KNEE BIOMECHANICS AND ELECTROMYOGRAPHY ANALYSIS FOR PATIENTS WITH TOTAL KNEE ARTHROPLASTY DURING DAILY ACTIVITIES

by

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ABSTRACT

FANGJIAN CHEN. Knee Biomechanics and Electromyography Analysis for Patients with Total Knee Arthroplasty during Daily Activities. (Under the direction of DR. NAIQUAN (NIGEL) ZHENG)

Total knee arthroplasty (TKA) serves as a standard intervention for severe knee OA, consistently improving functionality, mitigating pain, and augmenting patient satisfaction. Currently, TKA implants with posterior stabilized (PS) and bi-cruciate stabilized (BCS) designs are often employed during surgery with no consensus on the absolute superiority of one over the other. Additionally, the enhancement of daily activities post-surgery profoundly impacts the quality of life of TKA patients. It is reported that although patients recuperate their knee mobility within six months following surgery, deficits relative to CG persist. Specifically, tasks such as ascending slopes and stairs can be challenging due to increased knee abduction and extension moments. Bilateral discrepancies are also essential for TKA patients. Owing to compensatory strategies, TKA patients tend to over-rely on their contralateral limb for daily tasks, potentially heightening the risk of knee OA in that limb.

Age-, gender- and BMI-matched three groups (20 each in posterior stabilized TKA, bi-cruciate stabilized TKA, and CG) were recruited and tested pre-op and 6-month post-op to perform walking on level, slope, and stairs, and two clinical tests (timed-up-go, 10-time sit-to-stand). Knee joint kinematics and kinetics variables were calculated from motion data and ground reactions captured at 120 Hz and 1200 Hz, respectively. Muscle activities of both low extremities were recorded using a wireless EMG system at 1500 Hz. A knee biomechanics index (KBI) was developed based on these variables relative to CG. The longitude comparison of KBI and the differences of KBI across

various daily activities, bilateral differences of TKA patients and the differences of two TKA implants were identified and compared in this study.

The participants undergoing TKA displayed notable post-op enhancements, particularly in the sagittal and frontal planes' range of motion and knee moments, underscoring a substantial recovery from their pre-op state. However, the degree of improvement diverged significantly based on the type of daily activity undertaken. Stair ambulation, for instance, posed greater challenges and distinctions compared to level or inclined walking. This discrepancy was quantitatively captured through the KBI, which registered significant advancements in all examined daily activities post-TKA, with the most considerable progress observed during level walking.

The analysis between posterior stabilized and bi-cruciate stabilized TKA implants revealed minimal variations in outcomes concerning knee kinematics and muscle activities. However, a key differentiation emerged in the sagittal plane range of motion during stair ambulation, emphasizing the nuanced yet specific efficiencies of each implant type in practical scenarios. Notwithstanding these subtleties, both implant types manifested a credible record of pain alleviation and functional augmentation for recipients.

For the bilateral differences, the study illuminated disparities in knee kinematics, kinetics, and quadriceps muscle activities between the involved limb and its contralateral counterpart. Although there was a significant improvement in the ratio of knee forces, such as a significant improvement in knee force ratios, the persistence of bilateral discrepancies six months post-op for unilateral TKA recipients cannot be overlooked. This enduring inequality was particularly evident during strenuous activities like the ten-time sit-to-stand test, where a progressive reduction in the ground reaction force ratio was recorded with each repetition, along with noteworthy observations in quadriceps muscle activity.

This study can provide surgeons with comprehensive guidance on implant selection and offer therapists a robust framework for devising optimal rehabilitation protocols, prioritizing function restoration, and mobility enhancement.

ACKNOWLEDGMENTS

Firstly, I would like to express my deepest gratitude to my advisor, Dr. Nigel Zheng. The completion of my thesis would have been impossible without his invaluable assistance and guidance. As this TKA project commenced in 2018 and had numerous participants, I extend my heartfelt thanks to everyone involved in the study.

Secondly, my sincerest appreciation goes to my close friends, Chang Shu, and Hannah Stokes. Their companionship and unwavering support were essential to my perseverance throughout this five-year program.

In addition, I am indebted to the previously graduated student, Shangcheng Wang, who provided crucial technological support for data analysis. My gratitude also extends to the Tyvola Senior Center, which generously provided us with healthy control subjects.

Finally, to all the TKA patients who participated in my study, thank you for your patience and support in completing the motion test. Your contribution was vital to the success of this project.

Again, I am grateful for the people who have journeyed with me through this academic pursuit, and your assistance will always be remembered.

DEDICATION

This dissertation is heartily dedicated to my mother and grandmother, whose love for me is unparalleled in this world.

I would also like to leave a personal note to myself: Life may not always align with our expectations; it is neither as perfect as we envision, nor as terrible as we fear. Both our fragility and strength often surpass what we believe we are capable of. There are times when a simple, delicate remark can bring forth a cascade of tears, and there are moments when we surprise ourselves by persisting, teeth gritted, after having traversed a long, arduous path.

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LIST OF ABBREVIATIONS

Knee kinematics and kinetics:

AAM	abduction-adduction moment
FEM	flexion-extension moment
FEROM	flexion-extension range of motion
IEM	internal-external moment
INTROM	internal-external range of motion
KF	knee force
VVROM	varus-valgus range of motion
ROM	range of motion
GRF	ground reaction force
KBI	knee biomechanics index

Ligaments:

ACL	anterior cruciate ligament
LCL	lateral collateral ligament
MCL	medial collateral ligament
PCL	posterior cruciate ligament

Muscles:

BF	biceps femoris
GL	gastrocnemius lateral
GM	gastrocnemius medial
SN	semimembranosus
TA	tibialis anterior

VL vastus lateralis

VM vastus medialis

Motion tasks:

STS sit-to-stand

TUG time-up-and-go

Total Knee Arthroplasty:

TKA total knee arthroplasty

BCS bi-cruciate stabilized

CR cruciate retaining

PS posterior stabilized

Post-op 6-month after TKA surgery

Pre-op before TKA surgery

CG healthy controls without knee disease

Patients reported outcome measure:

FJS forgotten joint score

KSS knee society score

PROM patient-reported outcome measure

Electromyography:

EMG electromyography

MVIC maximum voluntary isometric contractions

PMA peak muscle activity

RMS root mean square

Others:

BMI	body mass index
OA	knee osteoarthritis

CHAPTER 1: INTRODUCTION

1.1 Motivation

Knee osteoarthritis (OA) is one of the most common causes of disability, and the risk increases steadily for people over the age of 65. Pain and other symptoms of knee OA limited the patients' ability to perform daily activities such as walking, running, squatting, and stair ambulation. Total knee Arthroplasty (TKA) was an effective orthopedic surgery for treating end-stage knee OA, aiming at reducing pain and improving function. Although the postoperative questionnaires showed an increased knee society score and satisfaction score, biomechanical motion tests could provide more professional and comprehensive results on performance and muscle function recovery.

The primary motivation behind this study is to understand the performance of elderly TKA participants during functional daily activities and to discern if any differences exist when compared to age-matched participants without knee issues. By analyzing variables such as knee kinematics, kinetics, and muscle activity, we can quantitatively measure the improvements in TKA patients. Furthermore, any deficits in performance during daily activities can be identified in comparison to healthy subjects. This research aims to provide a comprehensive perspective that will assist clinicians in making informed decisions, especially concerning the selection of TKA implants.

1.2 State of Problem

TKA was a prevalent treatment for end-stage knee joint osteoarthritis (OA). Initial TKA designs typically retained both anterior (ACL) and posterior cruciate ligaments (PCL). However, recent designs often sacrificed the ACL, while the PCL might either have been retained or replaced with a cam-post mechanism for posterior knee stabilization [1].

Although one of the major goals for TKA is to restore normal knee kinematics, this goal has not been fully achieved [2-4]. With the recent advances of TKA designs and a shift of patients to a younger and more active population, patient expectations have increased considerably to meet their active lifestyles [5]. The JOURNEY II Bi-Cruciate Stabilized Knee System has been specifically designed to address the rapidly changing demands and sought to bridge the gap of improving patient satisfaction and implant longevity through improved function, motion, and to regain their pre-arthritic lifestyles' durability.

Apart from restoring normal knee kinematics, the success of TKA requires a thorough, long-term evaluation of factors such as performance during daily activities, balance, proprioception, patient satisfaction, and knee joint pain. While studies in vivo knee kinematics during limited activities have been conducted on the bi-cruciate stabilized (BCS) implants providing valuable insights into prosthesis design, a comprehensive examination of this TKA design—including knee kinematics, kinetics, EMG activities in gait-related tasks, balance, knee joint proprioception, pain, functional capacities, and patient satisfaction—have not been undertaken [3, 4, 6]. At that time, the functional and biomechanical characteristics of gait-related activities during recovery after TKA for patients with BCS remained unknown. Moreover, it is undetermined whether patients with this TKA would outperform those with a competitor's design in aspects such as gait-related activities, balance, knee proprioception, and clinical function tests. Therefore, there were three aims in this study as follows:

Aim 1: to compare knee biomechanics and EMG muscle activities, clinical functional test of TKA follow-ups during daily activities.

Aim 2: to compare knee biomechanics and EMG muscle activities, clinical functional test, knee joint proprioception of two different TKA implants during daily activities.

Aim 3: to compare knee biomechanics and EMG muscle activities of the involved limb with contralateral limb for TKA patients during daily activities.

1.3 Research Hypothesis

While a majority of individuals who underwent TKA reported improvements in function, pain relief, and satisfaction with their surgical outcomes, these outcomes alone might not have convincingly represented the full picture of patient recovery if based solely on paperwork and clinical results [7] [8] [9]. Enhancements in the ability to perform daily activities were crucial for TKA patients, as these significantly impacted their quality of life. Although previous studies have reported improvements in tasks like walking, ramp up and descent, and stair ambulation, comprehensive biomechanical studies comparing performance across different daily activities are lacking at the time [2] [10] [11]. Due to the complexity of biomechanical variables - including three-dimensional knee kinetics and kinematics, gait parameters, and bilateral differences - it is challenging for clinicians to gain a comprehensive understanding and make well-informed decisions. To tackle this, a simplified integrated variable, known as the Knee Biomechanics Index (KBI), was developed. The KBI was based on biomechanical variables relative to CG and was used as the primary variable to explore both longitudinal differences and the comparison of different daily activities across a horizontal plane. Findings of this study might provide a criterion in biomechanics that could assist clinicians in determining the degree of recovery for TKA patients. Additionally, they might aid therapists in developing appropriate rehabilitation protocols for those recovering from TKA.

Aim one: we hypothesized that there were no significant differences in KBIs of TKA patients among different daily activities, and there were no significant differences compared to the knee kinematics, kinetics, and clinical functional test.

Aim two: we hypothesized that there were no significant differences in KBIs of TKA when compared with the posterior stabilized and Bi-cruciate stabilized implants. There were no significant differences comparing EMG muscle activities, clinical functional test, knee joint proprioception of two different TKA implants during daily activities.

Aim three: we hypothesized that there were no significant differences comparing knee biomechanics and EMG muscle activities of the involved limb with the contralateral limb for TKA patients during daily activities.

1.4 Organization of Content

This thesis was structured into seven distinct chapters:

- Chapter 2: Provided background information pertinent to the subject matter. This included details on the anatomy of the knee, the motion capture system, and the clinical tests employed.
- Chapter 3: Constituted a literature review. This section shed light on existing research in the domain, elaborating on studies previously undertaken by other researchers and identifying the knowledge gaps that our study endeavored to address.
- Chapter 4: Outlined the methodology adopted for our research. This chapter elucidated the approaches and techniques employed during the study. It also introduced the customized MATLAB code developed specifically to compute knee kinematics and kinetics.

- Chapter 5: Provided the results based on the three main purposes. It delineated the findings and outcomes of our research.
- Chapter 6: Engaged in a comprehensive discussion of these results, shedding light on the implications, and highlighting the study’s limitations.
- Chapter 7: Served as a summative segment. It encapsulated the primary conclusions drawn from the research and offered insights into the broader takeaways.

CHAPTER 2: BACKGROUND

2.1 Knee Anatomy

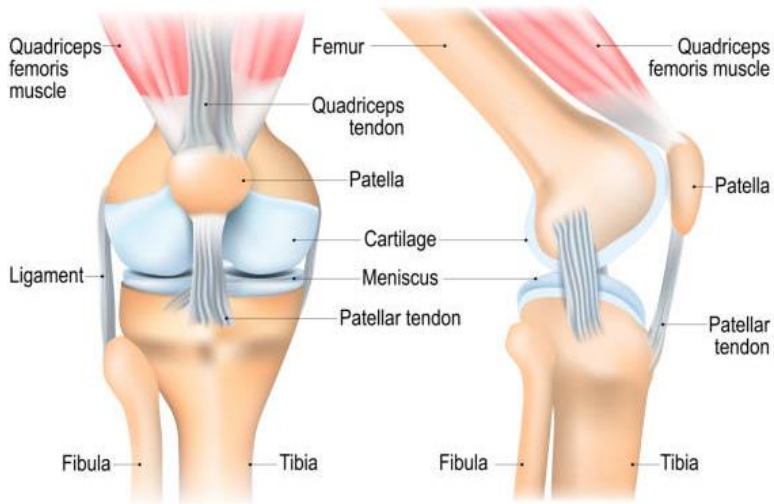

Figure 2.1: Knee Anatomy (https://www.istockphoto.com/photos/knee-anatomy).

The human knee joint (Figure 2.1), when considered in its primary motion, could be likened to a hinge joint in mechanical engineering. It serves as a connection between the thigh bone (femur) and shin bone (tibia) of our lower extremity, allowing the knee to bend and straighten. This movement is facilitated by almost frictionless articular cartilage between the femur and tibia. Alongside the tibia lay another bone known as the fibula. Its main function is to combine with the tibia and lend stability to the ankle joint. The distal end of the fibula features several grooves for ligament attachments, which helps stabilize and provide leverage during ankle movements. The patella, also known as the kneecap, is another essential structure of the knee bones. It articulated above the femoral groove and is central to the function of the quadriceps. Acting like a pulley, the patella transmitted the pulling force of the quadriceps muscle to the tibia through the patellar tendon. The knee joint could be divided into three compartments: the lateral compartment (the outside part of the tibiofemoral articulation), the medial compartment (the inside part of the tibiofemoral articulation), and the patellofemoral compartment. These compartments contribute to the overall complexity and functionality of the knee, making it one of the most fascinating and essential joints in the human body.

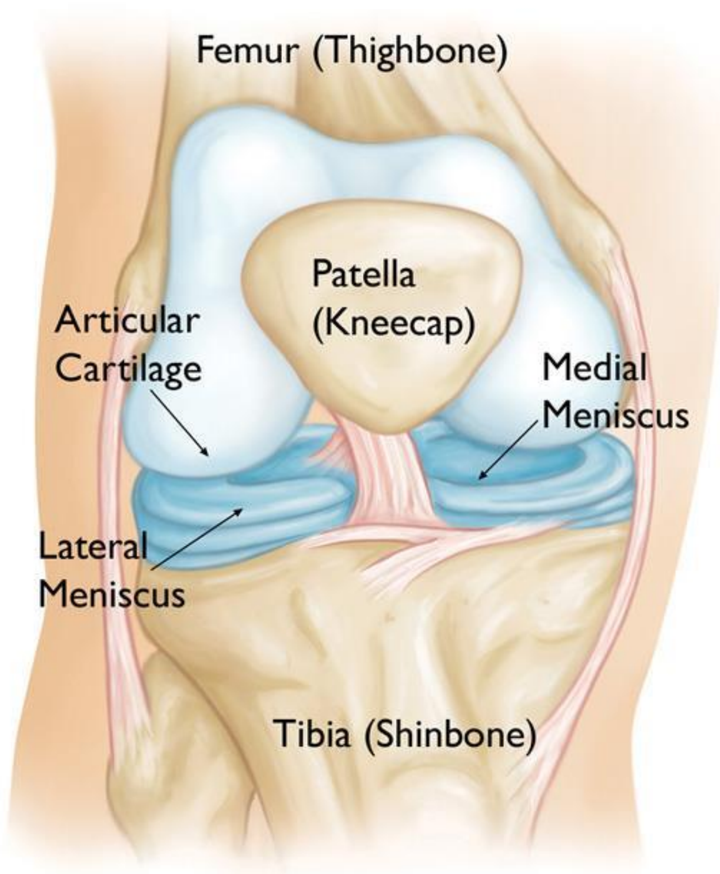

Figure 2.2: Knee Bones and Articular Cartilage (https://orthoinfo.aaos.org/en/diseases--conditions/discoid-meniscus).

The major bones (Figure 2.2) in the knee—femur, tibia, and patella—function like rods and links in a mechanical mechanism. They sustain and transmit external loading and provide attachment sites for other connective tissues. Both the femur and tibia are long bones, comprising dense and stiff cortical bone, and porous cancellous (sponge) bone. Cortical bone forms the outer shell of long bones, while the spongy bone, sandwiched within the cortical bone, adapts to external loading. This structure helped absorb shock and resist fracture. The patella, a small sesamoid bone, covers and protects the anterior articular surface of the knee. The shapes of the articulating surfaces play a crucial role in knee kinematics. The upper articulating surfaces of the tibiofemoral joint consist of the curved and smooth lateral and medial condyles of the femur. Conversely, the lower articulating surface, made up of the lateral and medial meniscus and the articular cartilage on the tibial plateau, is flat. The dome-shaped articulating surface of the patellar bone fits the groove shape of the anterior articulating surface of the femur.

Articular cartilage functions like a bearing in a mechanical mechanism, acting as a joint lining. Covering all articulating parts of the three bones, it consists of a very smooth, lubricated tissue, 2 to 4 mm thick, comprising water and an organic matrix. Though thin, it offers almost zero friction coefficient for dynamic joint articulation, facilitating load transmission. However, it lacks blood vessels and has limited intrinsic ability to heal or repair once damaged, leading to conditions like osteoarthritis, where cartilage degeneration may result in bone-on-bone contact. A meniscus is a crescent-shaped structure that partially divides the lateral or medial tibiofemoral joint cavity. The knee joint has two menisci: the lateral and medial meniscus. These structures serve as pads, increasing the congruity and contact area of tibiofemoral articulation. The concave surface of the meniscus on top of the tibial plateau enables effective articulation with the convex femoral condyles. The menisci could deform and move slightly to accommodate compression from body weight and other axial forces. The medial meniscus could move an average of 2-3 mm, while the lateral one could have greater anterior-posterior displacement (around 9-10 mm) during flexion [12]. This complex arrangement of bones, cartilage, and menisci contributes to the knee's functionality, allowing for both stability and movement. The intricacies of its design and the interplay of its components make the knee joint an extraordinary example of biomechanical engineering in the human body.

The muscles around the knee joint function as the primary movers, analogous to a motor in a mechanical mechanism. They drive the bones and joints to move, stabilize the joint, and balances external loading. For example, the quadriceps muscle group is the primary knee extensor, and its contraction generates torque, which could either balance an external knee flexion moment or extend the knee. Conversely, the hamstring is the key knee flexor, and its contraction produced torque that either balances an external knee extension moment or flexes the knee joint.

The ligaments surrounding the knee joint contribute to its internal passive stability and limited excessive motions, such as joint dislocation. There are four major ligaments in the knee joint: the anterior cruciate ligament, posterior cruciate ligament, medial collateral ligament (MCL), and lateral collateral ligament (LCL). Recent studies have discovered functioning mechanoreceptors (sensory nerve endings) in the ACL and PCL, which could act as sensors. These receptors detect changes in ligament tension and length and might have conveyed information about the joint's position to the brain [13] [14].

The ACL and PCL prevent the femur from sliding forward and backward on the tibia, while the MCL and LCL inhibited side-to-side sliding. Together, these ligaments contribute significantly to the stability of the knee, which is vital for both balance and movement.

Tendons also play a crucial role in the knee's structure, connecting the knee bones to the leg muscles that enable the knee joint's movement. These soft tissue structures work in harmony with the bones, muscles, and ligaments to create a dynamic and complex system that allows for a wide range of motions and activities.

In summary, the intricate interplay between muscles, ligaments, and tendons in the knee joint serves as a remarkable example of natural engineering. Their cooperative function allows for both the stability and mobility needed for everyday activities and strenuous physical exertion alike.

2.2 Knee Osteoarthritis

Knee OA (Figure 2.3) stands as one of the most common causes of disability, particularly among the population over 65 years of age. However, recent studies have found that OA was increasingly impacting younger individuals under 60, garnering significant attention from both surgeons and researchers [15]. In addition, nearly 50% of U.S. adults suffered from painful knee OA by the age of 85 years [16]. These symptoms could severely limit daily activities like walking, running, squatting, and stair ambulation.

The progression of knee OA can be broken down into four primary stages:

- Stage 1: This initial stage is characterized by minimal wear and tear. Patients typically do not experience pain or discomfort at this stage.
- Stage 2: Often characterized by stiffness and discomfort, particularly after physical activities, while the cartilage and soft tissues remain healthy.
- Stage 3 ("Moderate"): There is an evident loss of cartilage surface, narrowing the gap between the bones. Collagen fragments released into the synovial fluid cause pain during activities like jogging and stair ambulation.
- Stage 4 ("End Stage"): This stage sees considerable reduction in cartilage and synovial fluid, causing friction, significant pain, and discomfort during movement.

There are two common options for knee OA treatment: non-surgical treatment and surgical treatment, based on the infected OA stage, which ranged from mild OA to severe OA. The mild stage OA could be treated by medicine and physical therapy; however, to treat severe OA, knee surgery needed to be performed [17].

It was essential to recognize that knee OA is chronic, and its severity increased with age, following an irreversible course. As of then, there is no cure for this condition, with an average lifetime risk of 44.7% for developing symptomatic knee OA [16]. Knee OA could result in pain, stiffness, and swelling, leading to abnormal knee joint motion and stress concentration around the knee joint. Though not fatal, it significantly affects the quality of life and causes disability. Clinically, knee OA is indicated by the loss of knee joint cartilage, the appearance of bone spurs, and narrowing of the knee joint space. Various non-surgical treatments, including lifestyle modifications, physical therapy, assistive devices, medications, and alternative therapies, aim to alleviate related pain and disability. However, when these methods proved ineffective, surgical replacement of the knee joint surfaces might have been recommended. By understanding the stages and treatment options for knee OA, medical professionals could provide targeted care to improve patients' well-being, though challenges remained in finding a definitive cure for this prevalent and debilitating condition.

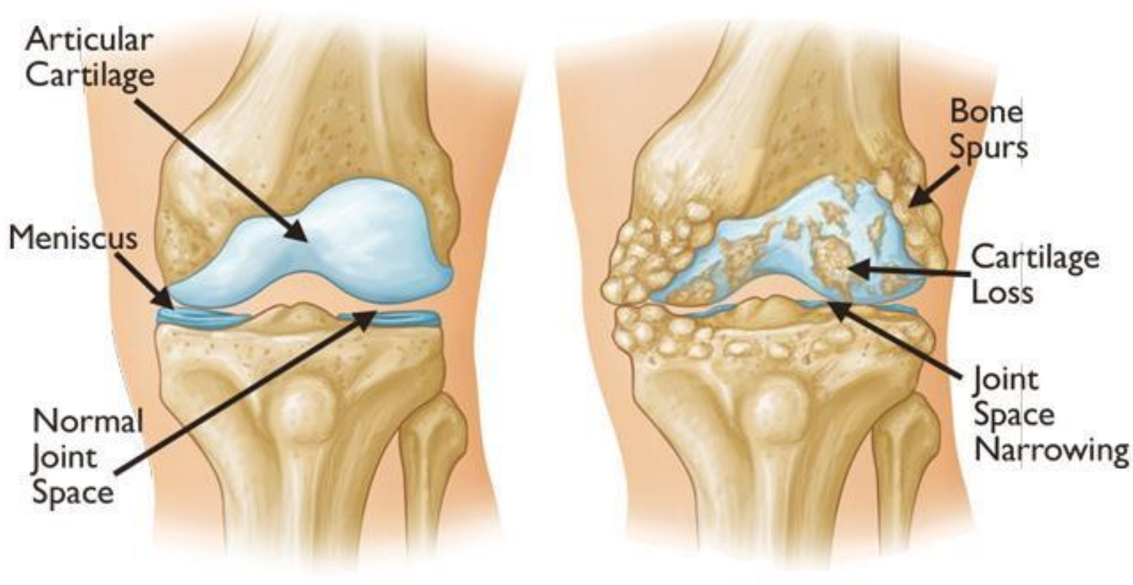

Figure 2.3 Knee Osteoarthritis(https://orthoinfo.aaos.org/en/diseases--conditions/arthritis-of-the-knee/).

2.3 Total Knee Arthroplasty

TKA is a surgical intervention to end-stage knee OA [18]. This common and effective orthopedic surgery is widely performed across the United States, with the number of surgical procedures expected to reach 3.48 million by 2030 [19, 20]. Furthermore, the average cost of a TKA is $16,497 per procedure, contributing to total national costs of 11.6 billion dollars in 2013 [20]. The overarching goal of TKA designs is to provide stability, longevity, and natural kinematics. The primary purpose of TKA surgery is to resurface the joint articulating surfaces [21]. During the procedure (Figure 2.4), the distal end of the femur and the proximal surface of the tibia are cut and replaced with a femoral component and a tibial component, respectively. The metal femoral component, which curves around the distal end of the femur, is grooved to allow the patella to slide smoothly during knee flexion and extension. The tibial component consists of a flat metal platform with a stem that inserted into the tibia, and a strong, durable cushion is placed between the two components [21].

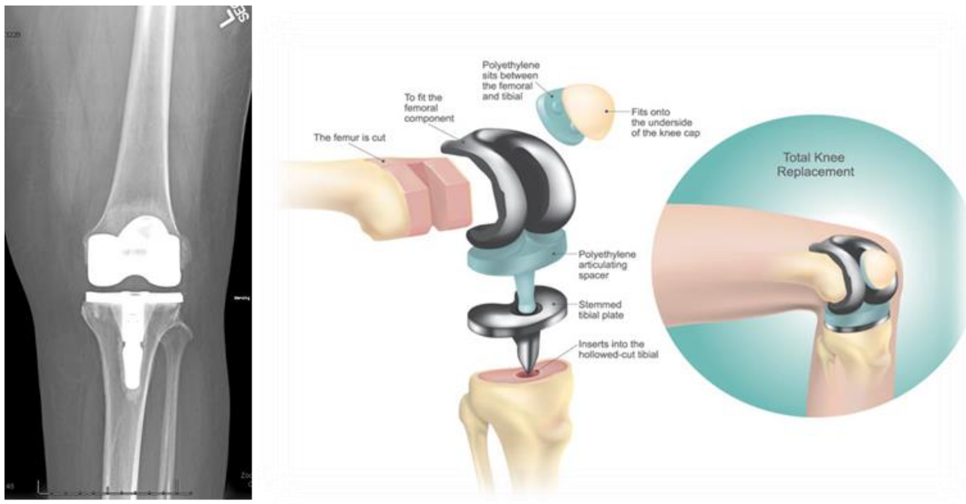

Figure 2.4 Total knee Arthroplasty Implants and the Detailed Procedures(https://www.schulzeorthopedics.com/procedures/knee-arthoscopy/).

A central controversy in TKA surgery revolved around the decision to retain or sacrifice the PCL. If the PCL is robust and healthy enough to preserve knee function during extension and flexion, the cruciate retaining (CR) knee implant could be used [22]. This decision often hinged on the surgeon's experience and judgment of the PCL's condition. However, achieving a balance in the knee with the PCL involved presented a surgical challenge. Consequently, CR TKA had a higher revision rate than posterior-stabilized (PS) TKA [23, 24]. The posterior-stabilized prosthesis is one of the most used types of implants in TKA surgery when the PCL is resected. The PS TKA, as shown in (Figure 2.5), uses the cam-post mechanism to replicate the function of the PCL implemented in such a TKA design. The PS TKA is commonly used when the PCL is resected and employed the cam-post mechanism to emulate the PCL's function. While PS TKA demonstrates reliable long-term performance, it is sometimes viewed less favorably by surgeons as it removes more bone than CR TKA during the bone reservation process. Therefore, the strength and condition of the PCL often becomes key factors in determining the choice of implant.

In 2012, a new posterior-stabilized total knee arthroplasty design (Figure 2.5), known as a BCS implant, was introduced with the intention of reproducing normal knee function during walking. This design employed a tibial post and two femoral cams to function as substitutes for both ACL and PCL. The inclusion of an anterior femoral cam in the design specifically aimed to inhibit excessive posterior movement of the femur on the tibia. A limited number of studies had suggested that BCS implants might more closely restore the femoral rollback characteristics of a healthy knee when compared to either CR implants or traditional PS implants [6, 25]. Additionally, it is reported that when the knee was in a fully extended position, the femur in a BCS implant was positioned more anteriorly relative to the tibia compared to a PS implant, due to the interaction between the anterior femoral cam and the tibial post [3].

In a healthy knee, the PCL induces a posterior shift of the femur relative to the tibia as the knee flexed. This action, known as the rollback phenomenon, pulls the femur backward concerning the tibia. However, contrasting evidence emerged when examining the effects of CR and PS implants [26-28]. Prior fluoroscopic research had shown that both CR and PS implants resulted in reduced posterior translation of the femoral condyle in comparison to healthy knees, particularly during deep knee bends. Interestingly, some studies asserted that PS implants could minimize the seemingly contradictory anterior movement of the femur while others argued that PS implants failed to replicate the normal anteroposterior motion of the knee [5, 28-31]. This divergence in findings underscored the complexity of fully emulating natural knee mechanics through artificial means.

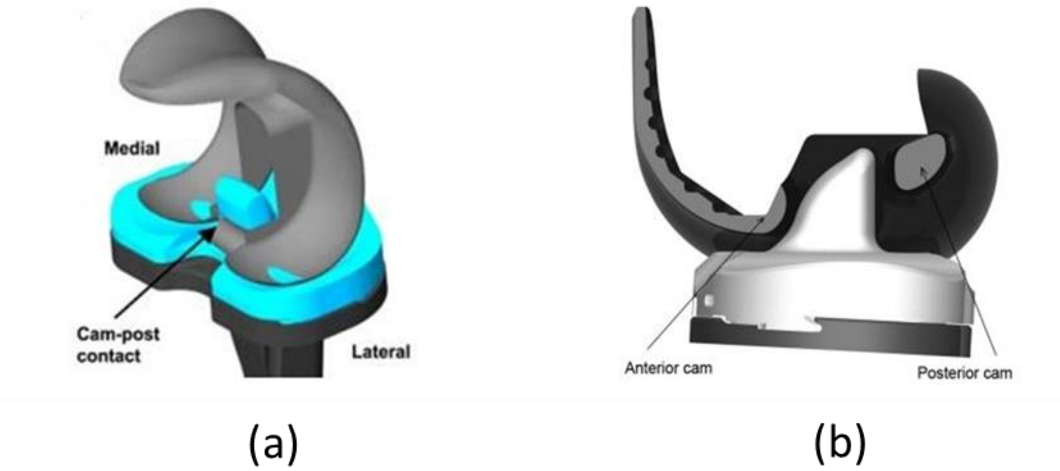

Figure 2.5 (a) Posterior Stabilized TKA Implants and(B) Bi-cruciate Stabilized TKA Implants [3, 32].

