3.5	1	3.2	2.1	1.8	0.9
S1	Satisfied	0.2	0.1	0.1	1.3	0.9	0.8
S2	Satisfied	2.7	2.7	0.2	2.2	1	1.8
S3	Satisfied	0.4	0.3	0.2	0.9	0.7	0.4
S7	Satisfied	0.5	0.3	0.3	0.7	0.4	0.4
S8	Satisfied	1.9	1.2	1.4	1.3	1.1	0.5
S9	Satisfied	0.5	0.4	0.2	1.2	0.7	0.9
S10	Satisfied	1.2	0.4	1	1.1	0.8	0.6
S11	Satisfied	0.3	0.3	0.1	1	0.5	0.7
S12	Satisfied	2.8	2.7	0.2	2.9	2.8	0.4
S14	Satisfied	0.5	0.4	0.2	3.3	3	1
S16	Satisfied	0.6	0.4	0.3	1.3	1.1	0.5
S17	Satisfied	0.6	0.5	0.3	1.2	0.9	0.7
S19	Satisfied	0.5	0.3	0.3	1.3	1.1	0.6
S29	Satisfied	0.4	0.3	0.2	1.5	1	0.9
S36	Satisfied	0.4	0.2	0.2	2.2	2.1	0.7
Mean	Dissatisfied	1.36±1.86	1.13±1.89	0.39±0.43	1.69±0.53	1.24±0.54	0.90±0.43
Mean	Satisfied	0.90±0.86	0.70±0.85	0.35±0.36	1.56±0.75	1.21±0.79	0.73±0.35
Mean	Healthy	1.40±1.36	1.06±1.20	0.65±0.84	1.79±0.65	1.39±0.74	0.85±0.27

VITA

Kevin Alan Valenzuela was the 3rd of four boys, born in 1985 to Penelope and John Valenzuela. He graduated from Orange Lutheran High School in 2003. After high school, he attended California State University Fullerton where he graduated with a B.A. in history and a secondary education teaching credential. In 2012, he returned to California State University Fullerton to pursue an M.S. in Kinesiology. Kevin completed his education at the University of Tennessee, earning a PhD in Biomechanics in 2017. He has accepted a tenure track, assistant professor position at California Polytechnic University in Pomona, CA.