2.4 Motion Capture System

Stereophotogrammetry is a measurement methodology extensively used in the analysis of human movement, focusing on gathering information about the mechanics of the musculoskeletal system during motor tasks [33]. This technique employs the concept of capturing two or more images from slightly varying angles which is akin to the difference in perspective experienced by our two eyes [34]. By analyzing these images, the disparity in the object's position between the two images can be utilized to calculate the object's depth relative to the cameras via a method known as triangulation.

Our research extensively utilizes the technology of a motion capture system (Figure 2.6). This system digitally records human movements, translating real-life motions into a digital model for subsequent study and analysis. In our lab, we employ ten high-speed cameras (VICON, Oxford, UK) at 120Hz to track motion for daily activities. Usually, the variables measured in this process includes the transient marker positions obtained from markers attached to the skin, external forces and moments measured using force plates, and the electrical activities of muscles recorded through electromyography [34-36]. Here is a step-by-step breakdown of the motion capture system setup procedures used in our lab:

Figure 2.6 Marker Set Used and High-speed Cameras of a Motion Capture System.

- The cameras were positioned around the performance area to capture varying views of the performance. Force plates were set up, and the NORAXON EMG system was activated.
- Cameras were adjusted to ensure they were aimed to the performance area. Calibration often involved a special object, called a "wand," adorned with five markers. Moving the wand around the performance area allowed the system to calculate the position and orientation of each camera.
- Reflective markers were affixed at key anatomical points on the subject's body, typically joints. Consistency in marker placement across different subjects and sessions was crucial to ensure accurate and repeatable results.

- Creating T-Pose (Figure 2.7): Prior to motion capture, the subject often adopted a standardized pose, such as standing with arms extended straight out to the sides (forming a "T"). This pose enabled the system to establish a baseline position for each marker.
- Motion Capture: The subject performed the desired actions while the system recorded the motion of the markers. It was important to monitor the capture during this stage to confirm accurate tracking of all markers and to ensure the motion was captured at the desired quality.
- Digitization: This last step involved converting the motion data into a 3D model, which could be further analyzed.

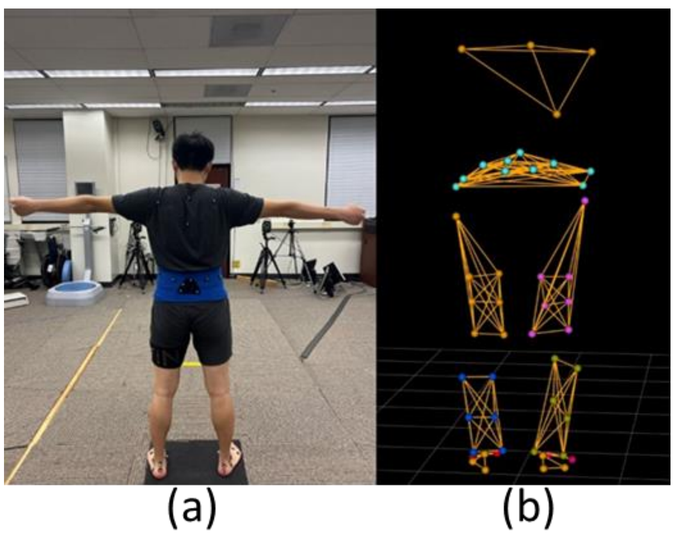

Figure 2.7 (a) T-pose and (b) Digitized Model.

2.5 Clinical Tests

2.5.1 Patient Reported Outcome Measure

The Knee Society Score (KSS) (Appendix D) is a recognized method for assessing pain levels and function in patients post-knee replacement surgery. Introduced in 1989 by the Knee

Society, an association of knee surgery specialists, the KSS consists of two separate scores: the Knee Score, which evaluates the knee based on pain, stability, and range of motion, and the Functional Score, which assesses the patient's capability to perform everyday activities. In both scores, the maximum attainable score was 100, where higher scores indicate improved function and reduced pain. Together, they provided a comprehensive assessment of post-surgery knee function [37]. The Knee Society Score consisted of two components: the knee score and the functional score. The combined score was used for comparisons between TKA patients and CG. The aggregate score was interpreted as follows: 80-100 was considered excellent, 70-79 was good, 60-69 was fair, and anything below 60 was rated as poor.

The Forgotten Joint Score (FJS) (Appendix D) is a patient-reported outcome measure (PROM) employed to evaluate the level of awareness of an artificial joint in patients who had undergone total joint arthroplasty, specifically targeting hip and knee replacements. The aim of the FJS is to measure how frequently patients 'forgot' about their artificial joint in their daily lives, indicative of a successful joint replacement. This scoring system offered a more nuanced evaluation of high-functioning patients who might not have exhibited substantial improvement on other outcome measures, such as the KSS or Oxford Knee Score, beyond a certain recovery threshold. Thus, it was invaluable for assessing improvements from the patient's perspective, especially those related to subtle benefits derived from advancements in surgical techniques, prosthetic designs, or postoperative care [38]. Responses were scored from 0 (Never) to 4 (Mostly). With a total of twelve questions, the final score was the sum of these 12 responses.

The Short Form Health Survey (SF-12) (Appendix D) is a compact version of the SF-36, a comprehensive general health survey extensively used in health research and clinical settings [39]. Created for utilization in large-scale health studies and medical practices, the SF-12 offers a time-effective alternative where the more exhaustive SF-36 might not have been feasible due to time limitations. The scoring for the SF-12 is calculated based on the answers provided to 12 specific questions, which are then converted into a scale ranging from 0, representing the worst imaginable health state, to 100, denoting the best conceivable health state. The SF-12 survey provided a quick overview of general health, comprising both physical and mental health sub-scores. Depending on the responses, scores ranged from 0 (Poor) to 4 (Excellent). These surveys offered invaluable insights in diverse settings, from clinical trials to public health research, presenting an encompassing view of a patient's health from their perspective.

The EQ-5D-5L (Appendix D) is a standardized tool used to measure general health status [40]. As a version of the EQ-5D, a measure developed by the EuroQol Group, the "5L" denotes five severity levels (no problems, slight problems, moderate problems, severe problems, unable to/extreme problems) for each of the five health dimensions it evaluated: Mobility, self-care, usual activities, pain, and anxiety. It offered a concise descriptor for health status, encompassing areas such as mobility, self-care, daily activities, pain/discomfort, and anxiety/depression. Each of the five dimensions was scored from 0 to 4.

2.5.2 Functional Test

The Time-Up-and-Go Test (TUG) and the Sit-to-Stand Test (STS) are fundamental clinical functional tests that physical therapists often use in evaluations to assess mobility, balance, and lower extremity strength (Figure 2.8). These tests prove especially beneficial for older individuals, or those on the road to recovery from post-injury or surgery.

The TUG is an uncomplicated mobility assessment tool that requires both static and dynamic balance, making it quite suitable for patients who had undergone TKA [41, 42]. The test quantifies the time taken by an individual to stand up from a chair, walk a certain distance, turn around, walk back to the chair, and sit down. The typical instructions to the individual may be: "On my mark 'go', I want you to stand up from the chair, walk briskly to the orange cone and back, then sit back down in the chair." The recorded time serves as an indicator of the individual's mobility and balance.

The STS test, on the other hand, is frequently employed to evaluate lower limb strength and balance in TKA patients [43, 44]. This test measures the time it takes for a person to rise from a chair without using their hands. To garner more in-depth data, the Ten Times Sit-to-Stand Test (TSTS) can be used, where the individual is timed while they repeatedly sit and stand ten times without hand support, as swiftly as possible. Both tests provide valuable insights into a person's lower body strength, balance, and susceptibility to falls. Furthermore, they serve as effective tools for tracking progress over time in rehabilitation programs, highlighting improvements in strength and balance.

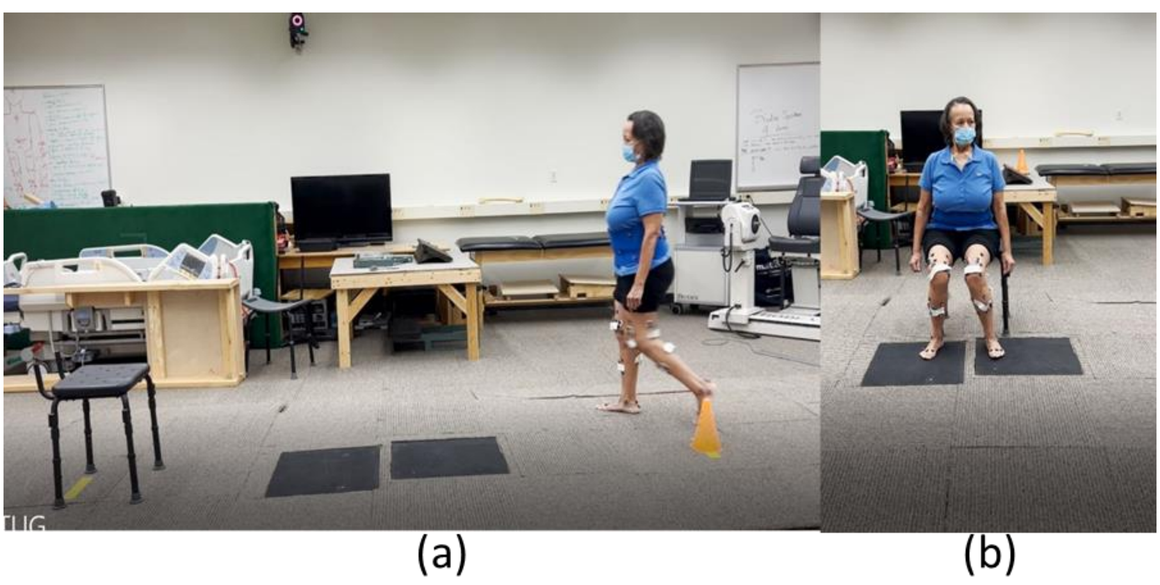

Figure 2.8 A Subject Performing (a) Time-up and go Test (TUG) and (b) Ten Times sit-to-stand Test (TSTS).

2.5.3 Balance Test and Proprioception Test

The Balance System (Biodex) (Figure 2.9) is a dynamic device frequently utilized by healthcare practitioners, physiotherapists, and sports trainers to evaluate and enhance balance, mobility, and overall biomechanical wellness [45]. It is primarily designed to detect and ameliorate balance, stability, and other motor control issues. It finds significant use in the rehabilitative process of post-injury or illness, as well as being a vital tool in holistic athletic training programs.

The balance system operates via a movable balance platform used to conduct balance assessments and provide balance training. The platform has multi-directional tilt capabilities, thereby challenging the user's balance. It quantifies postural stability by measuring the degree of sway during various balance tasks, which can then be analyzed to monitor progression over time, benchmark against normative data, or craft personalized treatment plans. During a balance test, an individual stands on the platform and strives to maintain balance while the platform moves or when asked to perform specific tasks. The degree of platform movement can be adjusted to suit the individual's current level of balance and stability, making the task challenging. Tests can be administered in either static or dynamic modes. In static mode, the platform remains stationary while the user attempts to maintain a central position. Conversely, in dynamic mode, the platform reacts to the user's movements, challenging them to preserve balance. The system incorporates visual feedback, an especially useful feature during training sessions. This feedback enables users to comprehend their current stability and understand what modifications are required to enhance their balance.

Proprioception refers to the body's ability to sense its own position, motion, and equilibrium. In other words, it is the ability to know where our limbs are in space without having to look at them. This is particularly important in the knee joint, where poor proprioception can contribute to injuries, falls, and poor athletic performance [46]. The balance system can be used to evaluate proprioception in the knee. A common way to do this is through a "joint position sense" test, which measures the ability of the individual to perceive the position of the joint. Here is how it works:

- A subject is seated in a dynamometer, and the knee is attached to the lever arm of the machine.
- The machine moves the knee to a certain angle, holds it there briefly, and then returns it to the starting position.
- The individual then attempts to reproduce the angle that was set early.
- The difference between the angle set by the machine and the angle the individual believed the knee to be at is recorded.
- This process is repeated several times, and the average difference is taken as a measure of knee proprioception.

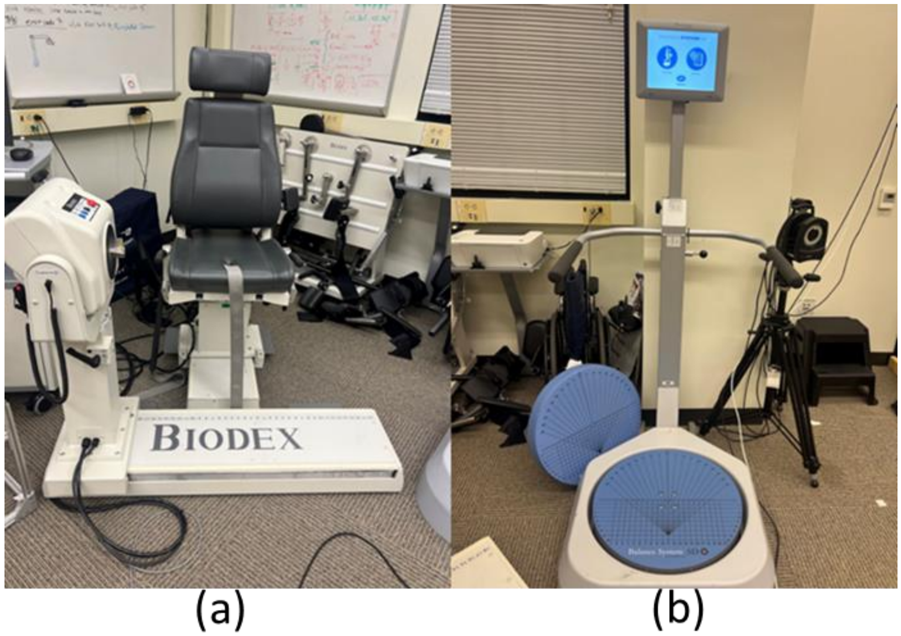

Figure 2.9 (a) Biodex Dynamometer and (b) Biodex Balance System.

CHAPTER 3: LITERATURE REVIEW

3.1 TKA Implants Design

Knee OA is a degenerative joint disease cahracterized by the progressive loss of articular cartilage. As the cartilage diminishes, the protective space between bones is decreased. This eventually leads to the bones rubbing against each other, resulting in pain and decreased functionality. Three primary factors contributes to knee OA: aging, being overweight, and injuries. The risk of OA increases with age due to the cumulative wear and tear that could cause cartilage degeneration [47]. Carrying excess weight exerts more stress on knee joints, accelerating cartilage breakdown [48]. Direct injuries to the knee, such as torn cartilage or ligaments, could elevate the risk of OA, even if the injury occurred years prior [49]. According to a study, the lifetime risk of developing symptomatic knee OA was substantial: 44.7% of individuals were likely to experience knee OA at some point in their lives, which could significantly impact their quality of life. Given its prevalence, knee OA exerts a considerable strain on healthcare systems globally. Direct costs, including treatments, surgeries, and medications, place a significant economic burden on societies [16, 50].

TKA serves as a surgical solution specifically designed for individuals afflicted with end-stage knee osteoarthritis. The primary goals of this orthopedic procedure are pain relief, correction of limb deformities, and the restoration of knee joint stability. The surgery entails several crucial steps: 1) Firstly, the damaged cartilage and bone surfaces from the tibia, femur, and patella are meticulously removed. 2) Following this, precision-engineered metal implants, often fabricated from high-quality alloys, are secured to replace the joint surfaces. 3) To conclude, a medical-grade plastic spacer is placed between the metal components. This provided a seamless and low friction articulating surface for the rejuvenated joint.

Surgeons, therapists, and biomechanics scientists play pivotal roles in TKA research. Surgeons diagnose and ascertain the suitability of patients for TKA based on clinical examinations, patient history, and imaging studies, choosing the right surgical approach and implant type, and guiding post-op care [51]. Therapists, as trained healthcare professionals, aid in post-TKA recovery, crafting rehabilitation protocols to restore function, mobility, and pain management, while continuously assessing recovery progression [52]. Biomechanics scientists applied physics and engineering principles to understand the body's mechanical aspects. Their research on the knee joint's forces and movements influenced the design of efficient knee implants and contributed to rehabilitation strategies, such as analyzing post-surgery walking patterns and understanding the broader mechanics of knee joints, especially when altered by procedures like TKA [53] [54]. This study used biomechanics to delve into TKA, exploring improved implant designs, gait analysis, rehabilitation methods, and outcome predictions.

There are evolutions of various implant designs and techniques tailored to cater to distinct anatomical and biomechanical needs. Three designs stood out prominently: cruciate retaining, posterior stabilized, and bi-cruciate stabilized. A central distinction among these designs arise from their approach to the PCL following the resection of the ACL during surgery [55]. CR implants prioritize the preservation of the PCL. Retaining the PCL offers stability to the knee and regulates the rearward motion of the tibia [56] [57]. In contrast, PS implants were conceptualized to substitute both the anterior and posterior cruciate ligaments. They incorporated a post and cam mechanism, compensating for the excised PCL, which facilitates a natural knee motion and bestowed posterior stability [58]. The BCS design struck a balance by aiming to emulate the function of both the ACL and PCL. These implants were crafted to mirror the movement and stability intrinsic to a healthy knee joint, either by conserving or reproducing the dual cruciate functions [3].

The role of the PCL in knee stability, particularly in constraining posterior tibial translation at low flexion angles, is crucial [59]. Jacobs et al. examined the difference between retaining and removing the PCL during motion, utilizing radiological outcomes. They discerned that the range of motion in PCL-retention groups was 8 degrees higher than in PCL-resection groups [56]. This finding aligns with other research: Mihalko et al. similarly found that sacrificing the PCL largely accounted for a more considerable flexion gap [60]. They also argued for a reevaluation of the role of PCL release in managing primary flexion contractures. Notably, the average ROM in designs that sacrificed the cruciate is approximately 10 degrees less than in designs that preserved it [57].

Conversely, the unique cam-post mechanism inherent in PS implants, which supplanted the PCL's function, delivered a higher ROM, and assured stability, particularly during deep flexion [32, 58]. Suggs et al. observed that in vivo cam-post engagement corresponded to increased posterior translation and decreased internal tibial rotation at high flexion in posterior-substituting total knee arthroplasty. Initial cam-post engagement also showed a mild correlation with the maximum knee flexion angle ($R = 0.51$, $p = 0.019$). When contrasting CR TKA with PS TKA, it is reported that there were no discernible differences in clinical outcomes [61, 62]. However, the flexion in the PS group surpassed that in the CR group. Kinematically, the posterior femoral roll-back during full flexion in PS was 9.6 mm, which was 3.5 mm more than in the CR group [61].

BCS implants aimed to replicate the functions of both the ACL and PCL. The design incorporated a tibial post and dual femoral cams as surrogates for both ligaments. An anterior femoral cam particularly targeted excessive posterior femoral movement [3]. End-stage OA patients could expect improved range of motion and more natural knee dynamics with BCS implants.

The knees with BCS implant were also compared with natural knees. For instance, Catani et al. compared BCS TKA with natural knees over a 6-month period via video fluoroscopy. Although six patients exhibited decreased knee adduction, the transverse plane moment mirrored that of a natural knee [2] [4]. In another study fluoroscopy was used during weight-bearing deep knee bends and observed rotation patterns like natural knees, albeit with reduced intensity.

Presently, clinical outcomes of knees with PS TKA and BCS TKA implants were compared. Using metrics like the Osteoarthritis Outcome Score (KOOS) and KSS, several studies assessed these implants [63-66]. Kuwashima et al. discerned no significant difference using the KSS, but the KOOS highlighted superior kinematics and clinical outcomes in BCS TKA over PS TKA. Digennaro et al. echoed these findings [67]. In one study, focusing on stair ambulation, knees with BCS TKA were better, suggesting superior replication of natural ligament function [6]. Revision rate comparisons revealed no significant differences between the implants [68].

Radiological studies comparing PS and BCS implants employed fluoroscopy and x-rays. One such study noted a smaller dynamic joint line orientation in BCS (1.8° ± 2.4°) compared to PS (5.5° ± 2.7°) [69]. Other studies used image-matching techniques to assess various kinematic patterns, revealing implant-design-dependent variations in gait. Ishibashi et al. found the medial femoral condyle in BCS to be more anteriorly positioned than in PS across flexion ranges [70].

From available research, most studies focused on clinical outcomes and radiological analyses. While clinical results provided subjective insights into mobility, fluoroscopic analyses might not have captured real-time dynamic movement. The performance dynamics of these two TKA implants remain uncharted. In our research, motion analysis was employed to contrast these implants during daily tasks, incorporating extensive biomechanical variables and EMG muscle activities for an exhaustive comparison.

3.2 Knee Biomechanics during Daily Activities

3.2.1 Knee Kinematics and Kinetics

The knee force (KF), ascertained by the ground reaction force (GRF), represented the cumulative external forces exerted on the human body. Captured through force plates, the GRF and corresponding knee joint forces are crucial biomechanical metrics. They allow researchers to discern asymmetries between the involved (surgery) limb and the uninvolved limb, which, in turn, illuminated the compensatory mechanisms adopted by TKA recipients. Christiansen et al. employed the concept of weight bearing, computed by dividing the peak vertical GRF of the involved limb by that of its contralateral counterpart, to examine the asymmetry in TKA patients [71]. Their findings revealed that the weight bearing at pre-op was 0.86, dipping to 0.67 one-month post-op. However, as patients continued to recover, this metric climbed to 0.87 at three months post-op and further improved to 0.97 by six months post-op. This trajectory demonstrated that while asymmetry in force distribution was exacerbated immediately after TKA, it tended to ameliorate over time. By the sixth month, patients approached a nearly symmetrical force distribution between limbs, indicating successful compensation and recovery from the surgical intervention.

Various methodologies existed for calculating knee kinematics, including the direction cosine matrix, Euler angle, quaternion, the joint coordinate system, and the projection method.

The direction cosine matrix method represented the transformation between two segments but tended to be intricate due to its many parameters, making it less intuitive for clinical professionals [72]. Euler angles relied on the sequence of rotations and were plagued by the Gimbal lock phenomenon [73]. Quaternions, with their four parameters, often found limited utility in clinical contexts [74]. The joint coordinate system method, utilizing two bone-fixed axes and a floating one, defined joint motion based on three rotational and three translational components in relation to the joint coordinate system axes and a reference point. However, it did not always yield an orthogonal coordinate system [75].

Several previous studies have utilized variables such as sagittal plane range of motion, sagital plane moment and the bilateral difference of the ground reaction forces as main variables to comapre the TKA patients with control group (CG) during level walking and stair ambulations [76-80] [81-84] [71, 85]. These variables were considered crucial for several reasons: optimizing knee flexion and extension moments enhances muscle strength and balance around the knee joint; improving these moments, along with knee flexion and extension range of motion, can reduce joint stress, thereby alleviating pain in patients with knee osteoarthritis and TKA; and bilateral differences can lead to increased stress and uneven weight distribution on the contralateral knee, thereby raising the risk of bilateral TKA [86]. Consequently, knee flexion and extension range of motion and moments, as well as the bilateral ratio of knee force, are critical for functional improvements in patients with knee osteoarthritis and total knee arthroplasty.

Additionally, studies on TKA have also examined knee kinematics and kinetics in the frontal and transverse planes. For instance, the maximum external knee adduction moment was found to be lower in TKA patients [80, 81]. Contradictorily, Standifird et al. reported an increased peak knee abduction moment compared to controls, while Saari et al. [87] reported no difference between TKA patients and control subjects in knee abduction moments Reduced knee abduction and adduction moments can alleviate medial or lateral forces on the knee, potentially decreasing the risk of excessive joint loading and degeneration [88] [82]. Additionally, improvements in transverse plane moments and rotations can be indicative of functional improvements in TKA patients. However, these were not the sole factors to consider when evaluating overall functional improvements.

Improvements in the ability to perform daily activities were essential for TKA patients and can significantly impact their quality of life. Although previous studies had found that TKA patients restored their knee range of motion during level walking within six months of the surgery, deficits in sagittal plane knee moment and angle were reported compared to the CG [2, 17, 88, 89]. Walking on a slope (ramp up and ramp down) was a challenging task compared to level walking in daily activities [10, 90-92]. It was reported that TKA patients generated higher knee abduction moments, greater knee extension moments, and quadriceps muscle activities than level walking [93, 94]. Stair ambulation (ascending and descending) was considered a high-demanding daily activity requiring greater knee flexions and synergy of low extremities [11, 95]. Researchers reported that the postoperative TKA patients still had significant deficits in the front plane moment and sagittal plane angle compared to CG during stair ambulation [88, 96, 97].

3.2.2 Knee Biomechanics during Level Walking

Three key parameters, gait speed, step length, and stride length, were analyzed. Gait speed, measured in meters per second, is used as a health indicator, with slower speeds often signifying increased risks like falls, frailty, or cognitive impairments. Step length represented the distance between successive heel strikes of alternate feet, and alterations in this parameter could hint at balance problems, neuromuscular disorders, or issues like Parkinson’s disease [98]. Stride length, encompassing the distance between heel strikes of the same foot, equated to twice the step length, offering insight into leg functionality and revealing potential orthopedic or neurological conditions. In conjunction with other metrics like cadence and base of support, these parameters equipped clinicians to diagnose underlying issues, evaluate fall risks, and tailor therapeutic interventions to bolster mobility and safety.

Gait analysis has served as a pivotal tool in biomechanics, offering insights into biomechanical anomalies in the lower extremities. This analysis, encompassing gait parameters, ground reaction forces, knee kinematics, and knee kinetics, elucidated the functional improvements and changes before and after TKA surgery. One major focus was on the comparison of gait parameters, such as gait speed, stride length, and step length, between TKA recipients and CG during level walking.

Benedetti et al. highlighted a "stiff knee gait pattern" in TKA patients, characterized by reduced gait speed and stride length relative to controls [17]. This observation was corroborated by Alnahdi and Zeni who assessed TKA patients at both 6 months and 1 year post-surgery [99]. They reported reduced step length (0.69 m) and walking speed (1.27 m/s at post-op) in comparison to the control group (0.75 m for step length and 1.43 m/s for speed). While 1-year post-surgery metrics indicated improvement, they still lagged CG. Ouellet and Moffet detected pronounced locomotor deficiencies in TKA recipients just 2 months post-surgery compared to controls, explaining the diminished performance in the Time-up-and-go and sit-to-stand tests [96]. Kramers-de Quervain et al. reported significant advancements in gait speed two years post-TKA relative to pre-surgery values [100]. However, they also noted an increased load on the non-operated limb relative to the operated one. Through gait analysis, biomechanical researchers could track and understand the gradual improvements in mobility and function after TKA surgery, helping refine rehabilitation methods and inform patient expectations.

Knee kinematics, encompassing the movement patterns of the knee joint, played a pivotal role in comprehending the functional changes after Total Knee Arthroplasty [89]. Levinger, et al. noted that post-TKA, the most evident changes were pain reduction and functional amelioration. Nonetheless, many post-TKA patients demonstrated a heightened sagittal plane ROM during ambulation, compared to their pre-op baseline [76-78]. This enhancement could be attributed to pain alleviation and the excision of osteophytes. However, even with these improvements, significant disparities in sagittal plane ROM were observed during load-bearing activities when juxtaposed with a control group [76].

Exploring knee kinetics during ambulation, researchers predominantly concentrated on sagittal plane flexion/extension moments, frontal plane abduction/adduction moments, and transverse plane external/internal rotation moments. Hatfield et al. identified decreased external rotation moments during early stance, alongside diminished adduction moments and amplified knee flexion moments [77]. This reduction in knee adduction moments can be correlated with enhanced knee stability, potentially influenced by the surgical realignment of the tibiofemoral joint [88]. The observed decline in extension moments in the early stance phase was noted. This could have stemmed from an initial heel strike in a more flexed knee position or could have been indicative of "quadriceps avoidance." Such avoidance was echoed in findings that highlighted post-TKA abnormalities in knee kinematics and kinetics during loading acceptance. These anomalies were linked to muscular co-contractions in activation patterns, supporting the notion of a protective or compensatory strategy [17].

3.2.3 Knee Biomechanics during Ramp Walking

Walking on an incline or ramp presents numerous challenges not encountered during level walking. When ascending a slope, one has to exert extra effort to overcome gravity, requiring greater engagement of the quadriceps and glutes to propel the body upward [101]. In contrast, descending a slope puts stress on the quadriceps as they work to decelerate or control the descent [102]. The biomechanical implications extend to the legs as well. Participants must increase muscle activity in their legs during slope walking, leading to elevated energy expenditure. Importantly, the forces acting on the knee joints are significantly altered during incline walking. Research shows that knee joint loading increased when walking on an incline, posing particular challenges for individuals with knee issues [91]. Beyond biomechanics, incline walking has metabolic repercussions as well. Heart rate and oxygen consumption typically rise more rapidly during incline walking than when walking on level ground, due to increased muscle activity [103].

Some researchers explored the differences in gait parameters during incline walking. Kawamura et al. recruited 17 young, healthy females to walk both uphill and downhill at inclines set at 3, 6, 9, and 12 degrees[104]. Their findings revealed that at a 12-degree incline, walking speed during both uphill and downhill walking was significantly lower compared to walking on flat ground. They also discovered a relationship between step length and the steepness of the slope: the steeper the incline, the shorter the step length. Similarly, Ferraro et al. recruited 78 self-reported healthy older participants (with a mean age of 77.8 years) to walk on inclines[105]. They found comparable results, observing that, compared to level walking, step length was shorter (63.1 cm vs 64.3 cm), and gait speed was slower (0.89 m/s vs 0.96 m/s) during incline walking.

Knee kinetics during incline walking is found to differ from those during level walking. Although the overall pattern of knee moments was similar, studies reported specific variances. For example, Haggerty et al. found that the peak knee extension moment in the early stance phase was greater in incline walking compared to level walking[10]. They also noted that the knee abduction moment during uphill walking was 20% lower than that during level walking. This reduced knee abduction moment could signify a decrease in the loading of the medial compartment of the tibiofemoral joint. Similarly, Lay et al. (2006) demonstrated that the knee extension moment during the stance phase of downhill walking was twice as great as that during level walking. Importantly, these studies were conducted on healthy subjects, providing valuable insights into the variations in knee kinetics during walking on different slopes [91].

Additionally, research into the performance of patients with TKA during slope walking emerged. Simon et al. aimed to compare knee kinematics, kinetics, and muscle activation in patients with cruciate-retaining TKA implants and bi-cruciate retaining TKA implants during downhill walking [92]. While no significant differences were observed in level walking, a notable variation in knee flexion at heel strike was found between the two implant types during downhill walking. Wen et al. conducted a study to investigate knee biomechanics during uphill walking at different slopes [93]. They found that the peak extension moment in the involved limb was significantly lower than that in the contralateral limb when walking on slopes of 10 and 15 degrees. Furthermore, both the sagittal and frontal plane ROM increased with steeper slopes. Recent work by Wen et al. also examined downhill walking in TKA patients [94]. Compared to CG, the TKA group exhibited lower peak knee extension moments. The study also found that increased ROM, vertical ground reaction force, and knee extension moment led to greater knee loading, which may not be advisable for early-stage TKA patients in rehabilitation protocols.

3.2.4 Knee Biomechanics during Stair Ambulation

Stair ambulation, which involved both ascending and descending stairs, is often considered a more demanding daily activity for older individuals compared to level walking or slope walking [106]. When performing stairs, the body must work against gravity to elevate its center of mass with each step, thereby requiring more energy than walking on a flat surface. Muscles such as the quadriceps, hamstrings, and calf muscles are called upon to exert greater force during this activity. Additionally, there is increased engagement of stabilizing muscles to prevent falls. Stair climbing also demands greater flexion angles at the knee and hip compared to level walking, resulting in increased joint loading. This could be particularly challenging for individuals with knee joint issues. Importantly, the forces exerted on the joints are not constant throughout the stair-climbing process; they peak at specific phases like the "push-off" and "landing" stages, thereby subjecting the joints to heightened stress.

The literature focused on the biomechanical changes in knee function during stair ambulation of patients with TKA [107]. During stair ascending, reduced knee flexion in TKA patients was found as compared to control subjects [80]. Similarly, sagittal plane ROM was found to be reduced in TKA patients [80]. When it came to maximum flexion-extension moments, a reduction was reported in the TKA group compared to the control group [81]. Regarding frontal plane knee kinetics and kinematics, multiple findings emerged. The maximum external knee adduction moment was found to be lower in TKA patients [80, 81]. However, Standifird et al. reported an increased peak knee abduction moment compared to controls, while Saari et al. reported no difference between TKA patients and control subjects in knee abduction moments [82] [87].

During stair descending, the sagittal plane ROM was also observed to be decreased in TKA patients compared to controls [79]. However, no significant differences were found between TKA and CG in several studies [87]. For sagittal plane knee moments, Wilson et al. found significant differences between the TKA and CG, whereas other researchers did not observe any such differences [79, 80] [108]. In terms of frontal plane variables, no significant differences were reported in knee abduction moments between the TKA and CG [80, 109].

Some studies have also delved into bilateral differences during stair ambulation. Standifird et al. reported that the peak knee extension moment in contralateral knees was greater during the loading response phase than in the involved knee [82]. Similarly, Sumner et al. and Yocum et al. found that, for unilateral TKA patients, knee extension moments in the involved limb were lower compared to the contralateral limb [83, 84].

However, longitudinal studies during stair ambulation were scant. A few reviewed studies compared TKA patients to their pre-surgery levels [88, 96, 97] [83]. They specifically showed that TKA groups had improvements in stair descending kinetics and kinematics at one-year postoperative. Given the paucity of such longitudinal data, there was a pressing need to understand how gait patterns on stairs changed following TKA. Future research should have aimed to compare post-surgery data at various time points with pre-surgery data, either from the same subjects or those with similar pre-surgery conditions. Studies of this nature could have offered a more comprehensive understanding of the extent to which recovery following TKA could be achieved [107].

3.3 Muscle Activities of Knee Extensors and Flexors

3.3.1 EMG Analysis

The simultaneous normalization of kinematics, kinetics, and EMG data within a gait cycle for all daily activities offers a comprehensive assessment of muscular activity and movement dynamics. For each daily activity, the peak muscle activity was identified as the maximum EMG signal during the gait cycle. To further refine this data, the root mean square (RMS) of the EMG signals from three functional test trials was used to normalize the filtered EMG signals of the testing movement trials. The mean RMS value was determined by averaging the normalized RMS signal across the gait cycle [110].

Interestingly, for the normalization of the EMG data, the maximum value recorded during the three functional test trials was used, rather than the more traditional approach of using maximal voluntary isometric contractions (MVIC). MVIC was a common method employed to normalize EMG data, as it represented the maximum force output of a muscle during contraction. However, in the context of this study involving total knee arthroplasty patients, a deliberate decision was made to forgo MVIC. This choice was driven by the need to ensure patient comfort and safety, given that TKA patients might have experienced discomfort or even pain when attempting maximal muscular contractions. By using the maximum value from functional test trials instead of MVIC, the study reduced potential discomfort for these patients while still achieving meaningful normalization of the EMG data.

The onset detection of EMG signals played a pivotal role in EMG signal analysis. The Teager-Kaiser Energy Operator, which merged the amplitudes and instantaneous frequency, was frequently employed for this purpose [111]. When muscle activation exhibited a signal-to-noise ratio lower than a given threshold, it was identified as the onset of muscle activation [112]. his approach had been instrumental in the EMG analyses of dynamic trials [85, 113]. Integrated EMG quantified the cumulative electrical activity of a muscle within a set time. This method was notably beneficial when comparing muscle activity across varying conditions or tasks, especially if the duration of the muscle contraction differed between them. The resultant integrated EMG provided a comprehensive measure of the muscle's electrical activity for that duration. This consolidated metric proved invaluable when comparing muscle activation across varied tasks [114].

3.3.2 Muscle Activities during Daily Activities

Monitoring EMG activities in patients who had undergone TKA is significant. Prior to surgery, EMG assessments could offer valuable insights into muscle activity and function, thereby informing the surgical approach and setting expectations for postoperative outcomes. In the postoperative phase, EMG served as a reliable tool for tracking rehabilitation progress. By offering real-time data on muscle function, EMG could effectively guide physiotherapy regimens, providing clinicians with evidence-based metrics to determine when a patient is ready to advance to more demanding activities.

The quadriceps muscles played a pivotal role in supporting the body during various motor tasks. Postoperatively, quadriceps weakness was commonly observed, making their strengthening a central focus of rehabilitation efforts. Similarly, hamstrings, which were crucial for knee flexion and joint stability, were engaged particularly when the leg swung forward and during the initial contact of the foot with the ground. In the context of level walking, Benedetti et al. observed a prolonged muscular co-contraction during the stance phase, which they associated with abnormal knee kinematics and kinetics in post-TKA patients [17]. In a recent study, Yoshida et al. utilized surface EMG to examine the postoperative recovery of muscle function in the vastus medialis (VM), vastus lateralis (VL), and rectus femoris muscles [115]. Their longitudinal study, spanning 24 weeks post-surgery, revealed that VL activity declined until the 12-week mark compared to preoperative levels. However, it subsequently increased, aligning with control group values by the 24th week. In contrast, muscle activity of rectus femoris showed a slight uptick at three weeks post-surgery and remained stable thereafter.

During ramp walking, Lay et al. conducted an extensive study analyzing the electromyographic (EMG) activity of various muscles including the gluteus maximus rectus femoris , vastus medialis, biceps femoris(BF), semimembranosus(SN), medial gastrocnemius , soleus , and tibialis anterior(TA) [101]. They focused on uphill, level, and downhill walking at a 21° incline. The results indicated a significant increase in mean EMG activity for all muscles except TA during the uphill walking in the stance phase— rising by an average of 211% compared to level walking. Additionally, the burst durations for GM, BF, SM, RF, and VM were also markedly increased during uphill walking. In a similar vein, Lange et al. noted an average increase of 96% and 113% in mean and peak muscle activities of VM, VL, and BF as the incline increased from 0 to 10° [116]. Haight et al. studied the EMG patterns during uphill and level treadmill walking at a 6° incline but found no significant differences in EMG magnitude and duration between the two test conditions due to the distinct walking speeds chosen for the tests [117].

As for stair ambulation, Elkarif et al. analyzed the durations of muscle activity in several muscles, including the rectus femoris, semitendinosus, medial gastrocnemius, soleus, and tibialis anterior [118]. They compared these durations between groups with TKA and group without TKA during ascending and descending stairs. The researchers found that the activation duration of the tibialis anterior in the osteoarthritis (OA) limb was higher in the TKA group compared to the group without TKA during both stair ascending and descent. However, no significant differences were found in muscle activation durations when comparing the limb with OA to its contralateral limb.

Muscle fatigue and compensatory muscle activation are known issues for patients post-Total Knee Arthroplasty. Roldan-Jimenez et al. utilized surface EMG to measure muscle activity and fatigue in various lower extremity muscles during a 30-second Sit-To-Stand task [119]. They assessed the gastrocnemius, biceps femoris, vastus medialis of the quadriceps, abdominal rectus, erector spinae, rectus femoris, soleus, and tibialis anterior. Their results showed a trend of increasing fatigue in the MG and SO muscles. Additionally, asymmetry in quadriceps muscle activity was notably observed in TKA patients in previously reported studies [43, 120]. To further explore the notion of compensatory muscle activation, Davidson et al. discovered that TKA patients had a higher coactivation index compared to a CG [85]. This elevated level of coactivation was attributed to a sustained distribution of quadriceps activity during the STS task. As a compensatory mechanism, patients with TKA seemed to have activated their hamstrings more than the CG, as a protective strategy. However, this compensatory muscle activation could have impeded the optimal recovery of quadriceps function.

3.4 Clinical Tests

The TUG test is a commonly utilized clinical test to assess the functional performance of elderly individuals [121] [122]. Among TKA participants, the TUG test is often employed to gauge the functional improvements in follow-up assessments. Mizner and Snyder-Mackler used the TUG as a functional test to explore the correlation between the time taken to complete the TUG and muscle strength [120]. Additionally, Farquhar and Reisman adopted the completion time of the TUG as a variable in comparing TKA patients at three months and one-year post-surgery [43]. Their findings revealed no significant differences between the TKA group at one year and three months post-surgery. When contrasted with the CG, no significant differences were observed between the one-year and three-month marks following TKA.

The STS test is another frequently administered clinical assessment in TKA research. Beyond just timing the STS performance, symmetry of motion, strength, and functional performance metrics are typically observed to discern bilateral differences and compensatory mechanics in TKA patients [43]. Farquhar, et al. noted enhancements in symmetry of motion, strength, and functional performance in TKA participants one year after the procedure. However, in comparison with CG, TKA subjects still exhibited increased hip flexion and a more pronounced hip extensor moment during the STS task. Alnahdi et al. investigated bilateral discrepancies using kinetic and kinematic variables during the STS [123]. Their findings highlighted that the involved limb exhibited diminished quadriceps strength, reduced hip and knee extension moments, and lesser vertical ground reaction forces. Meanwhile, Davidson, et al. employed EMG muscle activity readings to discern the coactivation between the quadriceps and hamstring muscles during the STS [85]. They reported heightened coactivation in TKA participants, suggesting challenges in coordinating muscle firing, especially when descending rapidly onto a chair. This observed behavior, potentially a protective measure, might also hinder post-op muscle functional recovery.

CHAPTER 4: MATERIALS AND METHOLODY

4.1 Participants

The study protocol was approved by an institutional research board at the University of North Carolina at Charlotte (Appendix B). 54 unilateral TKA patients were recruited via initial screening and follow-up phone calls, and 20 subjects without any knee disease as CG were recruited via flyers (Appendix C). The participants who met the inclusion and exclusion criteria were invited to participate in the research study.

Inclusion Criteria:

- Adults between the ages of 50 and 75

Exclusion Criteria:

- Diagnosed with any type of lower extremity joint osteoarthritis as reported by the patients.
- Any lower extremity joint replacement.
- Any lower extremity joint arthroscopic surgery or intra-articular injection.
- Systemic inflammatory arthritis (rheumatoid arthritis, psoriatic arthritis) as reported by the patient.
- BMI greater than 38 kg/m^2.
- Inability to walk without a walking aid.
- Neurologic disease (e.g., Parkinson’s disease, stroke) as reported by the patient.
- Any major lower extremity injuries/ surgeries.
- Any visual conditions affecting gait or balance.
- Women who are pregnant or nursing.

- Any cardiovascular disease or primary risk factor which precludes participation in aerobic exercise as indicated by the Physical Activity Readiness Survey.

Informed consent was obtained from each subject before testing (Appendix A). All the subjects were tested before TKA surgery and 6 months after surgery. For those subjects who were unable to return 6 months after surgery or change the surgery type were excluded in this study. By the end of this study there were 20 patients who performed the posterior stabilized TKA, 24 patients who performed Bi-crucial stabilized TKA, and 10 subjects who dropped the study (Table 4.1).

Table 4.1 Demography of the Recruited Subjects for TKA Study. Mean (Mean ± Standard Deviation).

	Count	Age	Gender	BMI
PS	20	64.84 ±6.44	M/F 11/9	29.83 ±4.87
BCS	24	65.01±6.31	M/F 13/11	29.7 ±4.88
CG	20	63.75±6.11	M/F 11/9	28.14 ±5.17

4.2 Clinical Test

Before undergoing the motion test, participants completed four Patient-Reported Outcome Measures (PROMs) including the Knee Society Score, the Forgotten Joint Score, the Short Form Health Survey (SF-12), and the EQ-5D-5L score (Appendix D).

Participants underwent six tests using a balance system (Biodex). The first three tests involved a static platform where participants stood with both feet, only the left foot, and only the right foot, respectively. Before each test, the position of each foot and the center origin had been set. Participants aimed to maintain the black spot at the screen's center. Each test lasted approximately 30 seconds, with a 10-second rest period between trials. The subsequent three tests utilized a tilted platform, with all other parameters mirroring the initial set. The overall stability index served as a comparative metric between TKA follow-ups and the CG.

The second clinical test in the motion lab was the proprioception test, which assessed muscle memory for all participants. Subjects seated on a dynamometer with their knee attached to the machine's lever arm. In the passive muscle memory test, the machine moved the knee to 30 degrees and 70 degrees, paused briefly, and then reverted to the starting position. Participants then tried to replicate the angle set early. The active memory test differed only in that the participant moved the knee to a specific angle; all other parameters remained unchanged. The difference between the machine-set angle and the participant-perceived angle was recorded. This procedure was repeated three times, and the average difference was used to measure knee proprioception.

For the TUG test, the time an individual required to rise from a chair, walk a specified distance, turn around, walk back, and sit down was measured. The recorded time served as an indicator of the participant's mobility and balance.

The final functional test in our motion lab was the ten-time STS test (Figure 4.1). In this assessment, participants were timed as they alternated between sitting and standing ten times in succession without the aid of their hands, aiming to complete the sequence as quickly as possible. Throughout this activity, we simultaneously recorded marker positions, ground reaction forces, and muscle activities of the lower extremities.

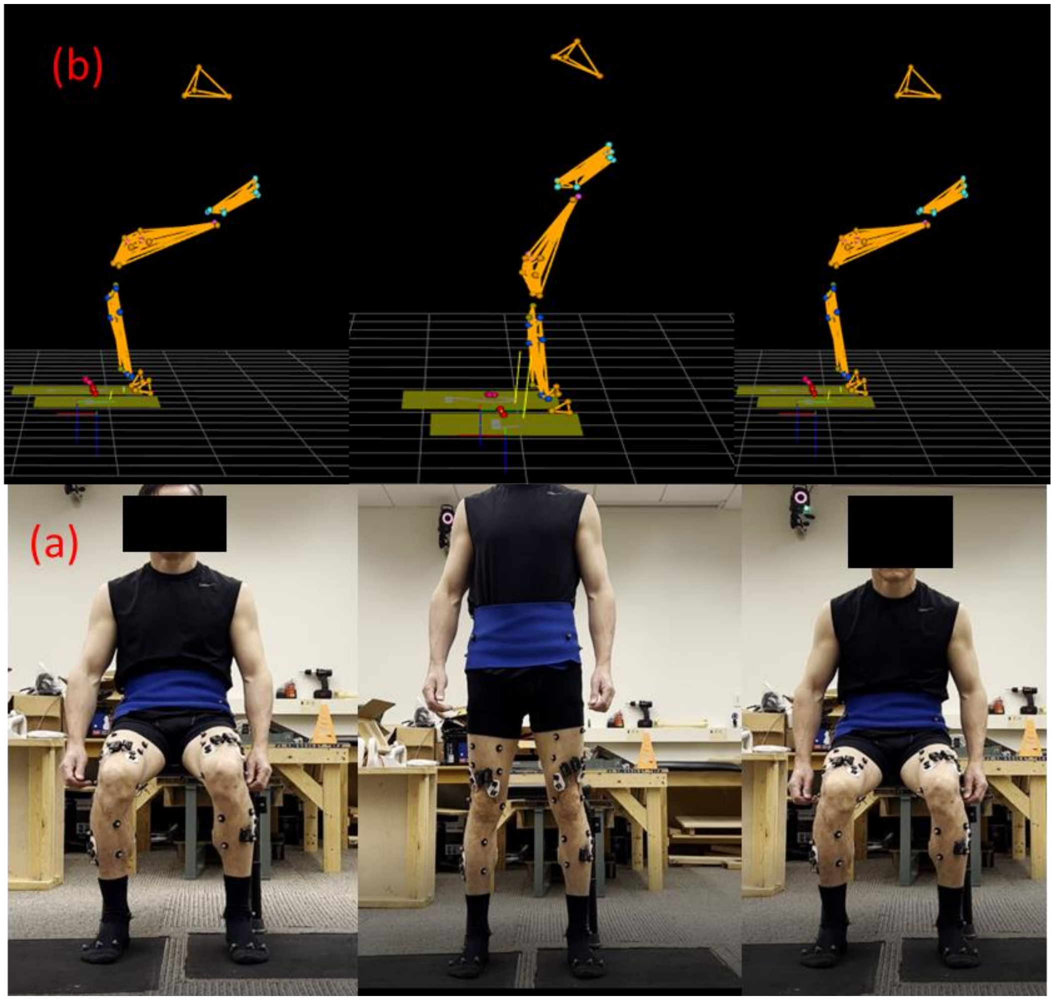

Figure 4.1 (a) Process of Ten Times Sit to Stand Test and (b) Digitized Model.

4.3 Motion Capture

4.3.1 Experimental Setup

For stair climbing, a custom-built staircase of two steps was used and the step height is about 18 cm. The lower step matched the dimensions of a force plate (46.4 cm x 50.8 cm) and was placed on one of the two force plates to measure ground reaction force during stair ascending or descending (Figure 4.2). The higher step was 70 cm in width and had an attached lower step for transition. A customized ramp (3m long, 1m wide, 15 degrees) were used to simulate common daily-life activities. Wood plates were placed above the force plates during ramp walking to capture ground reaction force, and the steps contacting each force plate during stair ambulations ensured that the ground reaction force of one foot was captured by one force plate.

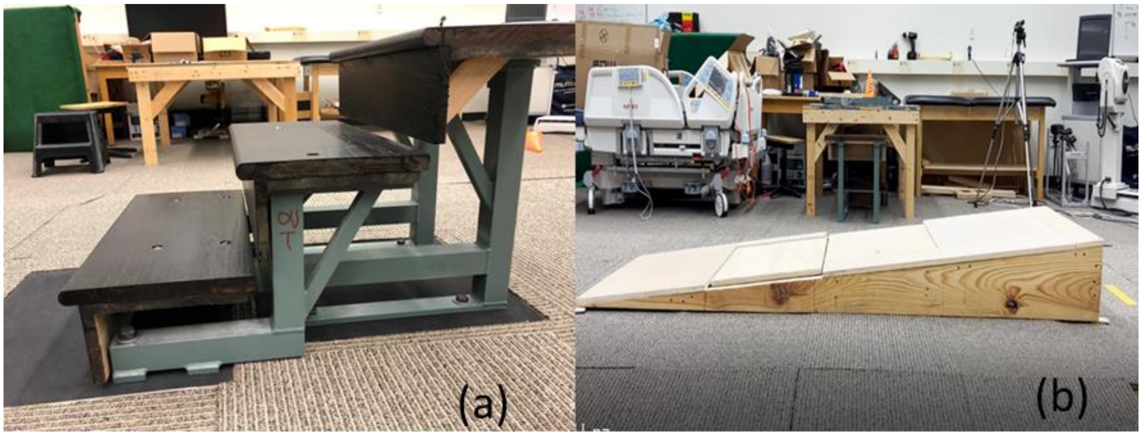

Figure 4.2 (a) Customized Stairs (18cm Height, 70cm Wide) and (b) Ramps (3m Long, 1m Wide, 15 Degrees) in Motion Lab.

Participants were asked to perform a series of tasks in this following order: proprioception and balance test, static trial (T-pose), level walking, stair ascending, stair descending, ramp up and ramp down, time up and go and sit-to-stand (Figure 4.3). All these tests followed previously reported procedures and methodologies to collect kinematic and kinetic data for level walking, stair climbing [124, 125](Table 4.2).

Figure 4.3 : A Subject Performing Motion Tasks (Left to Right: Level Walking, Ramp Up, Ramp Down, Stair Ascending, Stair Descending).

Table 4.2 Total Motion Tests Performed by TKA Participants in Motion Lab.

PROMs	Motion tasks	Functional test
Knee society score	Level walking	Time-up-and-go
FJS score	Ramping-up	Sit-to-stand
SF 12 score	Ramping-down	ROM test
EQ-5D-5L	Stair-ascending	Balance test
	Stair-descending	Proprioception test

4.3.2 Motion Data Analysis

A 10-camera motion capture system (Vicon, Oxford, UK) was used to capture the three-dimensional motion of the reflective markers at 120 Hz. A total of 52 reflective markers were placed bilaterally on bone landmarks and body segments, which included anterior superior iliac spines, posterior superior iliac spines, sacrum, medial and lateral femoral epicondyles, medial and lateral ridges of the tibial plateau, the medial and lateral malleoli and the second metatarsal head and the heel, anterolateral side of the thigh and the shank. An elastic wrap was affixed on the waist to minimize the movement of artifacts (Figure 4.4).

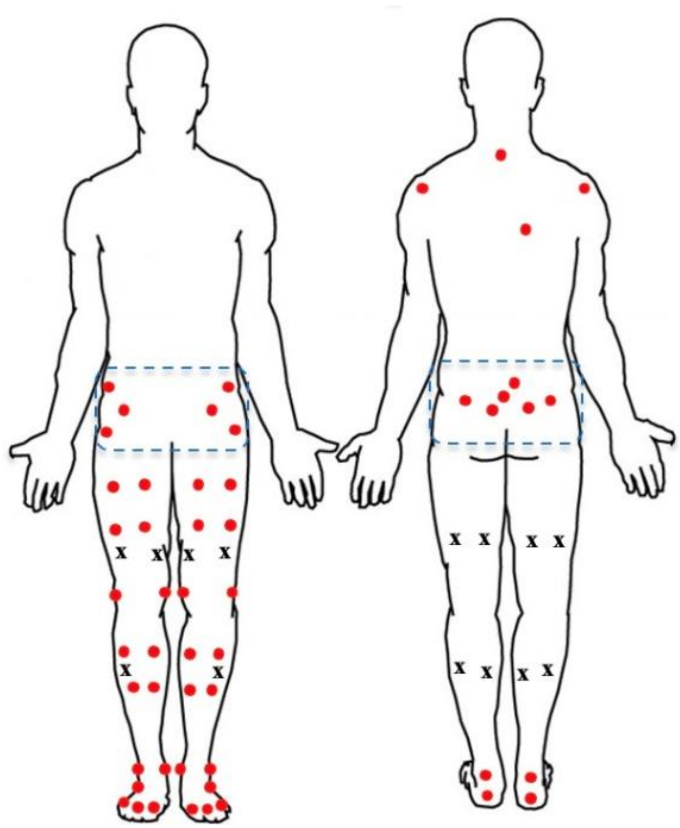

Figure 4.4 Marker Placements of TKA Subjects (Red circle: Position of Markers, Black Cross: Position of Electromyography).

The anatomical coordinate systems for the femur, tibia, and foot were constructed with specific origins and orientations. For the femur, the origin was at the knee joint center, which was the midpoint between the lateral and medial femur epicondyles. From this origin, the Z-axis was drawn towards the hip joint center. The Y-axis was defined parallel to the cross product of the Z-axis and a vector stretching from the heel marker to the second metatarsal head. The X-axis emerged from the cross product of the Y and Z axes. Moving to the tibia, its coordinate system's origin sat at the midpoint between the medial and lateral ridges of the tibia plateau. The ankle joint center, identified as the midpoint between the lateral and medial malleoli, determined the Z-axis, which pointed from the ankle joint center to the tibia's origin. Parallel to the cross product of the Z-axis and the vector from the heel to the second metatarsal head, the Y-axis was formed, and the X-axis resulted from the cross product of the Y and Z axes. For the foot, when in a neutral position, its anatomical coordinate system mirrored the tibia, but its origin was positioned at the ankle joint center [126].

In addition, two floor-embedded force platforms (AMTI, Massachusetts,USA) synchronized with the motion capture system were used to measure ground reaction forces and moments at 1200Hz. Wood plates were placed above the force plates during ramp walking to capture ground reaction force, and the steps contacting each force plate during stair ambulations ensured that the ground reaction force of one foot was captured by one force plate [125, 126].

The motion trajectories were filtered with a low-pass filter at 6 Hz to remove high-frequency noise, while ground reaction force and moment data were filtered with a cut-off frequency of 15 Hz. Joint kinematics were derived from the motion of lower body segments, including the foot, tibia, femur, and pelvic regions, with the defined local coordinates system. The joint centers of the ankle, knee, and hip were predicted with the mid-point between the lateral and medial malleoli, between the lateral and medial femoral epicondyles, and markers on the pelvic region [84, 127]. The motion of each segment during daily activities was then calculated using a least mean square-based algorithm [128, 129]. Three-dimensional joint angles (flexion/ extension, varus/ valgus, internal/external rotation) were calculated using the projection method [130]. The initial contact (foot strike) and toe-off were detected using a threshold of 5% body weight of ground reaction force to determine the stance and swing phases of joint kinematic and kinetic patterns. A gait cycle from both limbs of each trial was used for analysis, and time was normalized to 100% of the step cycle [126].

A gait cycle spanned from one heel strike to the subsequent heel strike (Figure 4.5). A force threshold of 10 Newtons was employed to identify both the initial heel strike and toe-off.

As the second heel strike did not occur on the force plate, it was discerned based on the kinematics of the heel marker. At the instant of heel strike, the heel's motion was halted, leading to an almost negligible heel velocity. These three gait events were captured for both sides, collectively determining the different phases of level walking.

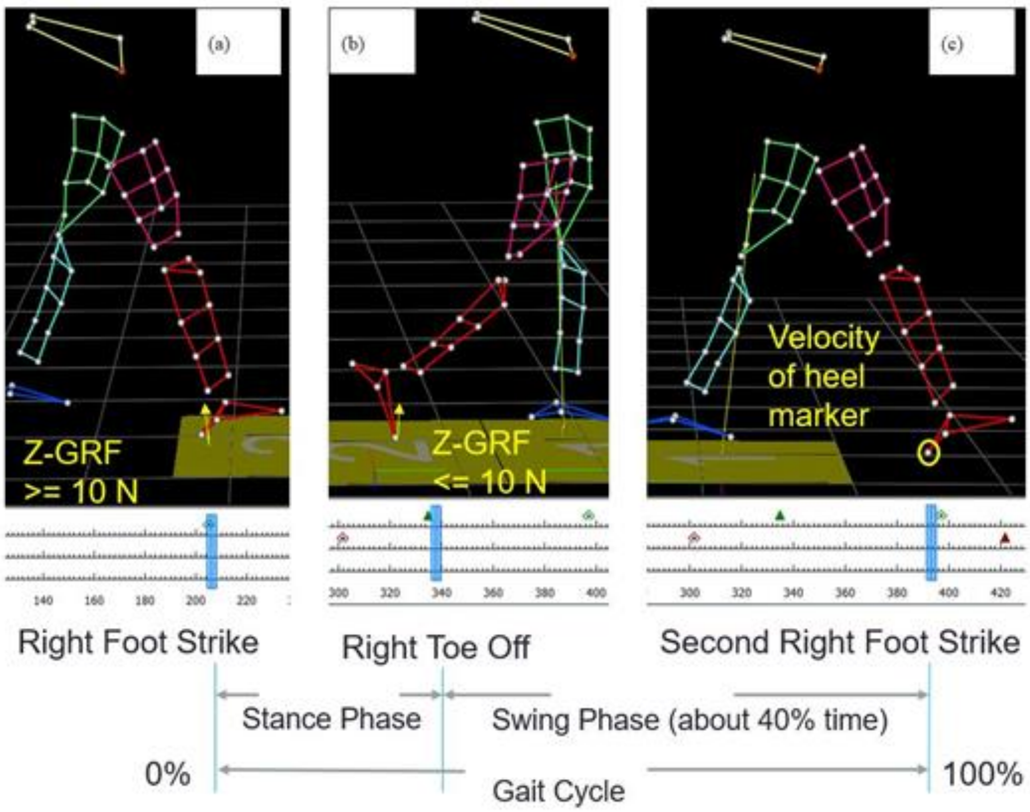

Figure 4.5 Gait Events in Gait Cycle.

Motion of markers attached to a subject were captured by using a motion capture system (VICON, Oxford). EMG signals from 14 muscles were captured by using an EMG system (Noraxon). Markers' motion data were digitized to generate global positions (Figure 4.6). This data was saved as C3D files along with GRF and EMG signals. Custom MATLAB (MathWorks Inc., MA, USA) scripts were then employed for data analysis and normalization. Data from all motion tasks were consistently processed. Subsequent data analysis in MATLAB evaluated knee kinematics, kinetics, lower extremity muscle activities, GRF, and gait parameters for both limbs (Figure 4.7).

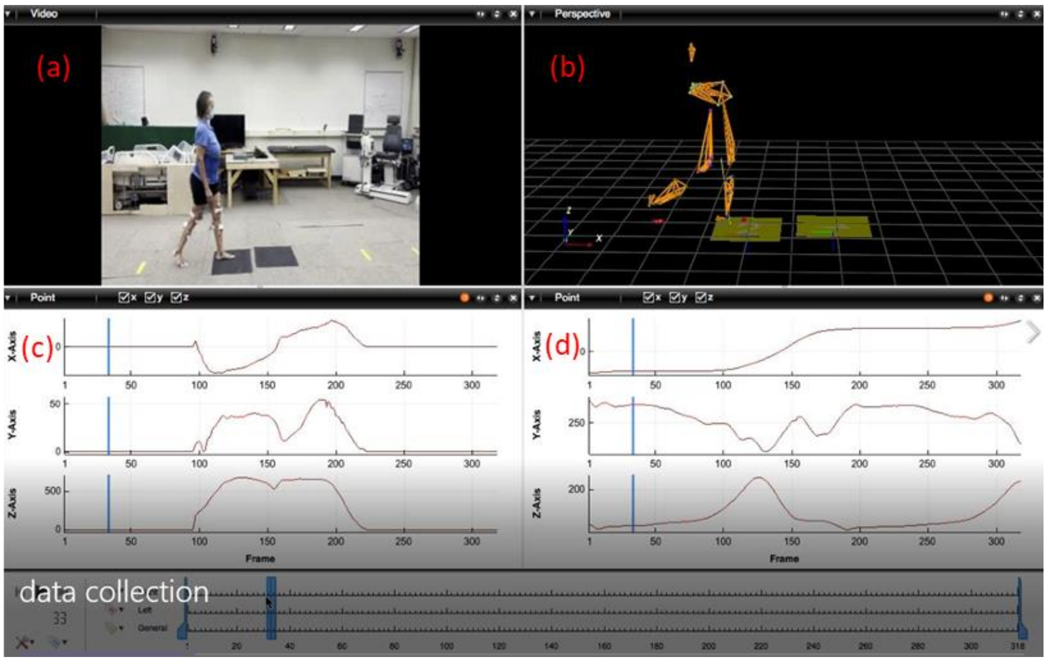

Figure 4.6 The Process of Data Collection. ((a)Subjects Performing Level Walking, (b)Synchronized Digitized Model during Level Waking (c) Raw Data of Ground Reaction Forces (d) Transient Marker Position of a Specific Marker).

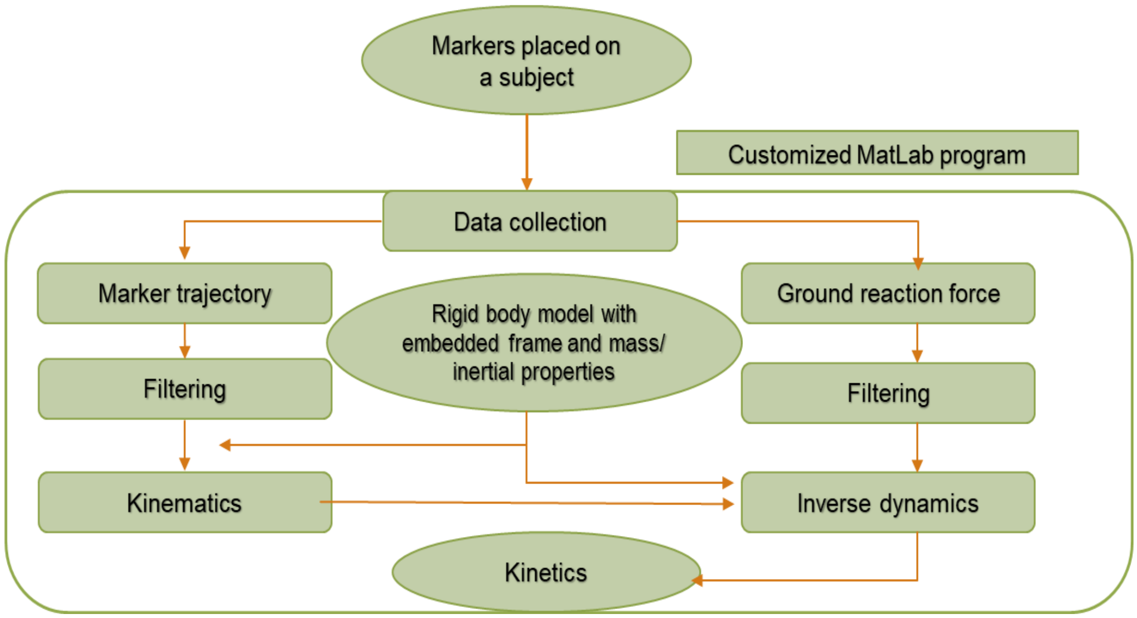

Figure 4.7 MATLAB Flow Chart for Motion Data Analysis.

For data normalization, all three-dimensional kinematics and kinetics were adjusted to fit within a standard gait cycle (0-100% of the gait cycle). Both the joint force and GRF were normalized to a percentage of body weight (%BW). Joint moments were further normalized to (%BW x H). This was necessary because heavier individuals exhibit higher joint moments due to the proportionality of the vertical component of the GRF to body weight. Additionally, taller subjects often demonstrate heightened joint moments because of the increased moment arm.

4.3.3 Knee Kinematics and Kinetics

The study's foundation was the body segment, which was conceptualized as a rigid body using markers. The kinematics of this rigid body encompassed both rotation and translation. An optimization method was employed to compute orientation and translation of a body segment from multiple markers attached to it. Here was the detailed process [128] (Figure 4.8):

- Collect marker positions: Gather the positions of at least three non-collinear markers in both the local and global coordinate systems. The marker positions in local coordinates were computed during the T-pose to serve as reference points (Equation 4.1).
- Averaging the markers: The average markers in specific body segments were found in both local and global coordinates.
- Translate marker positions: From the corresponding marker positions, the translated local marker positions were determined by subtracting the averaging markers.
- Calculate Cross-covariance matrix: The translated local marker positions were multiplied with the transpose of the translated global marker positions to obtain the cross-covariance matrix.
- Perform singular value decomposition on cross-covariance matrix (Equation 4.2).
- Compute the rotation matrix R (Equation 4.3).

$$P_g = R \times P_l + O \qquad \text{(Equation 4.1)}$$

where P_g: markers in global reference frame, R: Rotation matrix, P_l: markers in local reference frame, O: the origin of the specific body segment

$$[U, S, V] = svd(M) \qquad \text{(Equation 4.2)}$$

where U: left singular vector, V: right singular vector, S: a diagonal matrix containing the singular values of M

$$R = U \times V^T \qquad \text{(Equation 4.3)}$$

The relative motion between the marker and bone is termed as the soft tissue artifact (STA). Thus, the actual marker position could be represented as (Equation 4.4) Because the STA and noise were sources of errors, they could be optimized by this equation (Equation 4.5). Here, n signified the number of markers on the segments [129].

$$P_i^g(j) = R(j)P_i^l(j) + V(j) + STA + noise \qquad \text{(Equation 4.4)}$$

Where $P_i^g(j)$: markers in global reference frame at frame j, $R(j)$: rotation matrix at frame j, $V(j)$: translation vector at frame j, STA: soft tissue artifacts.

$$f(v,R) = \frac{1}{n}\sum_{i=1}^{n}(R(j)P_i^l(j) + V(j) - P_i^g(j))^T(R(j)P_i^l(j) + V(j) - P_i^g(j))$$

(Equation4.5)

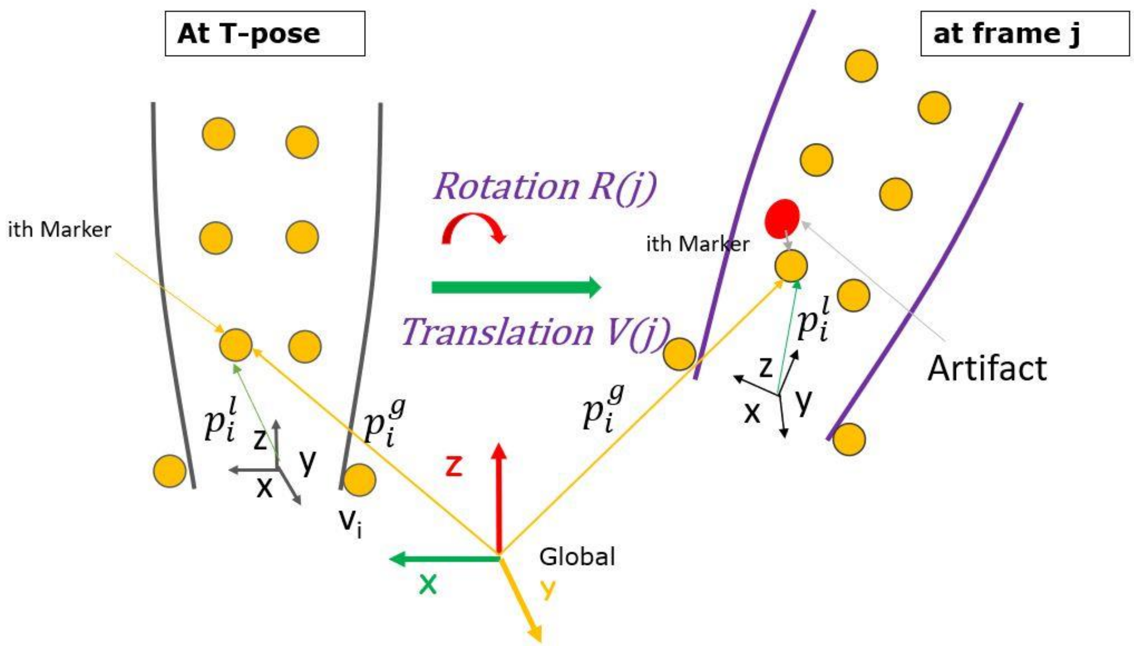

Figure 4.8 Tracking Motion of Rigid Body.

The projection method was used to compute the 3D ankle, knee, and hip joint translation and rotation[129, 131](Figure 4.9). Having already derived the rotation matrices for both the femur (R_f) and the tibia (R_t) during segment kinematics, we expressed them as (Equation 4.6). The matrix describing the relative rotation between the femur and tibia, or the knee joint transformation matrix R_f was given by (Equation 4.6). By projecting X_f (anteroposterior axis of femur) onto the sagittal plane of tibia (XZ plane) we obtained the projected vector X_{f-xz}. The knee flexion angle, represented by α, was then the angle between X_{f-xz} and X_t. Similarly, projecting Y_f (medial-lateral axis of femur) onto the coronal plane of tibia (YZ plane) gave us Y_{f-YZ} . This allowed us to determine the knee valgus angle, φ , as the angle between X_{f-YZ} and Y_t. Lastly, projecting Y_f onto the transverse plane of the tibia (XY plane) result in Y_{f-XY}. The knee's axial rotation angle, θ , was then defined as the angle between Y_{f-XY} and Y_t.

$$R_f = [X_f\ Y_f\ Z_f] \qquad R_t = [X_t\ Y_t\ Z_t] \qquad \text{(Equation 4.6)}$$

$$R_j = R_t^T \times R_f = [X_j\ Y_j\ Z_j] \qquad \text{(Equation 4.7)}$$

Figure 4.9 Projection Method to Calculate Three-dimensional Knee Rotation Angles[131].

Inverse dynamics is a fundamental concept within the field of biomechanics, allowing for the computation of force and torque from the kinematics of a body segment as well as the inertia properties of body segments (these include mass, center of mass, and moment of inertia) (Figure 4.10). The construction of the segment model, which outlines the segment size and the location of its center of mass, was largely based on the height of the subject in conjunction with historically established anthropometric relationships [132]. Furthermore, the determination of mass and body inertial parameters for each segment was done considering the overall body weight of the subject [133].

A significant source of external load on the body segments came in the form of the ground reaction force, which were meticulously measured using force plates (specifically the OR-6 model from AMTI) at a sampling rate of 1000 Hz. The standard setup ensured that only one foot was in contact with a force plate at any given moment. The interaction force between the foot and the force plate was gauged using four force sensors located at the corners of the force plate. The force plate subsequently provided readings for total forces (designated as F_x, F_y, F_z) and moments (notated as M_x, M_y, M_z). All these readings were presented with reference to the center of the force plate (points a, b, and c) within the global frame of reference.

The center of pressure (CoP), represented by the coordinates (CoP_x, CoP_y, 0), was found on the topmost surface of the force plate. Typically, in a gait lab setting, this surface was set as the zero vertical position. The calculation of CoP_x and CoP_y was based on specific equations (Equation 4.8) which derived from the forces and moments measured by the force plate. The CoP provided valuable insights into the distribution of force exerted by the foot during movement, offering a deeper understanding of gait dynamics and potential abnormalities.
The external torque could be calculated as (Equation 4.9).

$$CoP_x = \frac{M_z + c \times F_x}{F_z} + x \qquad CoP_y = \frac{M_z + c \times F_y}{F_z} + y \qquad \text{(Equation 4.8)}$$

$$T_z = M_z - (CoP_x - a) \times F_y + (CoP_y - b) \times F_x \qquad \text{(Equation 4.9)}$$

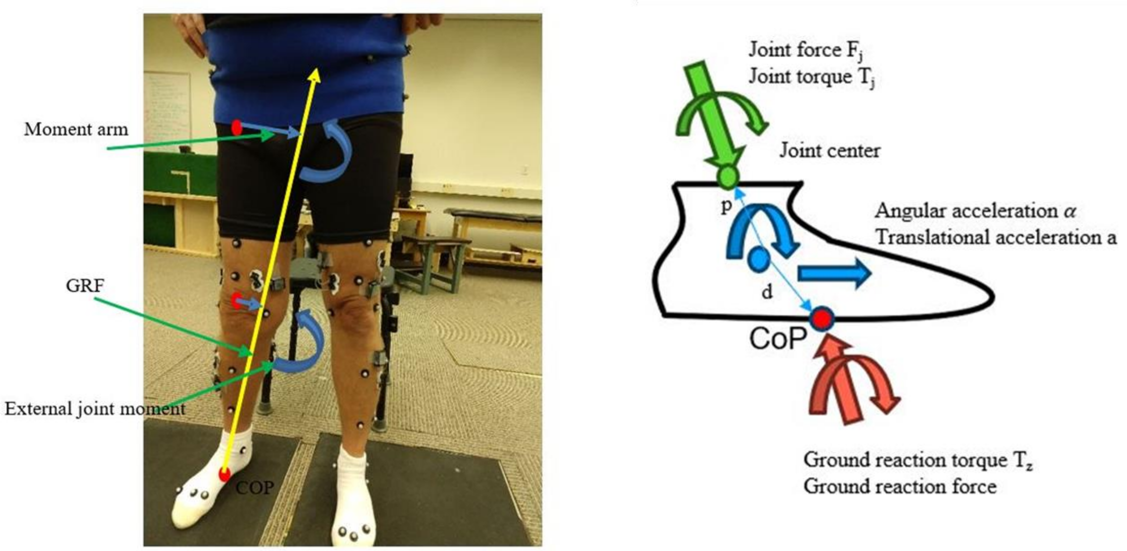

Figure 4.10 Inverse Dynamics.

The process of deriving the three-dimensional external ankle joint forces and moments was grounded in the principles of physics, utilizing translational acceleration a and angular acceleration α obtained from the foot's motion, and incorporating the foot's mass and inertia information based on the anthropometric model. First, the external loadings at the center of pressure were considered, incorporating both the ground reaction force and free torque T_z. The application of Newton's equations of motion led to the following simultaneous equations (Equation 4.10,4.11). Here, d was the distal vector pointing from the center of mass to the distal point (in this case, the center of pressure), and p was the proximal vector pointing from the center of mass to the proximal. The resolution of these equations in 3D provided the desired external ankle joint forces and moments. The same procedure was subsequently applied to the tibia and thigh segments, allowing for the determination of the knee and hip joint forces and moments, respectively. Inverse dynamics thus enabled the derivation of net forces and moments from two different perspectives. On one hand, the net joint forces and moments represented the external loading at the joint center. On the other hand, the internal net joint moment was a manifestation of muscular action. It served to actuate joint movement or counterbalance the external joint moment. Muscle force was not merely a product of muscle excitation; it was influenced by numerous factors, including muscle strength, activation level, muscle fiber length and velocity, the physiological cross-sectional area of the muscle belly.

$$F_j + GRF - ma = 0 \qquad \text{(Equation 4.10)}$$

$$T_j + T_z - I\alpha + d \times GRF + p \times F_j = 0 \qquad \text{(Equation 4.11)}$$

4.4 Electromyography

A 16-channel wireless surface EMG system [Telemyo DTS; Noraxon USA, Inc; Scottsdale, AZ] was used to measure muscle activities on 7 muscles of the knee bilaterally (Figure 4.11).

Figure 4.11 Noraxon EMG System. ((a): The Desktop DTS EMG Receiver (b): The EMG Transmitter and Electrodes)

The EMG signals from the following muscles were recorded: gastrocnemius lateral, gastrocnemius medial, vastus lateralis, vastus medialis, biceps femoris, semimembranosus and tibialis anterior. Electrode locations were shaved, cleaned, and lightly abraded with alcohol pads. Pregel (Ag/AgCl), dual EMG electrodes [#271; Noraxon USA, Inc; Scottsdale, AZ] with an inter-electrode distance of 42mm were placed on the most prominent aspect of each muscle belly and oriented parallel to the muscle fibers. The placement of the EMG electrodes on the selected muscles were based on the recommendations of SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles)[134]. EMG data were recorded at 1500Hz and a high pass, zero-lag 4th order Butterworth filter was applied at 10Hz to reduce the effect of motion artifact. The EMG data were then subsequently full wave rectified and RMS filtered with a 20ms smoothing window[135]. Finally, the linear envelop analysis was applied to the typical EMG processing during gait cycle [136, 137](Figure 4.12).

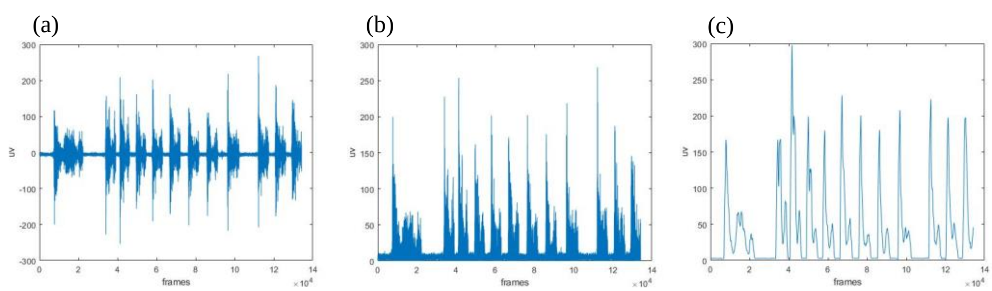

Figure 4.12 EMG Processing Progress From Left to Right: (a) Raw Data, (b)Rectification (c)Low Pass Filter and Window Averaging.

4.5 Knee Biomechanics Index

To better understand the differences in biomechanics during five distinct daily activities, KBI was developed based on knee kinetics and kinematics. Knee kinematics were analyzed across three different planes of motion: sagittal, frontal, and transverse. The sagittal plane (flexion-extension) range of motion (FEROM) was defined as the difference between the peak and valley flexion joint angles during the gait cycle. The frontal plane (varus-valgus) range of motion (VVROM) was defined as the difference between the peak and valley varus joint angles during the gait cycle. The transverse plane (internal-external) range of motion (INTROM) was defined as the difference between the peak and valley internal rotation joint angles during the gait cycle. Knee kinetics were analyzed in three different planes as well, including the peak and valley sagittal plane (flexion-extension) moment (FEM), the peak and valley front plane (abduction-adduction) moment (AAM), the peak and valley transverse plane (internal-external) moment (IEM) and KF during the gait cycle.

All variables from both the Pre-op and Post-op were compared to those of the CG. Z-scores were calculated based on the mean and standard deviation of the CG, serving as a threshold. Participants were then assigned probabilities based on a normal distribution curve using these Z-scores. For variables like Flexion-Extension Range of Motion (FEROM), Internal Range of Motion (INTROM), Flexion-Extension Moment (FEM), and Internal-External Moment (IEM), where higher values were preferable, probabilities were calculated as shown in Figure 4.13(a). For variables like Adduction-Abduction Moment (AAM), where lower values were preferable, probabilities were calculated as shown in Figure 4.13(b). For variables like the bilateral ratio of knee forces, where a value of one is ideal, probabilities were calculated as shown in Figure 4.13(c). Participants who failed to perform a specific motor task received zero points. The KBI was then calculated by summing the probabilities for these six variables. A perfect KBI score was six. The KBI scores for the Pre-op, Post-op, and CG were determined based on the mean and standard deviation of the CG.

$$Z = \frac{x - \mu}{\sigma} \qquad \text{(Equation 4.12)}$$

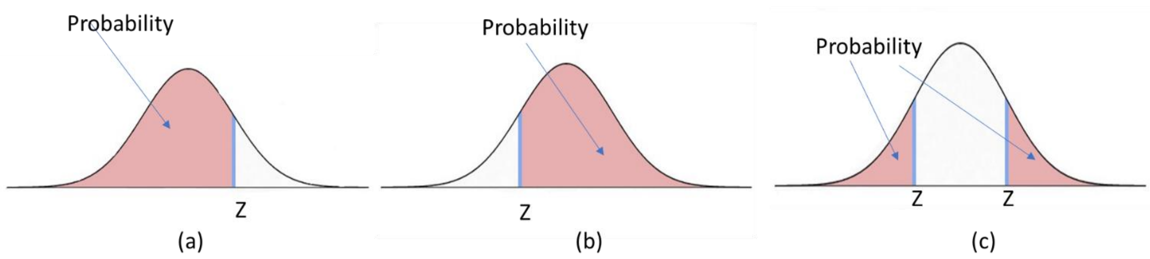

Figure 4.13: The Calculation Method of Probabilities of Normal Distribution Curve with Given Z-score.

4.6 Data analysis

4.6.1 Comparison of the Knee Biomechanics in Different Daily Activities

Three-dimensional joint angles (flexion/ extension, varus/ valgus, internal/external rotation) were calculated using the projection method [130]. Three-dimensional joint moments (flexion/ extension, abduction/adduction, external/internal) were derived using an inverse dynamics model and normalized to the product of height and body weight (%BW*H). The initial contact (foot strike) and toe-off were detected using a threshold of 5% body weight of ground reaction force to determine the stance and swing phases of joint kinematic and kinetic patterns. A gait cycle from both limbs of each trial was used for analysis, and time was normalized to 100% of the step cycle [126].

Knee kinematics were analyzed across three different planes of motion: sagittal, frontal, and transverse. The sagittal plane (flexion-extension) range of motion was defined as the difference between the peak and valley flexion joint angles during the gait cycle. The frontal plane (varus-valgus) range of motion was defined as the difference between the peak and valley varus joint angles during the gait cycle. The transverse plane (internal-external) range of motion was defined as the difference between the peak and valley internal rotation joint angles during the gait cycle. Knee kinetics were analyzed in three different planes as well, including the peak sagittal plane (flexion-extension) moment, the peak front plane (abduction-adduction) moment, the peak transverse plane (internal-external) moment and knee force during the gait cycle.

4.6.2 Comparison of the Knee Biomechanics in TKA Implants

The study began with the subjects filling out general medical history and demographics forms. They then filled out the Knee Society Score Form and the Short Form Survey – 12 scores pre-op, 1-month post-op, 6-month post-op, and 1-year post-op. The Forgotten Joint Score Form was also filled out 1-month post-op, 6-month post-op, and 1-year post-op. The subject's flexion and extension of their knee joint were measured using a goniometer in both active and passive positions, both at pre-op and post-op.

The balance test involved four different procedures, with each procedure having three trials. The goal of the test was, regardless of the settings, for the subject to keep the board balanced based on their center of mass. The first procedure involved both feet balancing on a static board. The second procedure involved both feet balancing on a dynamic board. The third and fourth procedures involved the subject balancing on their left and right foot on a static board, respectively. For proprioception, a dynamometer was used to evaluate the subject's ability to set the knee joint at the same position. The main procedure included two sections, the active angle reproduction test (active) and the threshold to detect passive movement (passive). For each section, the subject was performed at two different angles, 30 and 70 degrees, and each angle had three trials.

The kinematics and kinetics variables followed the same method presented in the last section. The gait analysis variables used were the gait speed, stride length, and step length. EMG data were filtered using a high pass zero lag 4th order Butterworth filter, then full-wave rectified, and finally root mean squared filtered with a smoothing window [138]. For the EMG analysis, seven muscles on each leg were analyzed using the peak muscle activities during the gait cycle.

4.6.3 Comparison of the Knee Biomechanics in Bilateral Differences

For the knee range of motion test, participants laid on a bed, and their knee range of motion was evaluated both passively and actively. Participants performed both flexion and extension to their maximum capabilities. The final range of motion was defined by the difference between flexion and extension. This range was then compared between the involved limb and the contralateral limb. For the assessment of knee kinetics and kinematics, three-dimensional knee rotations, knee moments, and knee forces were analyzed. The primary comparison was made between the involved limb and the contralateral limb. Muscle activity was assessed by recording the peak activities of the VL, VM, HL, HM, GL, GM, and TA muscles for both limbs. The activity ratio was calculated by dividing the specific value of the involved limb by that of the contralateral limb. This ratio was then used for comparisons across the Pre-op, Post-op, and CG during daily activities.

For the TSTS test, participants were instructed to perform the test "as quickly and safely as possible" both at pre-op and post-op. During this test, ground reaction force and EMG muscle activity were recorded. Quadriceps muscle activity was defined as the average of the summation of the vastus lateralis and vastus medialis activities. Similarly, hamstring muscle activity was calculated as the average of the summation of biceps femoris and semimembranosus activities. Loading symmetry was determined by the ratio of the peak vertical GRF of the involved limb to that of the contralateral limb. For frequency analysis, the power spectrum of the raw EMG signals was generated using a fast Fourier transform, from which the median frequency was calculated. All these variables were assessed for each STS and then compared against averages taken from the first three, middle three, and last three STS repetitions.

4.7 Statistical Analysis

4.7.1 Differences in Daily Activities

A one-way analysis of variance (ANOVA) was used to identify demographic differences between the TKA and CG using SPSS (SPSS27; IBM). For the clinical functional test, one-way ANOVA with post hoc testing was performed in the Pre-op, Post-op, and CG at a 0.05 alpha level. To examine the group (Pre-op, Post-op, and CG) and daily activities (level walking, ramp up, ramp down, stair ascending, and stair descending) interaction and main effects of knee kinematics and kinetics variables, a repeated measure ANOVA was used. A post hoc comparison was conducted to identify differences between the Pre-op, Post-op, and CG. To investigate differences in the Knee Biomechanical Index among participants in the Pre-op, Post-op, and CG, an ANOVA followed by a post-hoc test was employed. This analysis aimed to identify differences in Total Knee arthroplasty follow-up during daily activities among the groups. To explore variations in daily activities, a repeated-measures ANOVA was conducted, with the groups (Pre-op and Post-op) and tasks (five different daily activities) as factors, to evaluate the KBI. Additionally, Pearson's correlation analysis was used to compare the functional tests and KBI measurements across the five daily activities.

4.7.2 Differences in TKA Implants

Statistical analyses were conducted using SPSS (version 27; IBM) to compare two types of knee implants: PS and BCS based on various defined variables. A one-way ANOVA was employed to assess differences among the PS, BCS implants, and CG. Post-hoc tests were subsequently utilized to elucidate differences between the PS and BCS, PS and CG, and BCS and CG. The comparisons encompassed variables from patient-reported outcome measure forms, proprioception, balance, gait parameters, EMG, and biomechanical factors. Furthermore, the influence of BMI and age on the two implants was probed using a multifactor ANOVA. A significance level (alpha) of 0.05 was established for all tests.

4.7.3 Bilateral Differences

Paired T-tests were utilized to compare the involved limb with the contralateral limb in terms of ROM test results, knee kinetics, and muscle activities of the lower extremities. These comparisons were conducted using SPSS (SPSS27; IBM). If significant differences were identified between the two limbs, the ratios of these variables were further compared across the Pre-op, Post-op and CG using a one-way ANOVA with post-hoc tests.

For Ten time sit -to stand, to examine the repetitions (1st, 5th, and 10th) and groups (Pre-op, Post-op, CG) interaction and main effects of loading asymmetries and ratio of quadriceps muscle activities and hamstring muscle activities, a repeated measure ANOVA was used. A post hoc comparison was conducted to identify differences between the Pre-op, Post-op, and CG. For fatigue analysis one way ANOVA with post-hoc test was used to compare different repetitions. Additionally, Pearson's correlation analysis was used to calculate the correlation between the time performing ten times Sit-to-stand and loading asymmetries.

CHAPTER 5: RESULTS

5.1 Differences in Daily Activities

5.1.1 Clinical Functional Test

No significant differences in age, height, or BMI were found between the TKA and CG (Table 5.1). While there were no significant differences in TUG performance time among the Pre-op, Post-op, and CG, the CG and Post-op performed TUG 20% faster than the Pre-op. Significant differences were observed in STS performance time among the Pre-op, Post-op, and CG. Post hoc testing revealed that the CG performed STS significantly faster than the Pre-op and Post-op, with the Post-op performing STS 15% faster than the Pre-op.

Table 5.1: Clinical Functional Tests (TUG: Timed-up-go, STS: Ten Time Sit-to-stand) (Mean ± Standard Deviation).

	Pre-op	Post-op	CG
TUG(s)	11.8± 6.4	9.9± 2.5	9.0± 1.9
STS(s)	33.9± 10.2[ab]	28.9± 8.6[a]	25.45± 4.8[b]

[a] significant different between Pre-op and Post-op

[b] significant different between Pre-op and CG

[c] significant different between Post-op and CG

5.1.2 Knee Kinematics Variables

The three-dimensional knee rotations for the Pre-op, Post-op, and CG during various daily activities were depicted in (Figure 5.1, Figure 5.2, Figure 5.3). These graphs illustrated the range of motion in knee rotations, commencing from the initial heel strike (HS) (marked as 0% in the gait cycle), progressing through toe-off (at 60% in the gait cycle), and concluding at the second heel strike (denoted as 100% in the gait cycle). This representation provided a comprehensive view of the knee's functional dynamics throughout the entire gait cycle during daily activities.

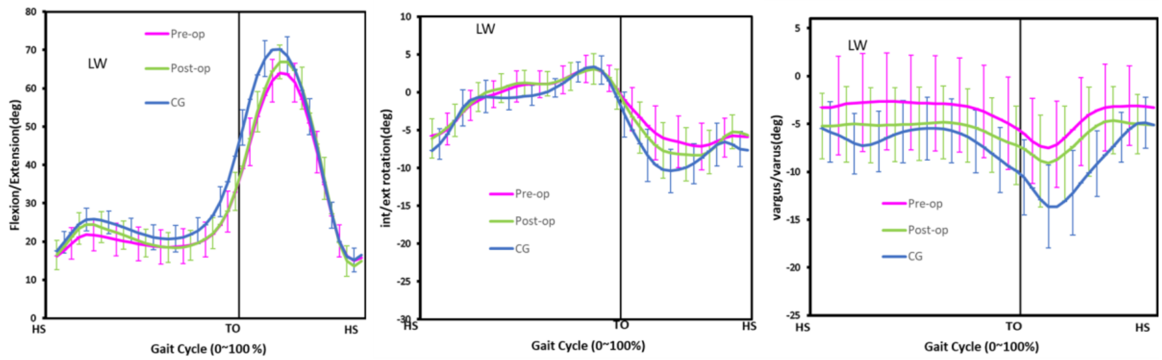

Figure 5.1 Three-dimensional Knee Rotations (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Level walking.

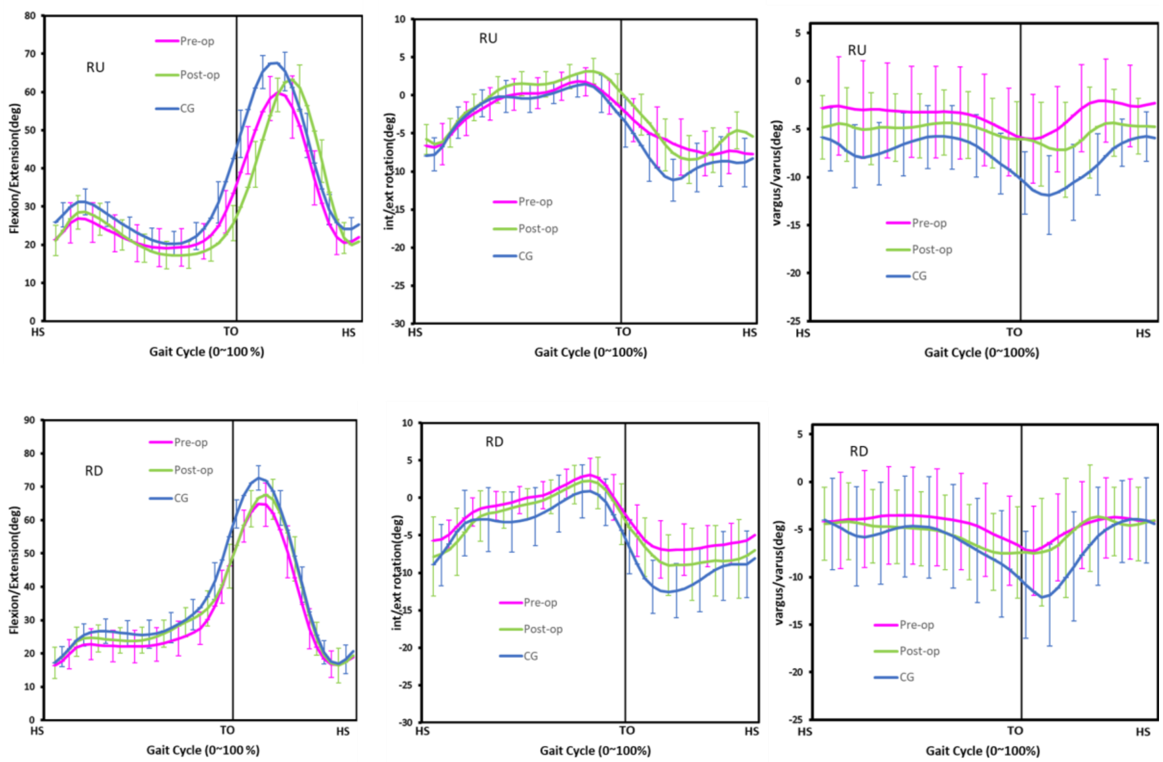

Figure 5.2 Three-dimensional Knee Rotations (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Incline Walking (Top: Ramp up, Bottom: Ramp Down).

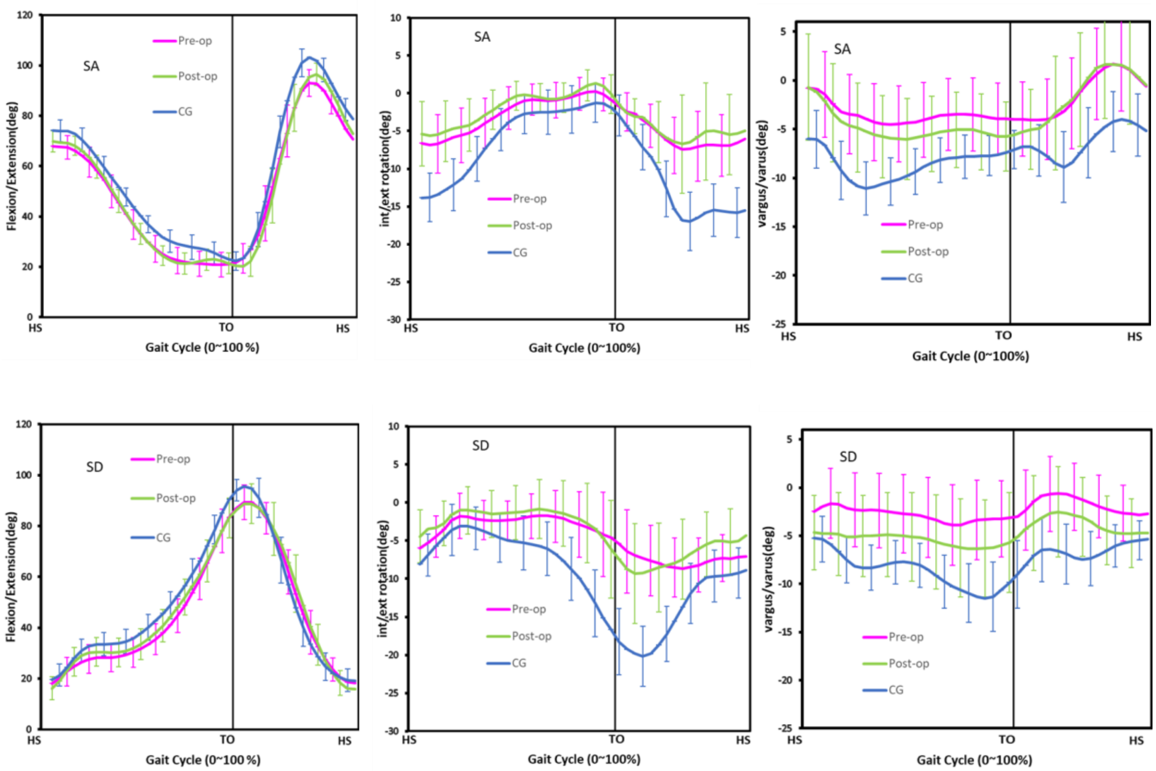

Figure 5.3 Three-dimensional Knee Rotations (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Stair Ambulation (Top: Stair Ascending, Bottom: Stair Descending).

A significant group×task interaction was found in FEROM ($p<0.01$, Table 5.2), with significant task effects indicating that FEROM increased notably in stair ascending and stair descending compared to the other three activities. Post hoc comparisons revealed that FEROM in the Post-op was significantly greater than that in the Pre-op, while both groups had smaller FEROM values than the CG. No significant group×task interaction or main effects were observed in VVROM. Similarly, no significant group×task interaction or task main effects were found in INTROM; however, post hoc analysis showed that the Post-op had significantly greater INTROM than the Pre-op, and INTROM in both groups was significantly lower than in the CG.

Table 5.2 : Knee Kinematics Variables during Five Daily Activities (FEROM: Flexion-extension Range of Motion, VVROM: Varus-valgus Range of Motion INTROM: Internal-external Range of Motion) (Mean ± Standard Deviation).

Variable	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascend	Stair Descend
FEROM[*^ab]	Pre-op	49.07±6.3	44.58±6.61	49.35±7.37	74.09±5.19	72.04±7.25
(degree)	Post-op	56.05±6.6	50.9±7.02	55.48±6.81	84.2±6.55	80.46±5.7
	CG	59.59±3.5	55.34±5.03	59.16±5.57	91.97±4.78	88.35±6.21
VVROM	Pre-op	9.7±2.65	9.08±3.16	9.47±3.56	10.65±3.6	9.75±3.36
(degree)	Post-op	10.11±4.5	11.87±8.72	11.14±9.02	14.06±5.64	12.22±4.41
	CG	12.35±5.7	11.08±4.28	13.43±5.5	11.51±4.08	11.33±5.15
INTROM[abc]	Pre-op	14.53±5.2	14.26±4.66	15.21±4.97	13.22±4.38	14.12±4.24
(degree)	Post-op	17.66±5.8	17.11±5.55	16.57±4.92	18.2±5.45	19.08±6.16
	CG	18.86±6.2	18.91±5.19	19.99±6.52	22.11±7.6	21.82±6.04

[*] significant task (daily activities) main effect

[^] significant interaction group× task interaction

[a] significant difference between Pre-op and Post-op

[b] significant difference between Pre-op and CG

[c] significant difference between Post-op and CG

5.1.3 Knee Kinetics Variables

The three-dimensional knee kinetics for the Pre-op, Post-op, and CG during various daily activities were depicted in (Figure 5.4-5.6) (Figure 5.7-5.9). These graphs illustrated the peak moments and knee forces during the daily activities, commencing from the initial heel strike

(HS) (marked as 0% in the gait cycle), progressing through toe-off (at 60% in the gait cycle), and concluding at the second heel strike (denoted as 100% in the gait cycle).

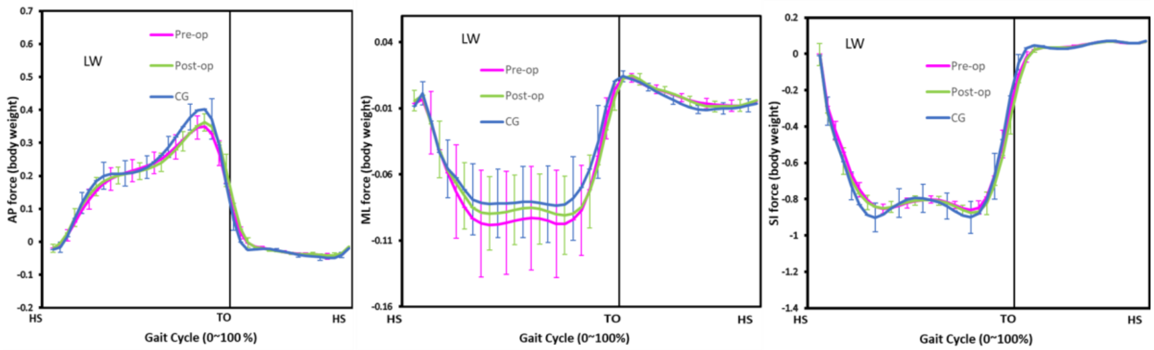

Figure 5.4 Three-dimensional Knee Forces (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Level walking.

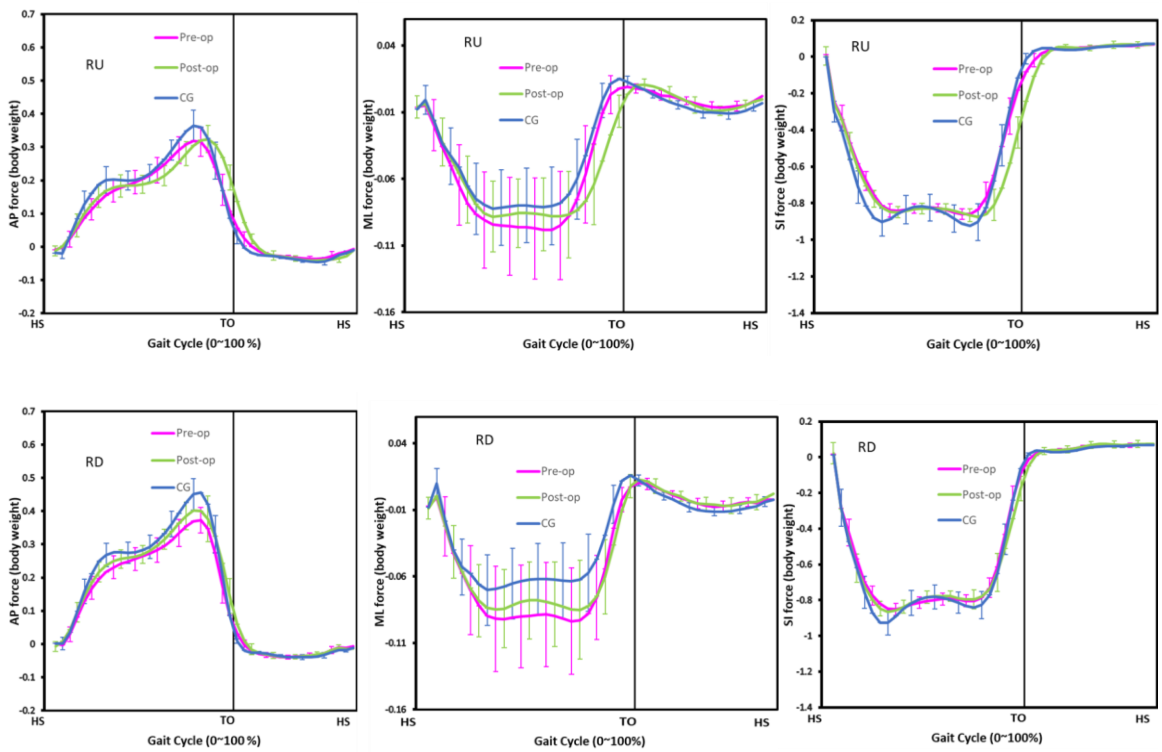

Figure 5.5 Three-dimensional Knee Forces (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Incline walking (Top: Ramp up, Bottom: Ramp Down).

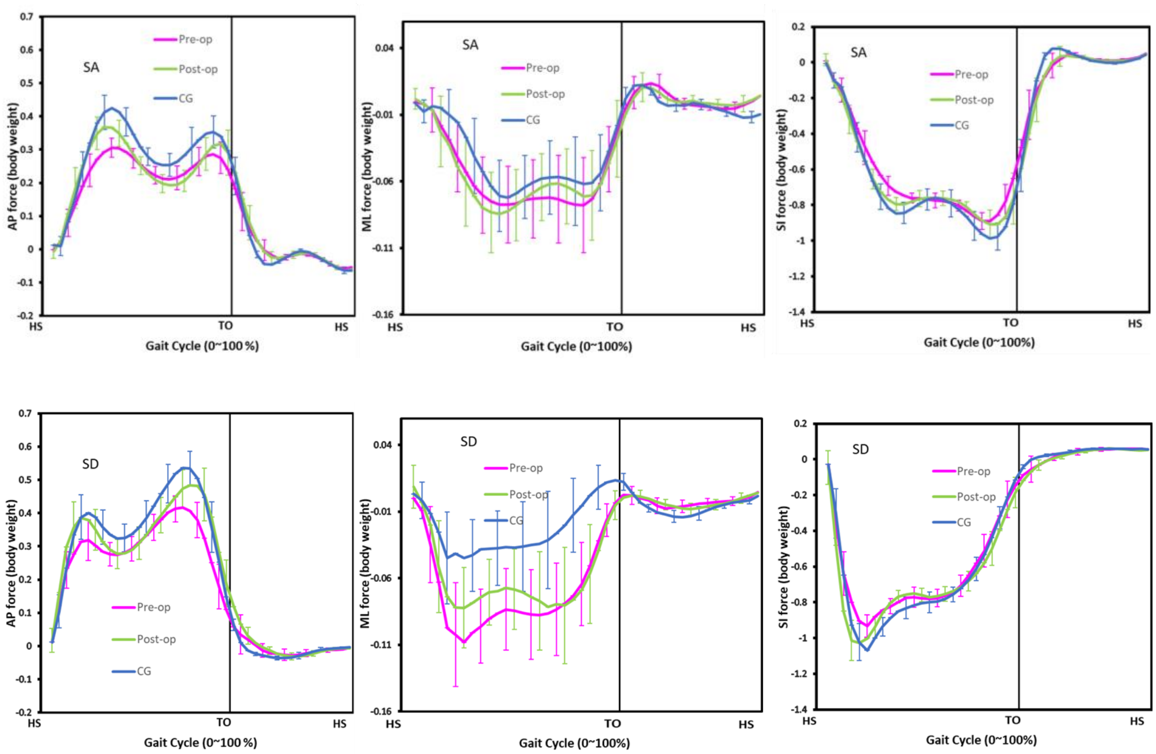

Figure 5.6 Three-dimensional Knee Forces (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Stair Ambulation (Top: Stair Ascending, Bottom: Stair Descending).

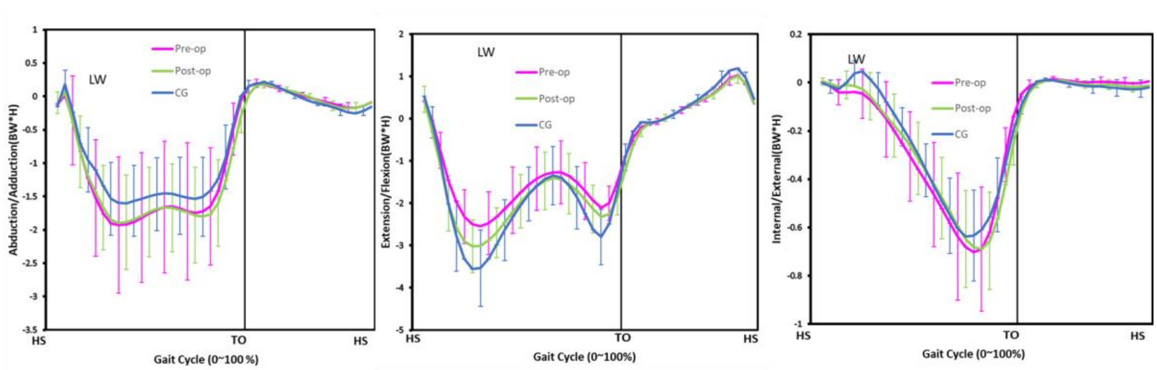

Figure 5.7 Three-dimensional Knee Joint Moments (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Level walking.

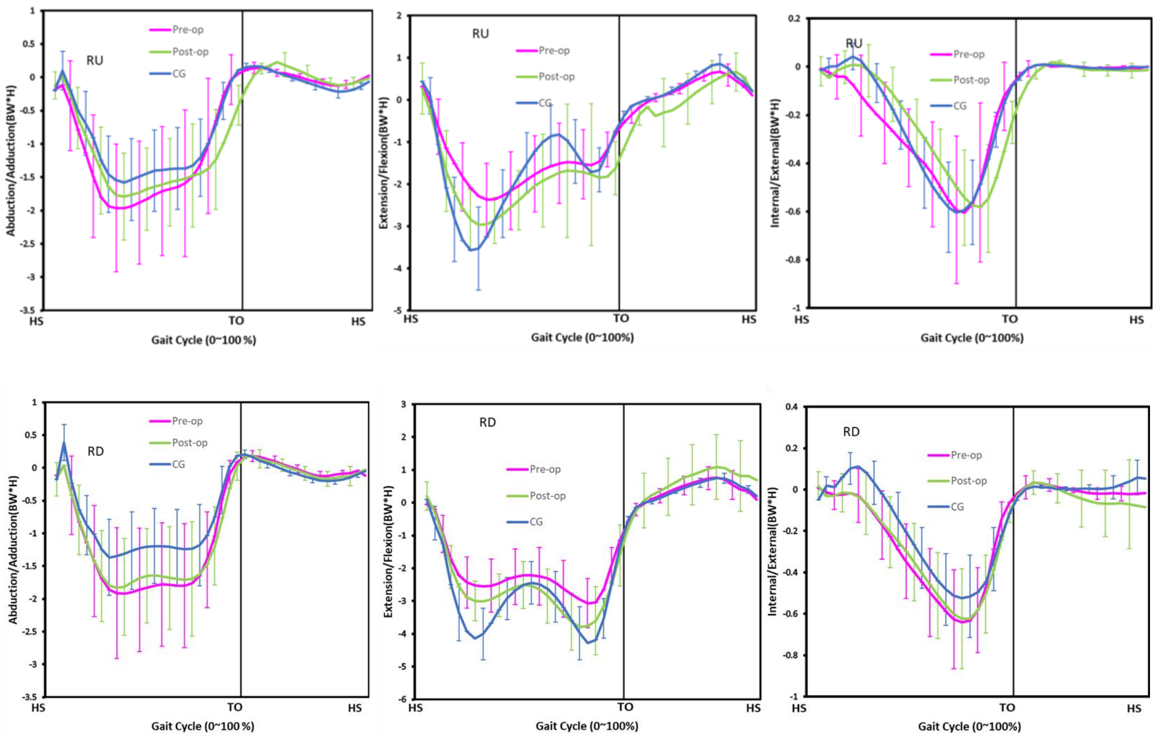

Figure 5.8 Three-dimensional Knee Joint Moments (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Incline Walking (Top: Ramp up, Bottom: Ramp Down).

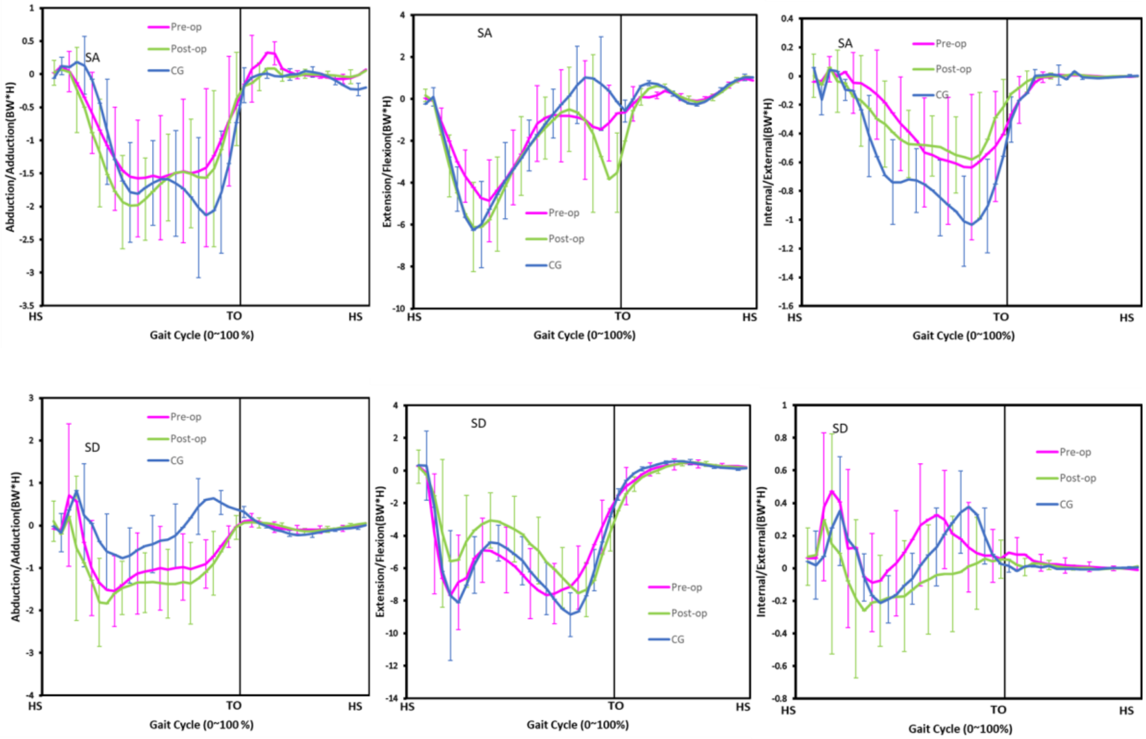

Figure 5.9 Three-dimensional Knee Joint Moments (Mean ± Standard Deviation) for Pre-op, Post-op, and CG during Stair Ambulation (Top: Stair Ascending, Bottom: Stair Descending).

A significant group×task interaction was observed in FEM ($p<0.01$, Table 5.3), with a significant task main effect indicating that FEM increased as the difficulty of daily activities increased. Post hoc comparisons revealed that FEM in the Post-op was significantly greater than in the Pre-op, and FEM values in both groups were significantly lower than in the CG. For IEM, no significant group×task interaction or main effect was found. Similarly, no significant group×task interaction or task main effects were observed in AAM; however, post hoc analysis showed that the Post-op had significantly lower AAM than the Pre-op, and AAM values in both groups were significantly higher than in the CG. A significant group×task interaction was detected in the bilateral ratio of KF ($p<0.01$, Table 4), with a significant task main effect. Post hoc comparisons indicated that the bilateral ratio of KF in the Post-op was significantly greater than in the Pre-op, and the bilateral ratio of KF in both groups was significantly lower than in the CG.

Table 5.3: Knee Kinetics Variables during Five Daily Activities (FEM: Flexion-extension Moment, IEM: Internal-external Moment, AAM: Abduction-adduction Moment, KF: Knee Force) (Mean ± Standard Deviation) (%BW*H).

Variable	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
FEM[*^abc] (%BW*H)	Pre-op	2.68±0.95	2.83±1.23	3.14±1.22	5.83±1.60	7.65±2.24
	Post-op	3.70±1.16	3.36±0.91	4.51±1.33	7.90±2.40	8.89±2.78
	CG	4.43±1.11	4.58±1.46	5.29±1.27	9.21±1.93	9.37±1.78
IEM (%BW*H)	Pre-op	0.78±0.46	0.78±0.47	0.74±0.40	0.92±0.88	0.88±0.64
	Post-op	0.82±0.33	0.73±0.32	0.75±0.51	0.90±0.73	0.84±0.61
	CG	0.60±0.27	0.47±0.29	0.59±0.28	0.57±0.52	0.45±0.31
AAM[*abc] (%BW*H)	Pre-op	2.95±1.35	3.02±1.39	3.10±1.34	3.81±0.66	3.81±0.73
	Post-op	2.58±0.89	2.16±0.88	2.41±1.19	3.51±0.63	3.64±1.13
	CG	1.62±0.62	1.53±0.71	1.87±0.88	2.85±0.24	2.87±0.36
Bilateral ratio of KF[*^abc]	Pre-op	0.82±0.03	0.82±0.04	0.8±0.04	0.78±0.07	0.77±0.08
	Post-op	0.9±0.04	0.88±0.06	0.85±0.08	0.84±0.06	0.83±0.08
	CG	1.02±0.04	1.03±0.03	1.00±0.05	1.03±0.08	0.95±0.07

[*] significant task (daily activities) main effect

[^] significant interaction group× task interaction

[a] significant difference between Pre-op and Post-op

[b] significant difference between Pre-op and CG

[c] significant difference between Post-op and CG

5.1.4 Knee Biomechanics Index

In the follow-up comparisons of TKA patients, significant differences were observed among the Pre-op, Post-op, and CG during various activities: level walking, ramp up, ramp down, stair ascending, and stair descending. Post-hoc analysis revealed that TKA patients experienced significant improvements in KBI. Specifically, there was a 61% increase during level walking, a 47% increase during ramp up, a 42% increase during ramp down, a 69% increase during stair ascending, and a 67% increase during stair descending when compared to pre-op measures. However, even after surgery, the Post-op's KBI values still lagged those of the CG. The CG exhibited a 20% higher KBI during level walking, 25% higher during ramp up, 30% higher during ramp down, 45% higher during stair ascending, and 65% higher during stair descending, as compared to the Post-op.

For the comparison with five difference activities, significant main effect for the group was detected in KBI (Figure 5.10) (Table 5.4), showing that KBI scores for five daily activities significantly increased at follow-up. Post hoc analysis revealed that the KBI for level walking was significantly higher than for stair ascending and stair descending. There were no significant differences between the KBI scores for level walking and ramp up, or between those for level walking and ramp down. Similarly, the KBI for ramp up was significantly higher than for stair ascending and stair descending but showed no significant difference compared to level walking and ramp down. As for ramp descending, the KBI was also significantly higher than for stair ascending and stair descending, and it showed no significant difference compared to level walking and ramp up. In terms of KBI improvements, the extent of enhancement in daily activities decreased as the difficulty of the activity increased. Specifically, the improvements in

KBI for level walking were significantly greater than those for stair ascending and stair descending.

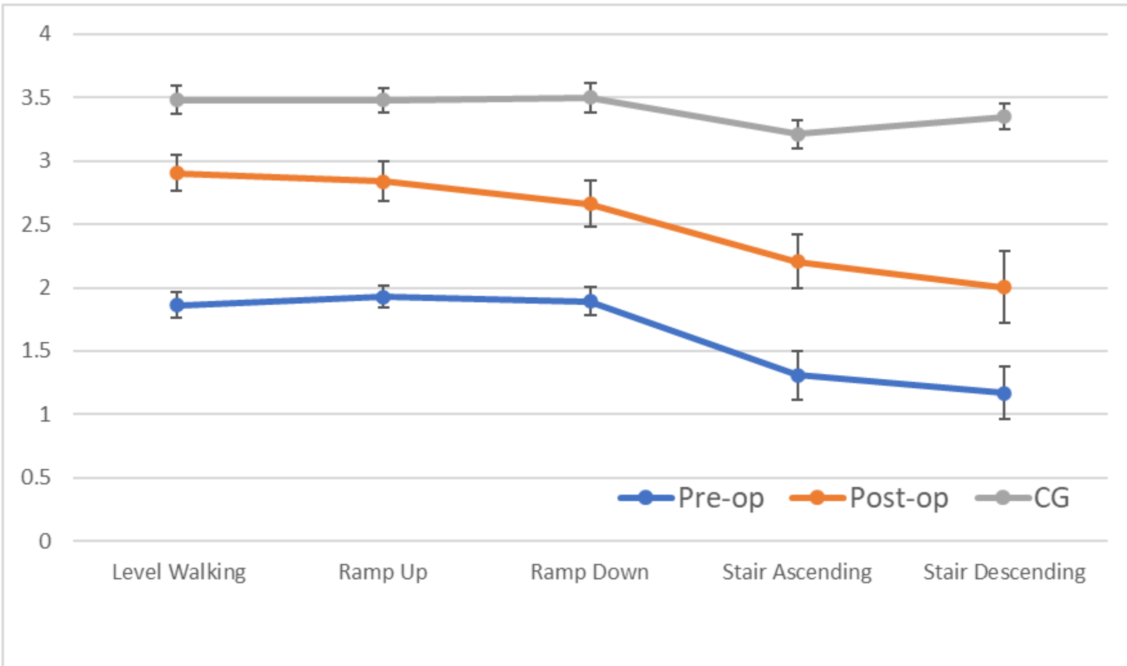

Figure 5.10 Knee Biomechanical Index in Five Daily Activities for TKA Follow-up and CG (Mean ± Standard Deviation).

Table 5.4: Knee Biomechanics Index (Mean ± Standard Deviation) for Participants during Daily Activities.

KBI*^	Pre-op	Post-op	CG
Level Walking[cd]	1.86± 0.2	2.91± 0.28	3.48±0.23
Ramp Up[fg]	1.93±0.18	2.84±0.31	3.48±0.19
Ramp Down[ik]	1.89±0.22	2.66±0.37	3.5±0.23
Stair Ascending	1.31±0.39	2.21±0.43	3.21±0.22
Stair Descending	1.17±0.42	2.01±0.57	3.35±0.2

[*] significant group main effect

[^] significant interaction group× task interaction

[a] significant difference between Level Walking and Ramp Up

[b] significant difference between Level Walking and Ramp Down

[c] significant difference between Level Walking and Stair Ascending

[d] significant difference between Level Walking and Stair Descending

[e] significant difference between Ramp Up and Ramp Down

[f] significant difference between Ramp Up and Stair Ascending

[g] significant difference between Ramp Up and Stair Descending

[h] significant difference between Ramp Down and Stair Ascending

[i] significant difference between Ramp Down and Stair Descending

[k] significant difference between Ramp Down and Stair Descending

In the Pre-op, significant correlations were observed between TUG performance time and KBIs for the Ramping down, Stair ascending and Stair descending (Table 5.5). However, no significant correlations were observed between STS performance time and KBIs for the five daily activities and between gait speed and KBIs for the five daily activities. ($p>0.05$ for all comparisons) (Table 8). In the Post-op, there were significant differences between TUG performance time and KBIs for the ramp up, ramp down, stair ascending and stair descending. And there were significant differences between STS performance time and KBIs for the level walking stair ascending and stair descending, though not significant, between gait speed and KBI for all daily activities.

In the Pre-op, significant correlations were observed between the TUG performance time and KBI scores for ramp down, stair ascending, and stair descending. However, no significant correlations were found between the STS performance time and KBI scores across the five daily activities, nor were any found between gait speed and KBI scores for these activities ($p > 0.05$ for all comparisons; Table 5.5). In the Post-op, significant differences were noted between TUG performance time and KBI scores for ramp up, ramp down, stair ascending, and stair descending. Additionally, significant differences were observed between STS performance time and KBI scores for level walking, stair ascending, and stair descending. However, no significant differences were detected between gait speed and KBI scores for any of the daily activities.

Table 5.5: Correlation Between KBI during Daily Activities and Clinical Functional Tests.

Activity	Stage	Timed-Up-Go		Sit-to-Stand		Gait Speed	
		r	P	r	P	r	P
Level Walking	Pre-op	0.12	0.46	0.05	0.76	-0.06	0.71
	Post-op	-0.23	0.15	-0.32	0.04*	0.24	0.13
Ramp Up	Pre-op	0.20	0.22	0.05	0.76	-0.27	0.09
	Post-op	-0.41	0.01**	-0.23	0.15	0.16	0.32
Ramp Down	Pre-op	0.35	0.03*	0.03	0.85	-0.12	0.46
	Post-op	-0.38	0.02*	-0.27	0.09	0.27	0.09
Stair Ascending	Pre-op	-0.33	0.04*	-0.11	0.50	-0.14	0.39
	Post-op	-0.41	0.01**	-0.50	0**	0.11	0.50
Stair Descending	Pre-op	-0.32	0.04*	-0.17	0.29	0.11	0.50
	Post-op	-0.45	0**	-0.50	0**	0.13	0.42

5.2 Differences in TKA Implants

5.2.1 Patient Reported Outcome Measure

For the functional scores, significant differences were observed among the PS, BCS, and CG (Table 5.6). Post-hoc analysis revealed these significant differences to be between the PS and CG as well as between the BCS and CG. Similar patterns were also evident in the objective scores. However, no significant differences were identified among the three groups when examining the SF-12 scores and the forgotten joint scores.

Table 5.6 The PROMS for Posterior TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG.

PROM	Posterior Stabilized	Bi-cruciate Stabilized	Control Group
Objective Score	6.25±3.00[b]	5.17±4.83[c]	0.65±2.30[bc]
Expectation Score	41.60±11.52	43.29±9.84	NA
Functional Score	72.05±18.46[b]	72.71±20.82[c]	96.40±8.04[bc]
Physical Healthy Score	64±7	60±8	63±4
Mental Healthy Score	67±6	69±10	67±5
Forgotten Joint Score	48.85±27.97	44.26±24.33	NA

a: PS vs. BCS

b: PS vs. CG

c: BCS vs CG

5.2.2 Clinical Test

Regarding active Range of Motion (ROM Active), significant differences were noted among the PS, BCS, and CG (Table 5.7). Post-hoc analysis pinpointed these differences to be between the PS and CG, and between the BCS and CG. For passive ROM, while the CG displayed higher values than both PS and BCS, no significant disparities were observed among the three groups. In the proprioception test, both 30-degree and 70-degree measurements showed no notable differences between the two implants. Similarly, for the balance test, the total score index did not present any significant differences among the PS, BCS, and CG. Furthermore, the timings for the TUG and STS tests were comparable across all three groups, even though the CG consistently recorded slightly faster times than the other two groups.

Table 5.7 The ROM Test, Proprioception Test, Balance Test and Clinical Functional Test for TKA Participants with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant and CG.

Functional test	Posterior Stabilized	Bi-cruciate Stabilized	Control Group
ROM Active (degree)	116.15±14.51[b]	115.42±14.84[c]	125.36±6.23[bc]
ROM Passive (degree)	122.54±11.53	123.75±14.79	128.35±8.23
Proprioception (70 degree)	3.99±7.89	2.55±4.67	3.14±6.98
Proprioception (30 degree)	1.22±3.29	3.68±5.22	1.61±3.44
Balance Test (total score index)	1.34±1.88	1.2±0.714	1.35±1.18
STS(s)	29.02±8.61	27.57±7.86	25.45±4.81
TUG(s)	10.45±2.71	9.84±2.42	9.00±1.99

a: PS vs. BCS

b: PS vs. CG

c: BCS vs CG

5.2.3 Peak Muscle Activity

Unfortunately, for the peak muscle activities, no significant differences were found between these three groups for all seven muscles during the five daily activities (Table 5.8).

Table 5.8 The Peak Muscle Activities for TKA Participants with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG in Low Extremities during Walking, Ramp Up, Ramp Down, Stair Ascending and Stair Descending.

PMA	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
Vastus Lateralis	PS	138.4±60	186.6±82	208±85	312.8±120	278±89.2
	BCS	172.7±79	225.4±88	188.4±92	403.7±138	345.1±157
	CG	205±89	208±85	228±100	433.8±146	353.1±132
Vastus Medialis	PS	148.7±69	187.8±95	214.6±88	304.2±108	308±90
	BCS	184.9±75	239±95	180.7±83	414.1±127	340.2±143
	CG	208.3±88	214.6±88	232.5±102	445.8±146	380±139
Semimembranosus	PS	193.4±73	214.6±83	251.3±88	285.3±114	288.8±153
	BCS	179.9±63	242.7±95	207.9±93	357.9±138	305.7±117
	CG	183.7±65	251.3±88	234.2±103	339.4±139	287.2±123
Biceps Femoris	PS	199.7±66	207.1±74	241.5±83	240.2±93	292.6±167
	BCS	182.2±64	256.6±91	187.9±95	352.4±124	317.1±110
	CG	209.1±75	241.5±83	241.9±100	347.1±154	286.5±118
Gastrocnemius Lateral	PS	249.3±70	347.8±80	363.8±50	546.9±40	388.1±117
	BCS	254.2±70	354.6±79	267.8±107	488.8±118	378.3±151
	CG	283.7±44	363.8±50	278.6±107	557.6±29	427.7±105
Gastrocnemius Medial	PS	244.2±65	347.4±79	355.9±39	545.8±43.1	389.1±118
	BCS	257.5±73	345±86.7	270.3±104	487.5±117	405.5±162
	CG	278.4±44	355.9±39	273.3±111	551.7±28	450.3±110
Tibialis Anterior	PS	283.5±39	394.3±27	404.8±22.3	551.8±31	538±29.3
	BCS	272.8±47	385.7±42	328.6±79	530.7±75	513.6±115
	CG	285.4±19	404.8±22	352.6±83	566.1±24	531.9±32

a: PS vs. BCS

b: PS vs. CG

c: BCS vs CG

5.2.4 Knee Kinematics

In the sagittal plane range of motion, one-way ANOVA identified significant differences among the PS, BCS, and CG during five tested daily activities (Table 5.9). Post-hoc analysis indicated significant differences between PS and CG during level walking, ramp up, ramp down, stair ascending, and stair descending, between BCS and CG during stair ascending and stair descending, and between PS and BCS during stair ascending and stair descending.

In the frontal plane, one-way ANOVA highlighted differences among PS, BCS, and CG during level walking and ramp down. Post-hoc analysis found significant differences between PS and CG during ramp down and between BCS and CG during level walking.

For the transverse plane, one-way ANOVA revealed differences among PS, BCS, and CG during ramp up, stair ascending, and stair descending. Post-hoc analysis determined that PS and CG differed significantly during ramp up, stair ascending, and stair descending, whereas differences between BCS and CG were notable during stair ascending and stair descending.

Table 5.9 Three -dimensional Knee Kinematics for TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG during Walking, Ramp Up Ramp Down, Stair Ascending and Stair Descending.

Variable	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
FEROM (degree)	PS	52.3±6.6[b]	49.59±6.4[b]	55.45±5.1[b]	76.07±7.4[ab]	76.31±3.6[ab]
	BCS	55.98±4.8	51.53±5.3	53.07±5.9	84.86±6.9[ac]	81.56±7.4[ac]
	CG	59.53±3.6[b]	55.45±5.1[b]	56.33±6.1[b]	91.97±4.8[bc]	88.35±6.2[bc]
VVROM (degree)	PS	9.64±3.0	9.94±4.2	10.89±4.3[b]	11.89±4.4	12.08±3.4
	BCS	9.05±3.8[c]	8.88±3.1	8.85±4.3	12.8±5.8	9.84±3.8
	CG	12.59±5.8[c]	10.89±4.3	8.12±3.2[b]	11.51±4.1	11.33±5.2
INTROM (degree)	PS	15.7±3.77	14.64±3.9[b]	18.61±5.2	15.43±4.8[b]	15.73±4.2[b]
	BCS	16.67±5.5	16.91±4.7	15.62±5.0	17.39±7.4	16.96±5.8[c]
	CG	18.82±6.4	18.61±5.2[b]	16.54±5.28	22.11±7.6[b]	21.82±6.0[bc]

a: PS vs. BCS

b: PS vs. CG

c: BCS vs CG

The three-dimensional knee rotations for the PS, BCS, and CG during various daily activities were depicted in (Figure 5.11-5.13). These graphs illustrated the range of motion in knee rotations, commencing from the initial heel strike (HS) (marked as 0% in the gait cycle), progressing through toe-off (at 60% in the gait cycle), and concluding at the second heel strike (denoted as 100% in the gait cycle).

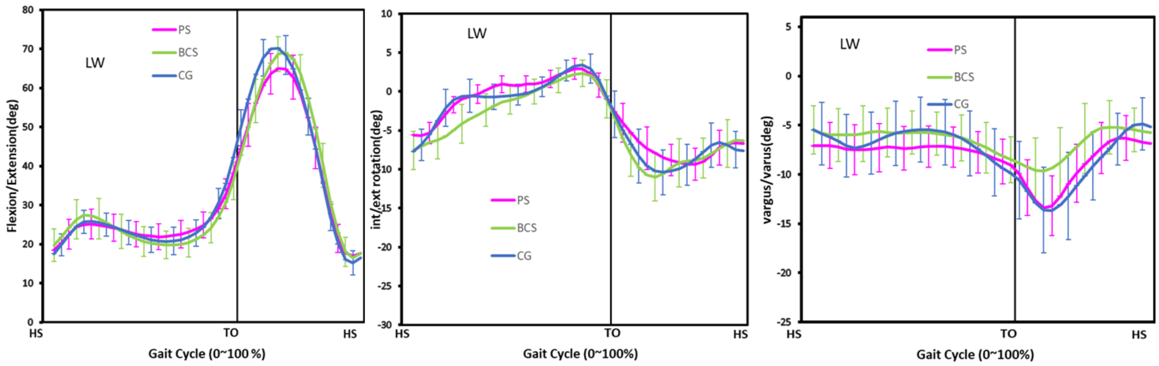

Figure 5.11 Three -dimensional Knee Kinematics Normalized with a Gait Cycle (Mean ± Standard Deviation) for TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG during Level Walking.

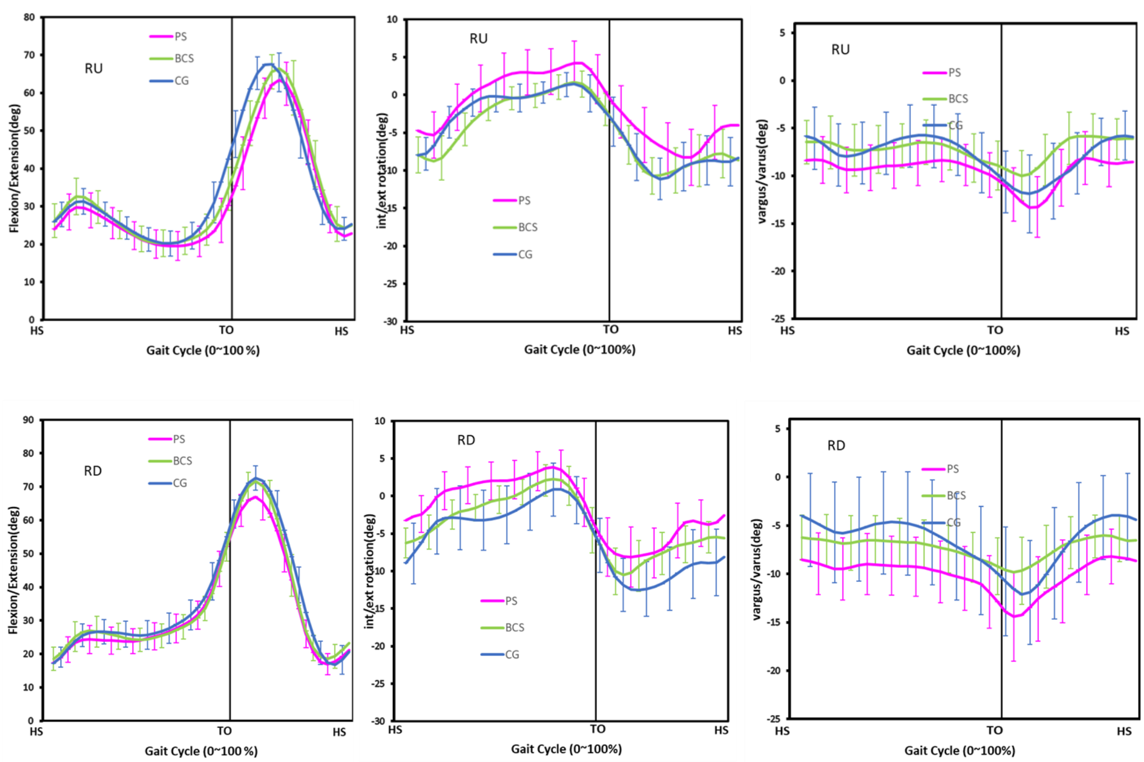

Figure 5.12 Three -dimensional Knee Kinematics Normalized with a Gait Cycle (Mean ± Standard Deviation) for TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG during Incline Walking (Top: Ramp up, Bottom: Ramp Down).

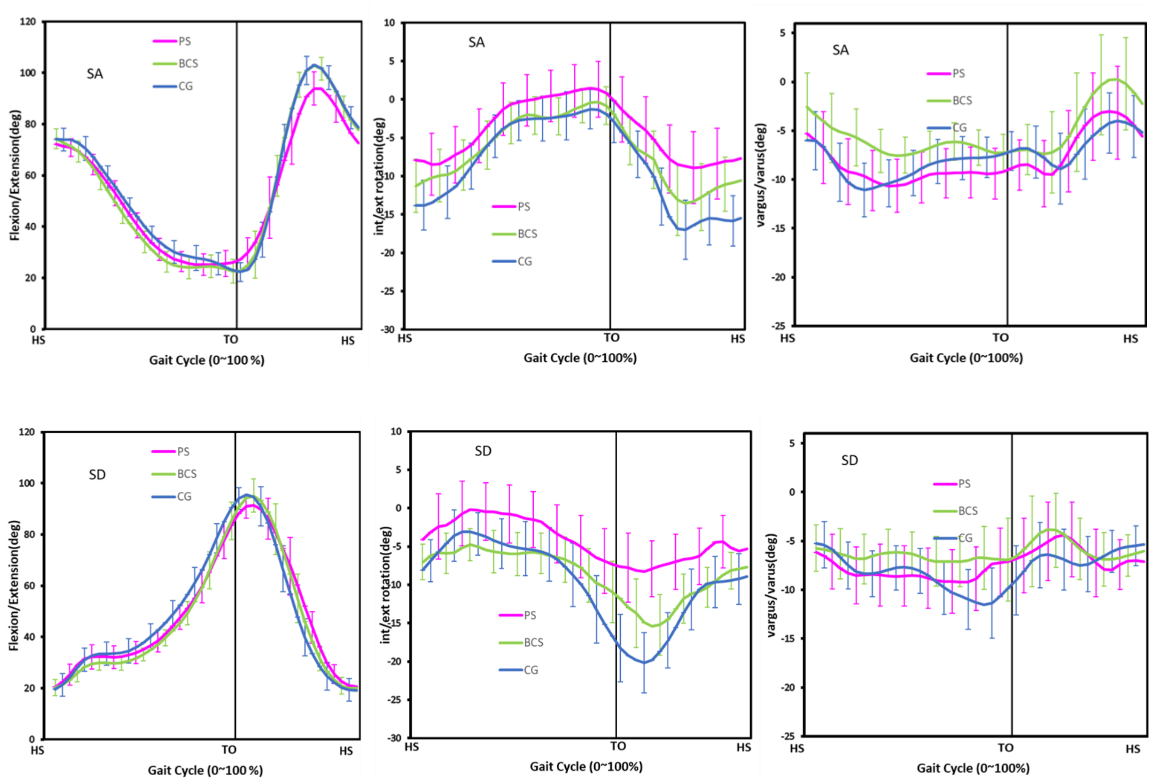

Figure 5.13 Three -dimensional Knee Kinematics Normalized with a Gait Cycle (Mean ± Standard Deviation) for TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG during Stair Ambulation (Top: Stair Ascending, Bottom: Stair Descending).

5.2.5 Knee Kinetics

For the flexion/extension moments, a one-way ANOVA revealed significant differences among the PS, BCS, and CG across all activities: level walking, ramp up, ramp down, stair ascending, and stair descending (Table 5.10). The post-hoc analysis showed marked differences between PS and CG for all these activities and between BCS and CG for the same activities. Regarding the abduction/adduction moments, one-way ANOVA discerned differences among PS, BCS, and CG during stair ascending and stair descending. The post-hoc analysis pinpointed significant differences between PS and CG during stair ascending and stair descending, as well as between BCS and CG during level walking, stair ascending, and stair descending. However, for the internal/external moments, no significant distinctions were observed among the three groups across all five daily activities.

Table 5.10 Three -dimensional Knee Kinetics for TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG during Walking, Ramp Up, Ramp Down, Stair Ascending and Stair Descending.

Variable	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
FEM (%BW*H)	PS	3.48±0.96[b]	3.15±0.81[b]	4.23±1.31[b]	7.63±1.94[b]	8.26±1.54[b]
	BCS	3.58±1.11[c]	3.06±0.93[c]	4.07±1[c]	6.06±1.74[c]	8.83±3.75[c]
	CG	4.44±1.14[bc]	4.6±1.5[bc]	5.32±1.3[bc]	9.22±1.94[bc]	11.37±1.78[bc]
IEM (%BW*H)	PS	0.68±0.31	0.58±0.29	0.65±0.32	0.56±0.34	0.72±0.54
	BCS	0.6±0.24	0.56±0.21	0.67±0.35	0.77±0.54	1.12±1.76
	CG	0.59±0.27	0.45±0.29	0.57±0.28	0.57±0.52	0.48±0.35
AAM (%BW*H)	PS	2.08±0.87	1.9±0.55	1.94±0.79	3.29±0.1[b]	3.52±0.55[b]
	BCS	2.3±0.76[c]	1.98±0.57	2.37±0.94	3.84±0.78[c]	3.95±0.89[c]
	CG	1.59±0.63[c]	1.51±0.73	1.83±0.88	2.85±0.24[bc]	2.87±0.36[bc]

a: PS vs. BCS,

b: PS vs. CG

c: BCS vs CG

The three-dimensional knee kinetics for the PS, BCS, and CG during various daily activities were depicted in (Figure 5.14-5.16). These graphs illustrated the peak knee joint moments during the daily activities, commencing from the initial heel strike (HS) (marked as 0%

in the gait cycle), progressing through toe-off (at 60% in the gait cycle), and concluding at the second heel strike (denoted as 100% in the gait cycle).

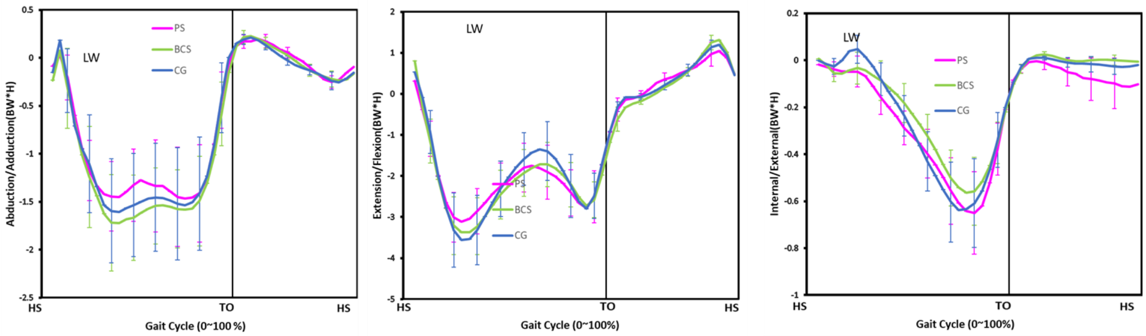

Figure 5.14 Three -dimensional Knee Kinematics Normalized with a Gait Cycle (Mean ± Standard Deviation) for TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG during Level Walking.

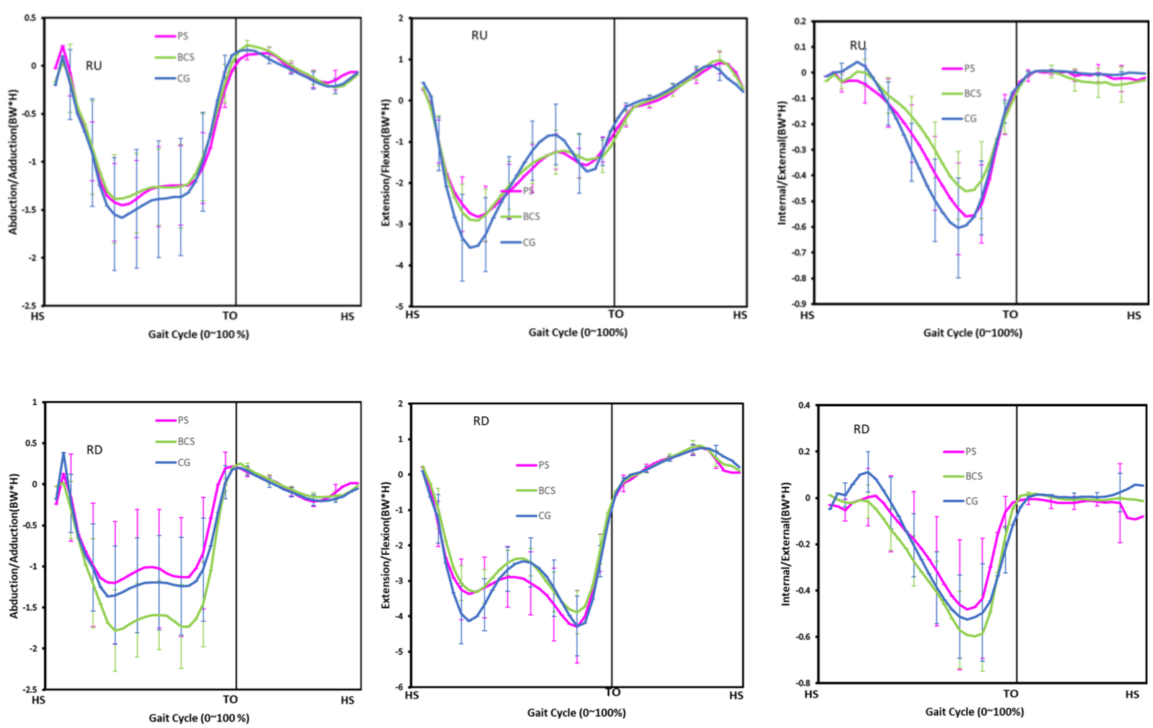

Figure 5.15 Three-dimensional Knee Kinematics Normalized with a Gait Cycle (Mean ± Standard Deviation) for TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG during Incline Walking (Top: Ramp up, Bottom: Ramp Down).

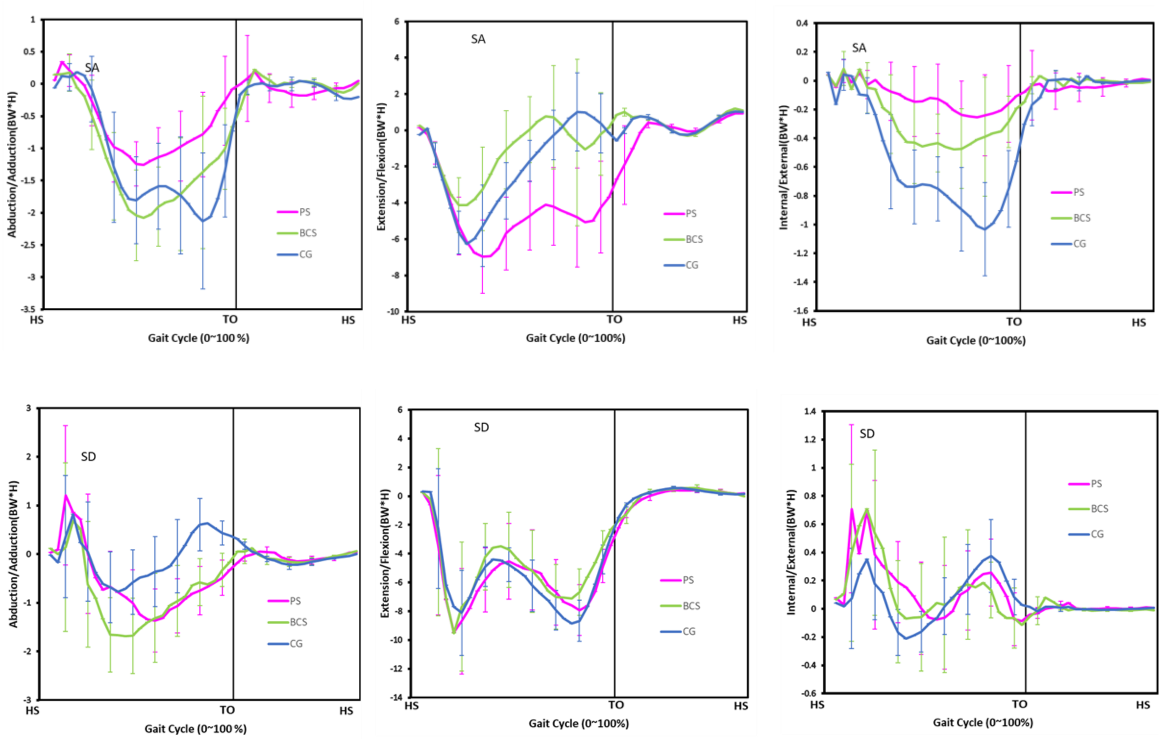

Figure 5.16 Three -dimensional Knee Kinematics Normalized with a Gait Cycle (Mean ± Standard Deviation) for TKA with Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG during Stair Ambulation (Top: Stair Ascending, Bottom: Stair Descending).

5.2.6 Knee Biomechanics Index

In the comparisons of TKA implants, significant differences were observed among the PS, BCS, and CG during daily activities: level walking, ramp up, ramp down, stair ascending, and stair descending (Table 5.11) (Figure 5.17). Subsequent post-hoc analysis indicated that both the PS and BCS implant groups differed significantly from the CG. For the comparison of PS and BCS, the BCS group displayed a higher KBI, particularly during level walking and ramp down, indicating the significant differences between these two implant groups.

Table 5.11 Knee Biomechanics Index (mean ± standard deviation) for Posterior Stabilized TKA Implants and Bi-cruciate Stabilized TKA Implants during Daily Activities.

KBI*^	Posterior Stabilized	Bi-cruciate Stabilized	Control Group
Level Walking[cd]	2.7±0.51	3.11±0.53	3.48±0.45
Ramp Up[fg]	2.75±0.63	2.92±0.63	3.48±0.39
Ramp Down[ik]	2.42±0.65	2.9±0.75	3.5±0.47
Stair Ascending	2.04±0.75	2.37±0.93	3.21±0.45
Stair Descending	1.85±1.06	2.16±1.21	3.35±0.4

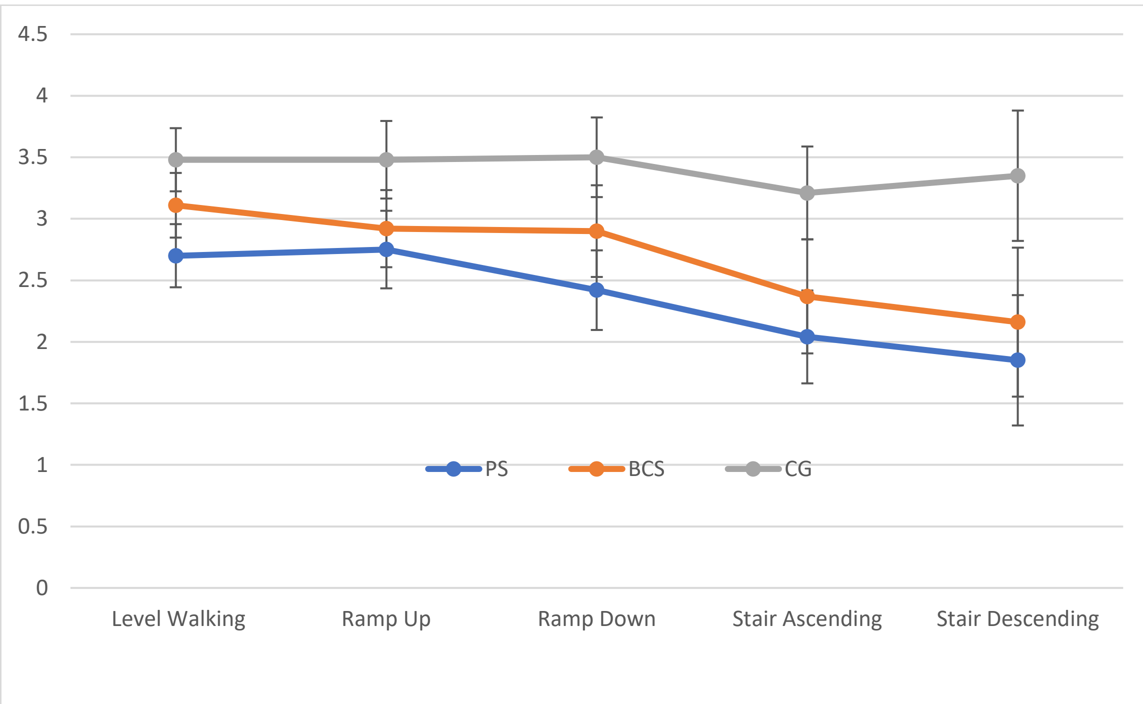

Figure 5.17 Knee Biomechanical Index (Mean ± Standard Deviation) in Five Daily Activities for Posterior Stabilized Implant, Bi-cruciate Stabilized Implant, and CG.

5.3 Bilateral Differences

5.3.1 Range of Motion Test

Using the paired T-test for the active ROM assessment, significant differences were observed between the involved limb and the contralateral limb during both the Pre-op and Post-op phases (Table 5.12). In the passive ROM test, results were notably greater than those in the active ROM test. Furthermore, the passive ROM test also revealed significant disparities between the involved and contralateral limbs during the Pre-op and Post-op phases. To summarize, even though the ROM in the Post-op phase increased by an average of 9 degrees, it still exhibited differences when compared to the contralateral limb.

Table 5.12 Bilateral Difference of Range of Motion Test for TKA participants during Pre-op and Post-op (Mean ± Standard Deviation).

		Pre-op	Post-op
Active	Involved	98.98±13.78*	107.94±16.78*
	Contralateral	115.44±12.18*	115.79±14.68*
Passive	Involved	107.23±15.23*	116.11±18.37*
	Contralateral	121.55±3.23*	123.15±13.16*

*: significant differences between Involved and Contralateral

5.3.2 Knee Kinematics

In the Pre-op, there were notable differences between the involved and contralateral limbs (Table 5.13). Specifically, FEROM differed during activities such as level walking, ramping up, ramping down, and stair ascending. VVROM showed disparities between the limbs primarily during ramping up and stair ascending. Furthermore, INTROM exhibited differences in ramping down and stair descending. For the Post-op (Table 5.14), FEROM revealed significant differences between the limbs during stair ascending. For VVROM, differences were evident during ramping up and stair ascending. Lastly, INTROM showed significant disparities during ramping up, stair ascending, and stair descending.

Table 5.13 Bilateral Difference of the Three-dimensional Knee Rotations for Pre-op TKA Participants (Mean ± Standard Deviation).

Pre-op	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
FEROM	inv	49.07±6.3*	44.58±6.6*	49.35±7.3*	74.09±5.1*	72.04±7.25
	col	52.82±6.4*	47.51±6.6*	52.83±7.2*	78.06±4.6*	74.51±8.81
VVROM	inv	9.7±2.65	9.08±3.16*	9.47±3.56	10.65±3.6*	9.75±3.36*
	col	10.73±3.71	10.66±3.7*	11.4±8.25	14.01±4.5*	12.25±3.5*
INTROM	inv	14.53±5.21	14.26±4.66	15.21±4.9*	13.22±4.3*	14.12±4.24
	col	16.07±4.12	15.28±4.61	17.71±7.2*	17.35±5.9*	17.86±8.33

*: significant differences between Involved and Contralateral

Table 5.14 Bilateral Difference of the Three-dimensional Knee Rotations for Post-op TKA Participants (Mean ± Standard Deviation).

Post-op	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
FEROM	inv	54.14±6	50.56±5.94	54.7±6.17	80.46±8.3*	78.93±6.36
	col	56.05±6.4	50.9±7.02	55.48±6.81	84.2±6.55*	80.46±5.7
VVROM	inv	9.35±3.41	9.41±3.65*	8.48±3.74*	12.35±5.0*	10.96±3.69
	col	10.11±4.8	10.82±4.9*	9.92±4.29*	14.06±5.6*	12.22±4.41
INTROM	inv	16.18±4.9	15.77±4.42	16.08±5.09	16.41±6.21	16.35±5.0*
	col	17.66±5.8	17.11±5.55	16.57±4.92	18.2±5.45	19.08±6.1*

*: significant differences between Involved and Contralateral

5.3.3 Knee Kinetics

For three dimensional moments (Table 5.15) (Table 5.16), significant differences were evident between the involved limb and its contralateral counterpart. Specifically, for FEM during the Pre-op phase, discrepancies were observed in level walking, ramping up, ramping down, stair ascending, and stair descending. In contrast, during the post-op phase, only ramping down exhibited a significant difference in FEM. Throughout all five daily activities, no significant differences between the limbs were noted for both the Pre-op and Post-op phases in IEM. Yet, the AAM demonstrated significant differences between the involved and contralateral limbs across all daily activities in the Pre-op phase, and this disparity persisted in level walking during the post-op phase.

Table 5.15 Bilateral Difference of the Three-dimensional Knee Moments for Pre-op TKA Participants (Mean ± Standard Deviation).

Pre-op	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
FEM (%BW*H)	inv	2.68±0.95*	2.83±1.23*	3.13±1.22*	5.83±1.6*	7.65±2.24
	col	3.69±1.03*	3.88±1.6*	4.53±1.39*	7.64±2.19*	8.91±2.24
IEM (%BW*H)	inv	0.78±0.46	0.78±0.46	0.74±0.4	0.92±0.88	0.88±1.28
	col	0.75±0.4	0.68±0.35	0.8±0.53	0.88±0.76	0.85±0.8
AAM (%BW*H)	inv	2.95±1.35*	3.02±1.39*	3.1±1.34*	3.8±0.66*	3.81±0.73*
	col	2.43±1*	2.26±0.84*	2.57±1.14*	3.39±0.65*	3.43±0.76*

*: significant differences between Involved and Contralateral

Table 5.16 Bilateral Difference of the Three-dimensional Knee Moments for Post-op TKA Participants (Mean ± Standard Deviation).

Post-op	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
FEM (%BW*H)	inv	3.53±1.03	3.1±0.86*	4.15±1.15	6.85±1.98	8.54±2.83
	col	3.7±1.16	3.36±0.91*	4.51±1.33	7.9±2.4	10±2.78
IEM (%BW*H)	inv	0.64±0.28	0.57±0.25	0.66±0.33	0.66±0.46	0.92±1.3
	col	0.82±0.33	0.73±0.32	0.74±0.51	0.9±0.73	1.17±1.28
AAM (%BW*H)	inv	2.19±0.8*	1.94±0.56	2.15±0.88	3.56±0.61	3.74±0.76
	col	2.58±0.8*	2.16±0.88	2.41±1.19	3.51±0.63	3.64±1.13

*: significant differences between Involved and Contralateral

For three-dimensional knee force (Table 5.17) (Table 5.18), no significant differences were found between the involved limb and the contralateral limb for anterior -posterior KF and medial-lateral KF during both the Pre-op and Post-op phases. However, the superior-inferior KF consistently displayed significant differences between the two limbs across all five daily activities, both in the pre-op and post-op phases.

Table 5.17 Bilateral Difference of the Three-dimensional Knee Forces (BW) for Pre-op TKA Participants (Mean ± Standard Deviation)

Pre-op	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
Anterior Posterior	inv	0.11±0.07	0.12±0.06	0.12±0.06	0.11±0.05	0.13±0.07
	col	0.11±0.05	0.1±0.04	0.11±0.06	0.11±0.05	0.12±0.06
Medial Lateral	inv	0.06±0.02	0.06±0.03	-0.06±0.03	0.07±0.02	0.04±0.02
	col	0.06±0.02	0.07±0.03	0.06±0.04	0.07±0.02	0.04±0.02
Superior Inferior	inv	0.76±0.04*	0.76±0.03*	0.76±0.04*	0.77±0.03*	0.91±0.17*
	col	0.91±0.05*	0.91±0.05*	0.91±0.06*	0.96±0.06*	1.16±0.22*

*: significant differences between Involved and Contralateral

Table 5.18 Bilateral Difference of the Three-dimensional Knee Forces (BW) for Post-op TKA Participants (Mean ± Standard Deviation).

Post-op	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
Anterior Posterior	inv	0.09±0.03	0.09±0.03	0.1±0.04	0.09±0.04	0.1±0.05
	col	0.11±0.05	0.1±0.05	0.1±0.06	0.1±0.06	0.11±0.06
Medial Lateral	inv	0.07±0.02	0.06±0.02	0.05±0.03	0.08±0.02	0.04±0.03
	col	0.07±0.02	0.06±0.02	0.06±0.04	0.08±0.02	0.04±0.02
Superior Inferior	inv	0.81±0.0*	0.8±0.05*	0.81±0.09*	0.85±0.06*	1.09±0.21*
	col	0.92±0.0*	0.91±0.06*	0.91±0.09*	0.95±0.06*	1.21±0.26*

*: significant differences between Involved and Contralateral

5.3.4 Bilateral Ratios

For the bilateral ratio of the FEROM (Table 5.19), a one-way ANOVA revealed significant differences among the Pre-op, Post-op, and CG in level walking, ramp down, and stair ascending. The post-hoc analysis showed marked differences between Pre-op and CG for level walking, ramp down, and stair ascending.

Regarding the ratio of the FEROM, a one-way ANOVA revealed significant differences among the Pre-op, Post-op, and CG in all daily activities. The post-hoc analysis showed that significant difference between Pre-op and Post-op during all daily activities and showed that significant different between Pre-op and CG during all daily activities.

Regarding the ratio of the AAM, a one-way ANOVA revealed significant differences among the Pre-op, Post-op, and CG in all daily activities. The post-hoc analysis pinpointed significant differences between Pre-op and Post-op during all daily activities as well as between Pre-op and CG during all daily activities.

For the ratio of the superior-inferior KF, a one-way ANOVA revealed significant differences among the Pre-op, Post-op, and CG in all daily activities. The post-hoc analysis showed the significant differences between Pre-op and Post-op, Pre-op and CG, and Post-op and CG during all daily activities,

Table 5.19 Bilateral Ratio (Involved / Contralateral) of the Flexion-extension Range of Motion, Flexion-extension Knee Moments, Abduction-adduction Knee Moments, and Superior-inferior Knee Force for Participants Pre-op, Post-op and CG (Mean ± Standard Deviation).

Ratio(inv/col)	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
FEROM	Pre-op	0.94±0.12[b]	0.95±0.16	0.94±0.13[b]	0.95±0.08[b]	0.98±0.1
	Post-op	0.97±0.12	1±0.13	0.99±0.13	0.96±0.1	0.98±0.07
	CG	1.03±0.09[b]	1.01±0.09	1.05±0.08[b]	1.01±0.08[b]	1.01±0.1
FEM	Pre-op	0.76±0.33[ab]	0.78±0.34[ab]	0.75±0.4[ab]	0.86±0.45[ab]	0.96±0.47[ab]
	Post-op	0.99±0.31[a]	0.95±0.27[a]	0.99±0.44[a]	1.02±0.61[a]	0.96±0.5[a]
	CG	1±0.25[b]	1.02±0.23[b]	1.04±0.19[b]	1.02±0.4[b]	1.03±0.35[b]
AAM	Pre-op	1.34±0.74[ab]	1.49±0.95[ab]	1.34±0.61[ab]	1.16±0.32[ab]	1.14±0.25[ab]
	Pos-op	0.92±0.44[a]	1±0.43[a]	1.04±0.52[a]	1.06±0.31[a]	1.1±0.34[a]
	CG	1.02±0.26[b]	1.02±0.11[b]	0.96±0.21[b]	1.05±0.23[b]	1.01±0.17[b]
KF	Pre-op	0.82±0.03[ab]	0.82±0.04[ab]	0.8±0.04[ab]	0.78±0.07[ab]	0.77±0.08[ab]
	Post-op	0.9±0.04[ac]	0.88±0.06[ac]	0.85±0.08[ac]	0.84±0.06[ac]	0.83±0.08[ac]
	CG	1.03±0.04[bc]	1±0.04[bc]	1.03±0.03[bc]	1.03±0.11[bc]	0.95±0.07[bc]

a: Pre-op vs Post-op

b: Pre-op vs CG

c: Post-op vs CG

For the SM and BF, a one-way ANOVA revealed significant differences among the Pre-op, Post-op, and CG in level walking, The post-hoc analysis showed the significant differences between Pre-op and CG in both muscles. However no significant differences were found in the other five muscles (Table 5.20).

Table 5.20 Bilateral Ratio (Involved / Contralateral) of the Low Extremities (Vastus Lateralis, Vastus Medialis, Biceps Femoris, Semimembranosus, Gastrocnemius Medial, Gastrocnemius Lateral) for Participants Pre-op, Post-op, and CG (Mean ± Standard Deviation).

Ratio(inv/col)	Group	Level Walking	Ramp Up	Ramp Down	Stair Ascending	Stair Descending
Vastus Lateralis	Pre-op	1.07±0.55	1.03±0.62	1.32±1.32	0.86±0.37	0.88±0.39
	Post-op	1.06±0.52	1.06±0.52	1.02±0.55	0.98±0.41	1.01±0.61
	CG	0.91±0.55	0.91±0.27	0.77±0.22	1.08±0.25	1.13±0.39
Vastus Medialis	Pre-op	1.06±0.56	1.03±0.54	1.25±1.28	0.85±0.37	0.81±0.4
	Post-op	1.04±0.51	0.99±0.41	1.04±0.58	1.03±0.43	1.03±0.6
	CG	0.94±0.46	0.77±0.21	0.7±0.24	1.09±0.25	1.11±0.38
Semimem-branosus	Pre-op	0.89±0.48[b]	1.08±0.68	0.97±0.6	0.97±0.79	1.1±0.74
	Post-op	1.09±0.55	1±0.66	1.11±0.56	1.02±0.38	1.05±0.63
	CG	1.24±0.47[b]	1.23±0.51	1.11±0.37	1.11±0.37	1.09±0.44
Biceps Femoris	Pre-op	0.89±0.41[b]	1.09±0.66	1.01±0.63	0.99±0.73	0.94±0.7
	Post-op	1.11±0.5	1.02±0.71	1.05±0.61	0.94±0.38	1.09±0.65
	CG	1.22±0.54[b]	1.31±0.46	1.09±0.39	1.06±0.36	1.23±0.52
Gastrocnemius Lateral	Pre-op	0.92±0.32	1±0.36	1.21±1.43	1±0.24	0.89±0.34
	Post-op	1.05±0.34	1.04±0.34	1.04±0.54	1±0.27	1.01±0.39
	CG	1.08±0.26	1.12±0.16	1.22±0.42	0.97±0.06	1.06±0.31
Gastrocnemius Medial	Pre-op	0.91±0.35	1±0.41	1.13±1.51	0.98±0.23	0.85±0.41
	Post-op	1±0.27	1±0.28	1.04±0.54	0.97±0.24	1±0.4
	CG	1.13±0.32	1.11±0.17	1.3±0.41	1.01±0.07	1.05±0.27
Tibialis Anterior	Pre-op	0.97±0.19	1.04±0.29	0.98±0.25	0.97±0.11	0.98±0.15
	Post-op	1.63±3.52	1.14±0.58	1.79±4.92	1.11±0.69	1.4±1.71
	CG	1.02±0.11	0.96±0.07	0.96±0.31	0.96±0.06	1.02±0.09

a: Pre-op vs Post-op

b: Pre-op vs CG

c: Post-op vs CG

5.3.5 Ten Time Sit-to-Stand.

Significant between-subject effects were observed for loading asymmetry during the Ten-test sit-to-stand, indicating discernible differences among the Pre-op, Post-op, and CG (Figure 5.18). Post hoc analysis revealed significant disparities between the Pre-op and CG in terms of loading asymmetry. While no significant within-subject effects emerged, there was a noticeable decrease in loading asymmetry with increasing repetitions during the Pre-op phase.

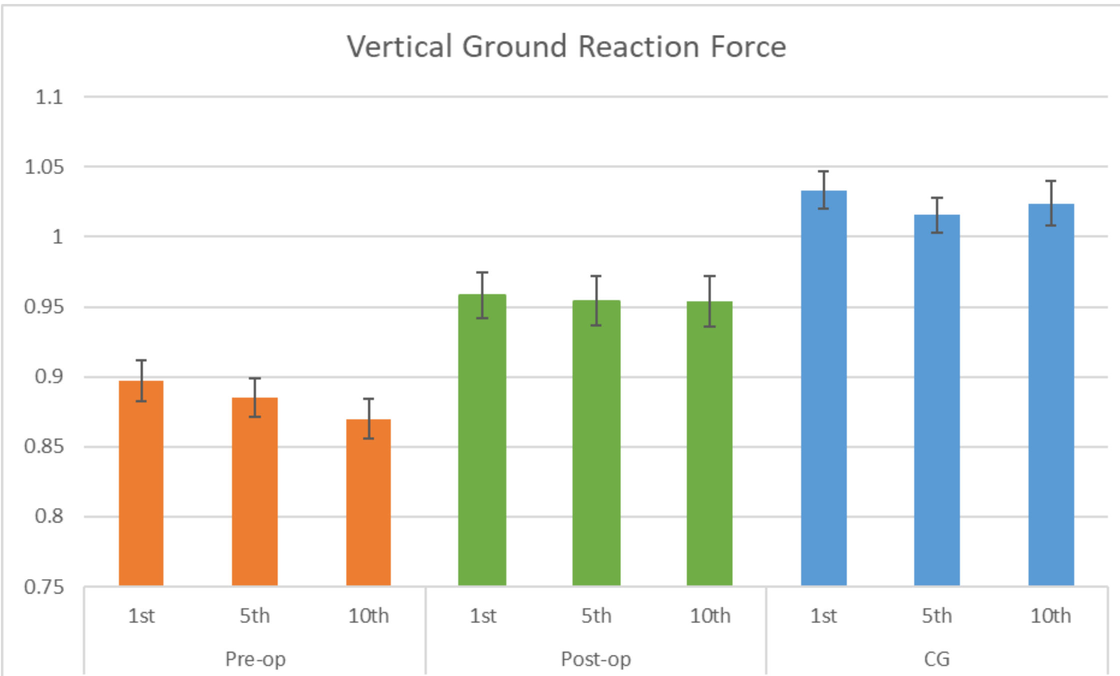

Figure 5.18 Loading Asymmetry (Involved / Contralateral) of the Ten Time Sit-to-stand for Participants Pre-op, Post-op, and CG (Mean ± Standard Deviation). (1st: Averaged of the 1~3 Repetitions 5th: Averaged of the 4~6 Repetitions 10th: Averaged of the 8~10 Repetitions).

For the ratio of quadriceps muscle activities, significant between-subject effects were observed for loading asymmetry during the ten-time sit-to-stand, indicating discernible differences among the Pre-op, Post-op, and CG (Figure 5.19) (Figure 5.20). Post hoc analysis revealed significant disparities between the Pre-op and CG in terms of loading asymmetry. No significant within-subject effects were found, indicating that there were no significant differences among the 1st repetitions, 5th repetitions, and 10th repetitions. However, there were no significant effects for both within-subjects and between-subjects for the ratio of hamstring muscle activities during the ten-time sit-to-stand.

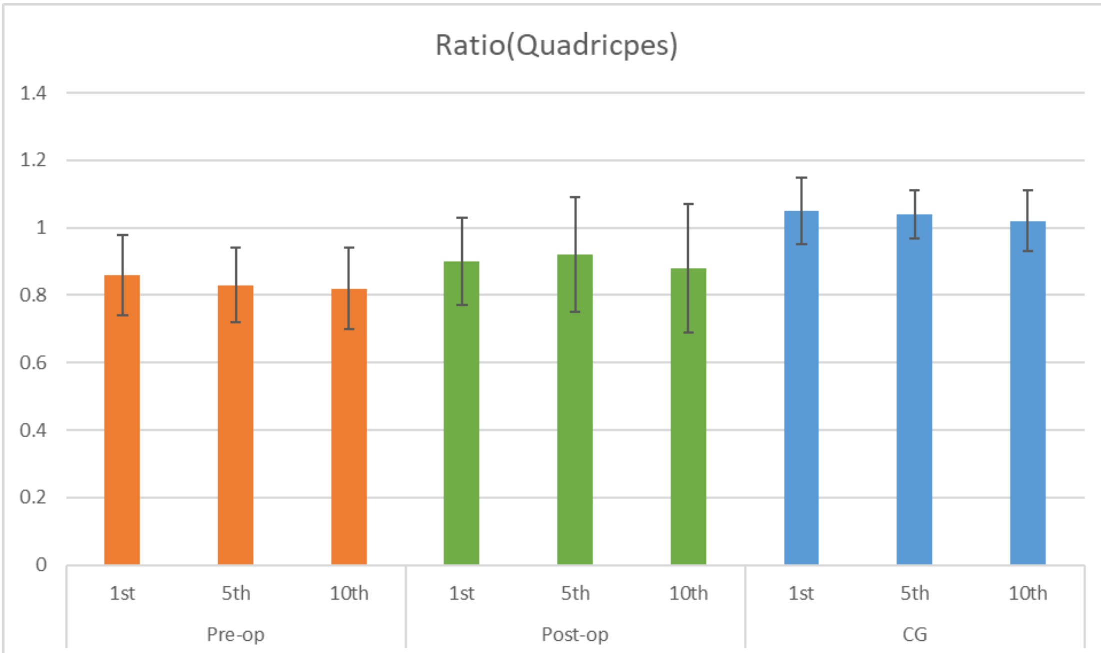

Figure 5.19 Ratio of Muscle Activities of Quadriceps (Involved / Contralateral) of the Ten Time Sit-to-stand for Participants Pre-op, Post-op, CG (Mean ± Standard Deviation). (Mean ± Standard Deviation). (1st: Averaged of the 1~3 Repetitions 5th: Averaged of the 4~6 Repetitions 10th: Averaged of the 8~10 Repetitions).

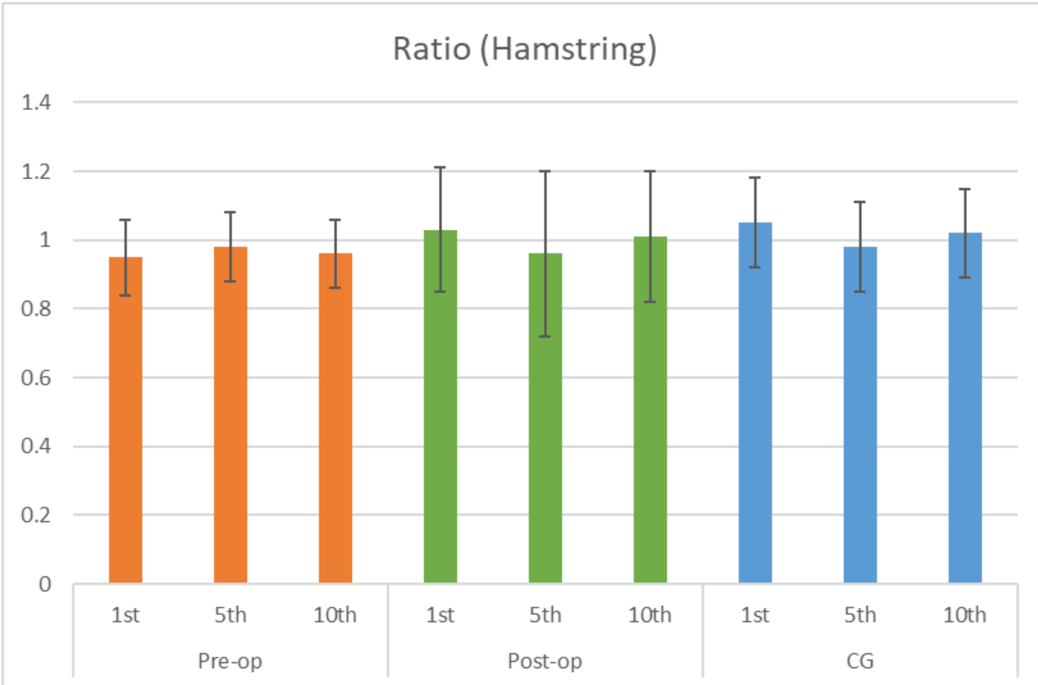

Figure 5.20 Ratio of Muscle Activities of Hamstring (Involved / Contralateral) of the Ten Time Sit-to-stand for Participants Pre-op, Post-op, and CG (Mean ± Standard Deviation). (Mean ± Standard Deviation). (1^{st}: Averaged of the 1~3 Repetitions 5^{th}: Averaged of the 4~6 Repetitions 10^{th}: Averaged of the 8~10 Repetitions).

For median frequency in involved limb during Pre-op, there was a significant decrease between the 1st and 5th repetition for VL and the 1st and 10th repetition for VL and VM (Table 5.21). For median frequency in Post-op, there was significantly decrease between the 1st and 5th repetition for VL and the 1st and 10th repetition for VL, VM, and BF. There was no significant difference in median frequency for the CG between the 1st, 5th, or 10th repetition in all knee muscles.

For the contralateral limb in median frequency (Table 5.22), there was a significant decrease between the 1st and 10th repetition for VL and VM. There was no significant difference in median frequency for the CG and Post-op between the 1st, 5th, or 10th repetition in all knee muscles.

Table 5.21 Median Frequency for the Involved Limb in 1st, 5th, and 10th Repetitions of STS for Quadriceps and Hamstrings (VL, VM, BF, and SM). *: p<0.05, **: p<0.01) (Mean±Standard Deviation).

	Pre-op			**Post-op**		
	1st	5th	10th	1st	5th	10th
VL	78±17	73±18*	72±19**	79±18	73±19*	72±19**
VM	75±31	73±33	68±31**	71±16	69±15	60±17**
BF	70±27	79±24	68±23	76±27	73±32	70±27*
SM	72±37	65±35	66±36	66±28	67±32	62±35

Table 5.22 Median Frequency for the Contralateral Limb in 1st, 5th, and 10th Repetitions of STS for Quadriceps and Hamstrings (VL, VM, BF, and SM). *: p<0.05, **: p<0.01) (Mean±Standard Deviation).

	Pre-op			**Post-op**		
	1st	5th	10th	1st	5th	10th
VL	77±13	75±13	69±16**	77±18	73±18	74±16
VM	71±23	70±21	63±21**	76±16	71±13	74±13
BF	79±22	79±24	66±23	73±27	73±17	70±27
SM	62±27	63±26	62±33	66±28	64±30	62±25

For the correlation analysis (Figure 5.21), there was a significant difference between loading asymmetry and time to performing ten time sit-to-stand during Pre-op (R= 0.376. p = 0.049). Also, there was a significant difference between loading asymmetry and time to performing ten time sit-to-stand during Post-op (R= 0.383. p = 0.044).

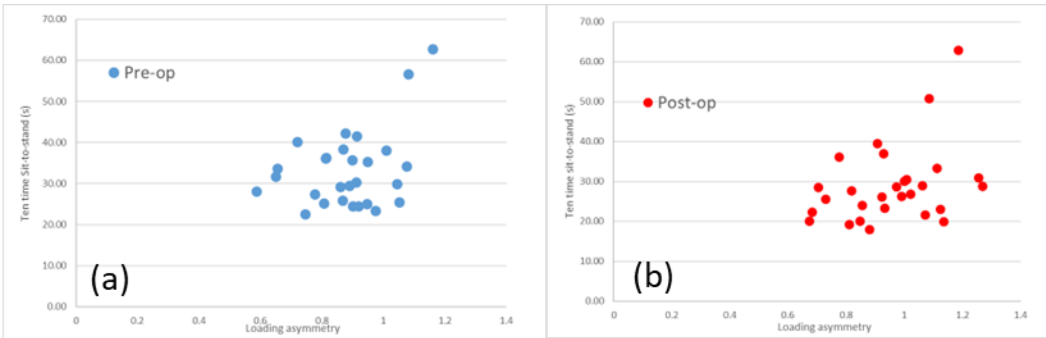

Figure 5.21 Correlations Between Loading Asymmetry and Time to Performing Ten Time Sit-to-Stand for (a)Pre-op and(b) Post-op.

CHAPTER 6: DISCUSSION

6.1 Knee Biomechanics in Daily Activities

Our first hypothesis was rejected as the KBI of stair ascending and stair descending were significantly lower than those of ramp up, ramp down, and level walking. Compared to level walking, the FEROM at Pre-op during stair ascending and stair descending was 51% and 46.7% higher, and 50.2% and 43.6% higher at Post-op, respectively. The FEM in level walking was 54.2% and 63.1% lower than that in stair ascending and stair descending at Pre-op, 53.1% and 78.9% lower at Post-op, respectively. These findings of sagittal plane knee kinematics and kinetics indicated that individuals with TKAs performing stair ambulation require greater functional capabilities. Previous studies had also reported differences between walking and stair ambulation [97, 108, 139, 140] and between level walking and ramp walking [91, 141-143]. Since our KBI was derived from six main biomechanical variables and weighted according to their contribution, no significant difference was found in KBI between level walking and inclined walking. Another explanation for this finding may be the unvaried degree of ramp and length of the ramp [93]. From the results of improvements in KBI, we found that the improvement in the KBI during level walking was significantly greater than that during stair ascending and stair descending. These findings also indicated that functional performance in high-demanding activities was not fully restored for TKA patients. This information may help clinicians define rehabilitation criteria and improve rehab protocols for TKA patients.

The second hypothesis was rejected based on the follow-up KBI scores for TKA patients. A significant main effect for the groups was detected in the KBI, indicating that KBI scores for the five daily activities showed a significant increase at follow-up. For the three-dimensional knee kinematics, both FEROM and INTROM showed significant differences with TKA follow-up. Compared to the Pre-op, the FEM was significantly greater at the Post-op, while the AAM was significantly lower during daily activities. The previous studies had reported similar results [88, 97]. The increased FEM in the post-op might have been attributed to the increased FEROM and the recovery of lower extremities' strength. The significant decrease in AAM indicated that the knee stability of the front plane was improved. These findings suggested that individuals with TKA experienced functional improvements and increased knee joint stability at follow-up. Unfortunately, when compared to the CG, participants in the Post-op still had deficits. The FEROM, INTROM, and FEM were significantly lower compared to the CG, consistent with previously reported studies [96, 144-146]. Furthermore, the deficits in high-demanding activities were more pronounced than those in other daily activities. Specifically, the FEROM in stair ascending and stair descending was 10% lower than CG, and the FEM in stair ascending and stair descending was 14% lower than that in CG. These findings indicated that stair ambulation remains a challenging activity for TKA participants at post-op, and the time required to reach the level of healthy control is longer than expected.

The third hypothesis was partly supported by the correlation found between the time taken to perform functional tests and the KBIs during daily activities. Clinical functional tests had been found useful for assessing TKA patients with limited mobility and for predicting their functional performance. Previous studies had reported negative correlations between clinical functional assessments and muscle strength, suggesting that higher muscle strength was necessary for faster performance times [135, 147]. The lack of significant differences found in the Pre-op group might have been due to the inconsistent conditions of the involved limb, which could cause performance variations across different activities. Nonetheless, our study found negative correlations between ramp down and TUG, stair ascending and TUG, as well as stair descending and TUG, in both the Pre-op and Post-op groups. This might suggest that the TUG functional test behaved similarly across daily activities. Moreover, the strong correlation observed during high-demand activities indicated that KBI scores might be related to clinical functional test outcomes. On the other hand, since the Sit-to-Stand test required higher lower extremity muscle strength compared to the TUG, significant correlations were only detected between stair ascending and STS and between stair descending and STS. These findings implied that clinical functional tests could be effective predictors of functional performance in individuals with TKA, particularly in high-demand activities.

Several limitations of this study warranted consideration. First, the analysis focused exclusively on knee kinematics and kinetics, neglecting the potential contributions and compensations of hip and ankle variables during high-demand activities. Second, the study involved only posterior stabilized and bi-cruciate stabilized TKA implants, leaving the performance of cruciate retaining implants during daily activities unexplored. Future research was suggested to gather more data to compare these implant types. Third, the investigation was limited to walking on a fixed incline, potentially constraining the applicability of the findings to other ramp walking situations. Finally, the stair ambulation test required participants to place one foot on each step, potentially excluding individuals who were unable to execute the task correctly.

The KBI offered a comprehensive insight into the functional performance of the knee during daily activities. This was achieved by its integration of the most used biomechanical variables. Such integration allowed for clear differentiation between the performance of participants during high-demand and low-demand activities. Additionally, the KBI visibly displayed functional improvements in TKA follow-ups, highlighting deficits when compared to

CG. The accuracy of the KBI, which was determined based on the normal distribution of CG, hinged upon the sampling size and composition of these controls. More convincing results could be obtained if the data were comprehensive, especially when matched with age, gender, and BMI.

In future applications, the KBI might have served as a tool to contrast differences between two distinct knee implants. When data from an entire population with a specific knee implant was available, an individual's KBI could be juxtaposed with the collective data of the same implant users. By comparing KBI scores in this group, individuals could discern their ranking among peers with the same knee implant, age, gender. This might have motivated TKA patients to engage more actively in rehabilitation to achieve a higher ranking.

6.2 Knee Biomechanics in TKA Implants

The primary hypothesis was rejected because there were significant differences between Persona and Journey II. The significant differences in knee kinematics during stair ambulation and the KBI differences indicated that the distinctions between the two implants were more pronounced on more demanding tasks compared to simple level walking. The variation in sagittal knee kinetics could have significant implications for implant wear. A study showed that abnormal valgus or varus positioning of the tibial component of a TKA implant might cause an increased propensity for loosening or implant wear and eventually lead to revision surgery [148]. The KBI showed that the BCS implants were closer to the CG. A previous study showed that kinematic differences through single fluoroscopic images could be linked to variations in the articular surface geometry. This might have varied because of the implant design between the two implants. Previous studies reported that the muscle activity of quadriceps highly affected the performance of the knee during daily activities, but none discussed the variation of tibialis anterior muscle activity [63]. This variation could be caused because of compensations after surgery [138].

When comparing specifically the Persona and Journey II implants, it was important to consider the variations in the implant designs. A study showed that posterior-stabilized knee implants were designed to decrease polyethylene insert wear with high surgical success rates [149]. This implant could be encouraged because of the increase in success rates. Posterior-stabilized knee implants were designed for patients with an incompetent or attenuated PCL [150]. The health of the patient before surgery made a huge difference in the best implant and the success of the surgery. Some differences that were found between Persona and Journey II might have been caused by the different implant designs. The difference that might have been linked to the different designs concerned the post-cam shape of the two implants. Considerations needed to be taken when determining the best implant design for the subject and for future implant designs.

Two further questions we wanted to address pertained to BMI and age. The first question was whether the patient should lose weight before having the TKA surgery. This was often thought to be true, but what was the ideal BMI? Following trends, determining the patient's post-surgery goals, along with other factors were important in helping answer this question. Machine learning techniques would have been extremely helpful in answering this question. The second question was when the right time to have the surgery was. This was a challenging question because of the battle between the patient's pain level and the longevity of the implant. Typically, patients, especially younger ones, were encouraged to wait as long as possible to have the surgery so that the patient would not need revision surgery; however, this often caused many further compensation injuries. Further investigation with a larger sample size or database could help provide more insight. The benefits of using artificial intelligence were endless in this field.

There was an abundance of self-reported forms, and they were often redundant. The Knee Society Score, Short Form Survey-12, and the Forgotten Joint Score were used in this study because they were comprehensive and commonly used. Even so, artificial intelligence would have radically transformed this process as it would have become much more interactive for the subjects. This improvement could have made it individualized for each subject and might have been better related to knee joint function after TKA surgery.

Findings of this study indicated that both subjective and objective measures were important when assessing functional improvement of subjects who underwent TKA. There were many factors that influenced the outcome of the TKA, including general health, BMI, age, knee function, and many others. The knowledge of so many variables affecting the subjects and the results of the surgery suggested the use of artificial intelligence could be extremely helpful [151]. In addition, creating a KBI would aid in improving the outcome of the TKA surgery. This new method would be able to predict the outcomes, create personalized matches, and aid in surgical planning. The understanding that conducting a large study with motion analysis was not feasible so creating a database could help identify key markers and variables that were related to the success of the surgery. Artificial intelligence could learn from past subjects and predict future subjects who would undergo the TKA procedure. Before artificial intelligence could be fully applied, we needed to explore all variables that might be used for better decisions. That was one of the purposes of this study. There were so many variables; with human power, we could only analyze a small portion of the data based on our judgement.

6.3 Knee Biomechanics in Bilateral Differences

The first hypothesis, suggesting no significant differences between the involved and contralateral limbs for unilateral TKA participants, was rejected. In the active ROM test, the involved limb displayed a deficit of 15 degrees relative to the contralateral limb in the pre-op phase, and this difference was reduced to 8 degrees in the post-op phase. Meanwhile, the passive ROM test indicated a disparity of 14 degrees in the pre-op phase and 7 degrees in the post-op phase. It was common for active ROM to be inferior to passive ROM, as TKA participants might not have achieved full flexion and extension, often due to pain or other limiting factors. Because of the knee joint disorders which limited the ROM, the ROM in the pre-op phase had lower ROM than in the post-op phases for the involved limb, but there were few differences for the contralateral limb in both phases. The increase in ROM in the involved limb indicated functional improvements and pain reduction, which made it possible to perform high-demanding activities during daily living. The decrease in time performing clinical functional tests had shown that improvement. This was also supported by other researchers that the new TKA implants helped improve participants' range of motion [152, 153].

Significant bilateral differences were observed in unilateral TKA participants during daily activities. In the pre-op phase, measures such as knee flexion-extension, knee flexion-extension moment, and superior-inferior knee force were notably lower in the involved limb compared to the contralateral limb during activities like level walking, ramp walking, and stair ambulation. Conversely, the knee abduction-adduction moment was significantly greater in the involved limb. In the post-op phase, these bilateral disparities persisted, particularly in the superior-inferior knee force. While peak muscle activities did not present significant bilateral differences, the muscle activity of the involved quadriceps was less than its contralateral counterpart. Earlier studies primarily used vertical ground reaction force to determine bilateral discrepancies, finding the force in the involved limb to be lower during daily activities [123]. In contrast, our study prioritized knee-specific variables, asserting that the superior-inferior knee force, calculated from the ground reaction force, offered a more accurate reflection of knee joint status. This loading asymmetry contributed to the bilateral differences in flexion-extension range of motion and flexion-extension knee moments. Past research also identified reduced quadriceps strength in the involved limb, although non-significant differences in vastus lateralis and vastus medialis muscle activities were observed in our study. This suggested TKA patients might have exerted lower quadriceps strength, compensating with altered gait patterns and increased flexion-extension moments in hip and ankle joints to maintain balance. Moreover, our research noted a ratio greater than one for abduction-adduction moments across all daily activities, signifying the involved limb has a more pronounced frontal plane moment than its counterpart. This echoes findings from previous studies on TKA participants. Reduced frontal plane knee joint moments imply heightened knee joint stability. Supporting this, the observed lower ratio of abduction-adduction moment in TKA follow-ups underscores enhanced knee joint stability, enabling TKA participants to undertake daily activities with reduced pain and a broader range of motion.

While significant differences were observed in knee kinematics and kinetics during daily activities, muscle activities of the lower extremities showed fewer pronounced differences for TKA participants. Nevertheless, bilateral discrepancies in EMGs became more evident during the ten-time-sit-to-stand. Our research identified an unbalanced vertical ground reaction force in TKA participants that decreased with successive repetitions, a finding consistent with prior studies [154]. Moreover, the quadriceps ratio presented significant differences when comparing the pre-op phase with the CG. This might have been attributed to an imbalanced muscle activation level of the quadriceps during the STS test, leading TKA participants in the pre-op phase to rely more heavily on their contralateral limb for the ten-time-sit-to-stand task. While this strategy could have been an easy way to perform TSTS, the heightened muscle activity of the quadriceps, spurred by the increasing vertical ground reaction forces, might have posed potential harm to the contralateral limb. This imbalance may have increased the susceptibility of the contralateral knee to osteoarthritis.

From our frequency analysis, the median frequency declined for both the quadriceps and hamstring muscles across both limbs during the pre-op phase. In the post-op phase, this decrease was observed exclusively in the involved limb's quadriceps. This trend suggested that after undergoing physical training and rehabilitation, the quadriceps function improved. Furthermore, our study identified a correlation between loading asymmetry and the time required to perform the ten-time-sit-to-stand task. Greater loading asymmetry ratios correlated with longer completion times. This indicated that bilateral discrepancies might have elucidated the reduced functional capability observed in TKA participants. Therefore, addressing these imbalances was essential for TKA participants, as it could enhance knee functionality and overall quality of life.

6.4 Limitations

This study had several inherent limitations. Firstly, the research timeline was disrupted due to the Covid pandemic, causing irregularities in patient testing schedules. The availability of participants was inconsistent due to surgery cancellations or postponements, with the average post-op surgery return being 9-months, which was greater than the anticipated 6-months. Furthermore, achieving a perfect match in terms of gender, age, and BMI between both implant groups and the CG proved challenging. While we endeavored to closely match these characteristics, minor variations persisted. These variations in the pre-op phase might have suggested that patients were at marginally different states of health before the procedure. Such discrepancies might have arisen from diverse demographic factors, including socio-economic status, race, and place of residence. Another limitation lay in the post-surgery rehabilitation phase; we did not monitor the individual rehabilitation regimens of participants, given they might have received physical therapy from different providers. Nonetheless, all participants had completed their rehabilitation by the time of their post-op laboratory visit.

6.5 Future Work

In future applications, the KBI might have served as a tool to contrast differences between two distinct knee implants. When data from an entire population with a specific knee implant was available, an individual's KBI could have been juxtaposed with the collective data of the same implant users. By comparing KBI scores in this group, individuals could have discerned their ranking among peers with the same knee implant, age, gender; this may have motivated TKA patients to engage more actively in rehabilitation to achieve a higher ranking. Through all these collective data, there might have been development of an optimal implant design. Further investigation might have also focused on the 1-year follow-ups of TKA participants, which could have explained better functional performance during daily activities.

CHAPTER 7: SUMMARY

7.1 Takeaways

The first objective was to investigate the knee biomechanics in daily activities for TKA follow-up. The three-dimensional knee kinematics and kinetics, clinical functional test such as sit-to-stand, time up and go, gait parameters and KBI were participated in comparison.

- Significant differences were observed in STS performance time among the Pre-op, Post-op, and CG. Post hoc testing revealed that the CG performed STS significantly faster than the Pre-op and Post-op, with the Post-op performing STS 15% faster than the Pre-op.
- A significant group×task interaction was found in FEROM indicates that FEROM increased notably in stair ascending and stair descending compared to the other three activities. Post hoc comparisons revealed that FEROM in the Post-op was significantly greater than that in the Pre-op, while both groups had smaller FEROM values than the CG.
- The Post-op group had significantly greater INTROM than the Pre-op, and INTROM in both groups was significantly lower than in the CG.
- A significant group×task interaction was observed in FEM, with a significant task main effect indicating that FEM increased as the difficulty of daily activities increased. Post hoc comparisons revealed that FEM in the Post-op was significantly greater than in the Pre-op, and FEM values in both groups were significantly lower than in the CG.
- The Post-op had significantly lower AAM than the Pre-op, and AAM values in both groups were significantly higher than in the CG.
- Post-hoc analysis revealed that TKA patients experienced significant improvements in KBI. Specifically, there was a 61% increase during level walking, a 47% increase during

ramp up, a 42% increase during ramp down, a 69% increase during stair ascending, and a 67% increase during stair descending when compared to Pre-op measures. However, even after surgery, the Post-op's KBI values still lagged those of the CG.

- For the comparison with five difference activities, significant main effect for the group was detected in KBI, showing that KBI scores for five daily activities significantly increased at follow-up. Post hoc analysis revealed that the KBI for level walking was significantly higher than for stair ascending and stair descending.
- In terms of KBI improvements, the extent of enhancement in daily activities decreased as the difficulty of the activity increased. Specifically, the improvements in KBI for level walking were significantly greater than those for stair ascending and stair descending.
- In the Pre-op, significant correlations were observed between TUG performance time and KBIs for the Ramping down, Stair ascending and Stair descending. In the Pre-op, significant correlations were observed between the TUG performance time and KBI scores for ramp down, stair ascending, and stair descending.

The second objective was to investigate the differences between posterior stabilized implants and bi-cruciate stabilized implants for TKA patients. PROMs, The balance test, proprioception test, three-dimensional kinematics and kinetics, EMG muscle activities and KBI were used to evaluate the differences between two implants.

- For the functional scores, significant differences were observed among the PS, BCS, and CG. Post-hoc analysis revealed these significant differences to be between the PS and CG as well as between the BCS and CG. Similar results were also observed in the objective scores.

- In the proprioception test, both 30-degree and 70-degree measurements showed no notable differences between the two implants. Similarly, for the balance test, the total score index did not present any significant differences among the PS, BCS, and CG.
- For the peak muscle activities, no significant differences were found among these three groups for all seven muscles during the five daily activities.
- In the sagittal plane range of motion, there were significant differences among the PS, BCS, and CG. Post hoc analysis indicated significant differences between PS and BCS during stair ambulation.
- For the flexion/extension moments, a one-way ANOVA revealed significant differences among the PS, BCS, and CG across all activities. The post-hoc analysis showed marked differences between PS and CG for all these activities and between BCS and CG for the same activities.
- For the comparison of PS and BCS, the BCS group displayed a higher KBI, particularly during level walking and ramp down, indicating the significant differences between these two implant groups.

The third objective was to investigate the bilateral differences for unilateral TKA follow-ups. The bilateral ratios of knee kinematics, kinetics and peak muscle activity of low extremities were used to compare the differences between involved limb and its contralateral limb. For ten time Sit-to-stand, the load symmetry and ratio of quadriceps and hamstring muscle activities, median frequency were used to evaluate the differences between TKA follow-ups and repetitions.

- For range of motion test, significant differences were observed between the involved limb and the contralateral limb during both the Pre-op and Post-op phases.
- In the Pre-op, there were notable differences between the involved and contralateral limbs. Specifically, FEROM differed during activities such as level walking, ramping up, ramping down, and stair ascending.
- For three dimensional moments, significant differences were evident between the involved limb and its contralateral counterpart, specifically, for FEM during the Pre-op phase.
- The AAM demonstrated significant differences between the involved and contralateral limbs across all daily activities in the pre-op phase, and this disparity persisted in level walking during the post-op phase.
- The superior-inferior KF consistently displayed significant differences between the two limbs across all five daily activities, both in the pre-op and post-op phases.
- For the ratio of the superior-inferior KF, a one-way ANOVA revealed significant differences among the Pre-op, Post-op, and CG in all daily activities. The post-hoc analysis showed the significant differences between Pre-op and Post-op, Pre-op and CG, and Post-op and CG during all daily activities,
- Regarding the ratio of the AAM, a one-way ANOVA revealed significant differences among the Pre-op, Post-op, and CG in all daily activities. The post-hoc analysis pinpointed significant differences between Pre-op and Post-op during all daily activities as well as between Pre-op and CG during all daily activities.
- Significant between-subject effects were observed for loading asymmetry during the Ten-time sit-to-stand, indicating discernible differences among the Pre-op, Post-op, and CG.

Post hoc analysis revealed significant disparities between the Pre-op and CG in terms of loading asymmetry.

- For the ratio of quadriceps muscle activities Significant between-subject effects were observed for loading asymmetry during the ten time sit-to-stand, indicating discernible differences among the Pre-op, Post-op, and CG. Post hoc analysis revealed significant disparities between the Pre-op and CG in terms of loading asymmetry.
- For median frequency in involved limb during Pre-op, there was a significant decrease between the 1st and 5th repetition for VL and the 1st and 10th repetition for VL and VM. For median frequency in Post-op, there was significantly decrease between the 1st and 5th repetition for VL and the 1st and 10th repetition for VL, VM, and BF.
- There was a significant difference between loading asymmetry and time to performing ten time sit-to-stand in the Pre-op. Also, there was a significant difference between loading asymmetry and time to performing ten time sit-to-stand in the Post-op.

7.2 Conclusions

TKA surgery provided functional improvements for patients in daily activities, but they might have still experienced deficits when performing high-demand activities such as stair ambulation. The proposed KBI was a valid and simplified tool to integrate all important biomechanical variables of the knee joint for clinicians. Clinical functional tests were helpful in predicting the functional improvements of daily activities for TKA patients. The differences between the two TKA implants were subtle, and both implants demonstrated efficacy in alleviating pain and improving function. It was essential to note that bilateral discrepancies persisted in post-op phase for unilateral TKA patients. This underlined the importance of an increased emphasis on physical training and muscle recovery, mitigating the risk of osteoarthritis in the contralateral limb.

7.3 Publications

Journal publications in process:

- Title: Comparison of the Knee Biomechanics of Patients with Total Knee Arthroplasty in Different Daily Activities, submitted to Heliyon, under review.
- Title: Patient Reported Outcome Measures and Biomechanical Variables that May Related to Knee Functions Following Total Knee Arthroplasty, in preparation

Conference Proceedings, Poster Presentations, and Abstracts:

- Fangjian Chen, Hannah Stokes, Nigel Zheng, Ronald Singer, Michaeal Bates. Knee joint Biomechanics of Total Knee Arthroplasty Patients during Daily Activities, Orthopedic Research Society (ORS), 2024.2.2 Long Beach, CA
- Fangjian Chen, Hannah Stokes, Nigel Zheng, Ronald Singer, Michaeal Bates. Limb Symmetry of the Knee Joint Kinematics During Daily Activities for Total Knee Arthroplasty Patients Orthopedic Research Society (ORS), 2023.2.10 Dallas, TX
- Fangjian Chen, Hannah Stokes, Nigel Zheng, Ronald Singer, Michaeal Bates. Muscle Function Restoration in Daily Living Activities for Total Knee Arthroplasty Patients, Orthopedic Research Society (ORS), 2023.2.10 Dallas, TX
- Hannah Stokes, Fangjian Chen, Nigel Zheng, Ronald Singer, Michaeal Bates. Anterior/Posterior Knee Joint Force Analysis in Daily Living Activities for Total Knee Arthroplasty Patients Orthopedic Research Society (ORS), 2023.2.10 Dallas, TX

- Hannah Stokes, Fangjian Chen, Nigel Zheng, Ronald Singer, Michaeal Bates. Investigating Quadriceps Muscle Activity and Pain Level Climbing Stairs for Total Knee Arthroplasty Patients. Orthopedic Research Society (ORS), 2023.2.10 Dallas, TX
- Fangjian Chen, Nigel Zheng, Ronald Singer, Michaeal Bates. Loading symmetry and compensatory strategy for TKA Patients During Sit-to-Stand, Orthopedic Research Society (ORS), 2022.2.4, Tampa. FL.
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Appendix

Appendix A: Informed Consent form

UNC CHARLOTTE

Department of Mechanical Engineering and Engineering Science
9201 University City Boulevard, Charlotte, NC 28223-0001
t/ 704-687-7301 f/ 704-687-8345

Informed Consent for

Prospective Evaluations of Patients with Journey II BCS in Gait Biomechanics, Proprioception, Balance and Functional Capacities

Project Purpose

You are invited to participate in a research study because you had a total knee replacement (TKR) or you are a healthy subject for our study. The primary purpose of this study is to learn the differences in how the knee works during level, incline and stair walking, balance and proprioception in people with one of two total knee replacement (TKR) designs (bi-cruciate posterior stabilizing and posterior stabilizing) and those whose knees are healthy. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Investigator(*s*)

Nigel Zheng, Ph.D., Professor and his research assistants at UNC Charlotte.

Eligibility

You are invited to participate in this study if you are going to have total knee replacement with either bi-cruciate posterior stabilizing or posterior stabilizing implants, or you are healthy to serve as one of our healthy controls.

Overall Description of Participation

If you agree to participate in the study as a TKA subject, you will be asked to attend these sessions, 1) a pre-surgery biomechanical test session within two weeks of your TKR surgery, 2) a phone interview session at one week, 3) two biomechanical test sessions at one month (optional) and six months after your TKR surgery, and 4) one session to fill out responses to survey forms at 12th month after your TKR surgery. Each of the three biomechanics laboratory testing session which will take about 2 hours to complete at the Biomechanics/Sports Medicine Lab on the UNC Charlotte campus. If you agree to participate in the study as a healthy control subject, you will be asked to attend one session.

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. The phone interview session will last no more than 20 - 30 minutes and the final survey session will not last more than 30 minutes.
At the start of each biomechanical test session, you will complete the patient satisfaction score, and a few survey forms [EQ-5D, SF-12, Knee Society Scoring system score, current pain medication, and Physical Activity Readiness Survey (PAR-Q)]. Following completion of the surveys, you will change into appropriate testing attire and footwear. Height and weight will be recorded. You may walk for a few minutes in the lab to get ready. You will then be asked to perform these daily activities:

- get out of a chair, walk about 9 feet, and walk back to the chair,

After these daily activities, we will also perform some tests. You will perform:

- balance test
- proprioception test (that measures a subject's ability to reposition a joint to a predetermined position)
- knee range of motion test

After completion of the aforementioned tests, you will be asked to complete level, ramp and stair walking tests. An EMG electrode will be placed on several lower limb muscles on you. You will be asked to perform several movements to test the electrode attachment for the muscles. The electrodes are used to record the electrical signals of the muscles and will not discharge any electrical shock or hurt to you. Reflective markers will be placed on your body using double-sided tapes. You will then perform 3-5 successful tests for each of five walking test movement conditions: level walking, uphill walking at 5°, downhill walking 5°, stair ascent, and stair descent. Tests need to be completed at your own speed. You will be asked to rate your knee pain before and after each of the five walking conditions.
None of the instruments will interfere with your ability to do the test. We have 4 home security cameras installed in the lab. If you do not wish us to record the tests, please let us know now so we will turn off these cameras.

If you have any further questions, interests or concerns about any equipment to be used in this test, please feel free to ask the investigators or other research personnel.

Length of Participation

Your participation will take approximately 2.5 hours for each session in the lab.

Risks and Benefits of Participation

The possible risk of injury in this study is highly unlikely, not higher than the risks you are facing in your daily living. Additionally, research assistants will be present to spot you during the test to ensure you are protected from losing your balance at any time during the study. Our 3D motion capture system and 3D whole body scanner work like regular cameras and do NOT have any radiation. You should not experience pain or discomfort with the testing procedure. However, if you do you should inform the investigators and testing will be stopped immediately.

You may not benefit from your participation in this study directly. If you want, you can receive your individual study information to share with your personal physician in case it might be helpful to your future health care. The information gained from your case may benefit others with your condition. Identifying the gait abnormalities following TKR with different TKR designs may be also beneficial in improving future TKR designs, and surgical and rehabilitation methods in order to achieve higher levels of patients' functions after their knee joint replacements.

Compensation/Payment/Incentives

If you are one of healthy controls, you will receive a $30 Walmart gift card at the completion of participation. If you are one of TKA subjects, you will receive a $150 Walmart gift card at the completion of participation.

Possible Injury Statement

All research involves a chance that something bad might happen to you. This may include the risk of personal injury. In spite of all safety measures, you might develop a reaction or injury from being in this study. If such problems occur, the researchers will help you get medical care, but any costs for the medical care will be billed to you and/or your insurance company. UNC Charlotte has not set aside funds to pay you for any such reactions or injuries, or for the related medical care. You do not give up any of your legal rights by signing this form.

Volunteer Statement

You are a volunteer. The decision to participate in this study is completely up to you. If you decide to be in the study, you may stop at any time. You will not be treated any differently if you decide not to participate in the study or if you stop once you have started. Unfortunately, you will not receive a Walmart gift card.

Confidentiality Statement

Any identifiable information collected as part of this study will remain confidential to the extent possible and will only be disclosed with your permission or as required by law.

The records of this study will be kept private. In any sort of report we might publish, we will not include any information that will make it possible to identify a patient. Your record for this study may, however, be reviewed and/or photocopied by Carolinas HealthCare System, UNC Charlotte, OrthoCarolina, or by representatives of the Food and Drug Administration or other government agencies. To that extent, confidentiality is not absolute.

Statement of Fair Treatment and Respect

UNC Charlotte wants to make sure that you are treated in a fair and respectful manner. Contact the Office of Research Compliance at 704-687-1871 or uncc-irb@uncc.edu if you have questions about how you are treated as a study participant. If you have any questions about the actual project or study, please contact Dr. Nigel Zheng (704-687-7301, nzheng@uncc.edu).

Approval Date

This form was approved for use on *Month, Day, Year* for use for one year.

Participant Consent

I have read the information in this consent form. I have had the chance to ask questions about this study, and those questions have been answered to my satisfaction. I am at least 18 years of age, and I agree to participate in this research project. I understand that I will receive a copy of this form after it has been signed by me and the principal investigator of this research study.

__________________________________ ____________________

Participant Name (PRINT) DATE

____

Participant Signature

__________________________________ ____________________

Investigator Signature DATE

Appendix B: IRB Approval Notice

CHARLOTTE
DIVISION OF RESEARCH

To:	Naiquan Zheng Mech Engineering & Engineering Sci
From:	IRB
Approval Date:	06-Aug-2023
Expiration Date of Approval:	05-Aug-2024
RE:	Notice of IRB Approval by Expedited Review (under 45 CFR 46.110)
Submission Type:	Renewal
Expedited Category:	4~6~7
Study #:	IRBIS-17-0300
Study Title:	Prospective Evaluations of Patients with Journey II BCS in Gait Biomechanics, Proprioception, Balance and Functional Capacities

This submission has been approved by the IRB for the period indicated. Carefully review the Investigator Responsibilities listed below.

Your approved consent forms and other documents are available online at Submission Page.

Investigator's Responsibilities:

1. Amendments **must** be submitted for review and the amendment must be approved before implementing the amendment. This includes changes to study procedures, study materials, personnel, etc.
2. Researchers must adhere to all site-specific requirements mandated by the study site (e.g., face mask, access requirements and/or restrictions, etc.).
3. It is the Principal Investigator's responsibility to submit for renewal and obtain approval before the expiration date. Complete a Renewal submission at least two (2) weeks prior to the above cited expiration date of approval.
4. You may not continue any research activity beyond the expiration date without IRB approval. Failure to receive approval for continuation before the expiration date will result in automatic termination of the approval for this study on the expiration date.
5. Data security procedures must follow procedures as approved in the protocol and in accordance with OneIT Guidelines for Data Handling.

6. Promptly notify the IRB (uncc-irb@charlotte.edu) of any adverse events or unanticipated risks to participants or others.
7. Be aware that this study is included in the Office of Research Protections and Integrity (ORPI) Post-Approval Monitoring program and may be selected for post-review monitoring at some point in the future.
8. Complete the Closure eform via Niner Research once the study is complete.

Please be aware that approval may still be required from other relevant authorities or "gatekeepers" (e.g., school principals, facility directors, custodians of records).

This study was reviewed in accordance with federal regulations governing human subjects research, including those found at 45 CFR 46 (Common Rule), 28 CFR 46 (DOJ), 21 CFR 50 and 56 (FDA), and 40 CFR 26 (EPA), where applicable.

Appendix C: Participants Recruitment Flyers

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

UNC CHARLOTTE

A team of researchers from the Biomechanics and Motion Analysis Lab at UNC Charlotte 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 one 2 hour testing session in the lab. You will be compensated for your time for participating.

Qualifications to participate in the study include:

- Between the ages of 55 and 75
- No lower limb surgeries
- No diagnosed arthritis issues in the legs
- Able to ascend/descend stairs without help

If you would like to participate or for more information contact Ms. Hannah Stokes at the Biomechanics and Motion Analysis Lab.
Office: 610-717-8013
Email: hstokes3@uncc.edu

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hstokes3@uncc.edu

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Appendix D: Patient Reported Outcome Measure

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KNEE SOCIETY SCORE: PRE-OP

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

1- Today's date

☐☐ / ☐☐ / ☐☐☐☐

Enter dates as: mm/dd/yyyy

2- Date of birth

☐☐ / ☐☐ / ☐☐☐☐

3- Height (ft' in")

☐ ☐☐

4- Weight (lbs.)

☐☐☐

5- Sex

○ Male ○ Female

6- Side of this (symptomatic) knee

○ Left ○ Right

If both knees will be operated on, please use a different form for each knee

7- Ethnicity

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

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

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

Date

☐☐ / ☐☐ / ☐☐☐☐

Enter dates as: mm/dd/yyyy

Name of Surgeon

☐

9- Will this be a primary or revision knee replacement?

○ Primary ○ Revision

To be completed by surgeon

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

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

4973569407

OBJECTIVE KNEE INDICATORS (To be completed by surgeon)

ALIGNMENT

1- Alignment: measured on AP standing Xray (Anatomic Alignment) **25 point max**

Neutral: 2-10 degrees valgus	(25 pts)
Varus: < 2 degrees valgus	(-10 pts)
Valgus: > 10 degrees valgus	(-10 pts)

INSTABILITY

2- Medial / Lateral Instability: measured in full extension **15 point max**

None	(15 pts)
Little or < 5 mm	(10 pts)
Moderate or 5 mm	(5 pts)
Severe or > 5 mm	(0 pts)

3- Anterior / Posterior Instability: measured at 90 degrees **10 point max**

None	(10 pts)
Moderate < 5 mm	(5 pts)
Severe > 5 mm	(0 pts)

JOINT MOTION

4- Range of motion (1 point for each 5 degrees)

Deductions

Flexion Contracture **Minus Points**

1-5 degrees	(-2 pts)
6-10 degrees	(-5 pts)
11-15 degrees	(-10 pts)
> 15 degrees	(-15 pts)

Extensor Lag **Minus Points**

<10 degrees	(-5 pts)
10-20 degrees	(-10 pts)
> 20 degrees	(-15 pts)

SYMPTOMS

(To be completed by patient)

1- Pain with level walking **(10 - Score)**

0	1	2	3	4	5	6	7	8	9	10
none										severe

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

0	1	2	3	4	5	6	7	8	9	10
none										severe

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

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

Maximum total points (25 points)

PATIENT SATISFACTION

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

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

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

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

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

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

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

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

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

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

Maximum total points (40 points)

PATIENT EXPECTATIONS (To be completed by patient)

What do you expect to accomplish with your knee replacement:

1- Do you expect your knee joint replacement surgery will relieve your knee pain? **(5 points)**

O no, not at all (1 pt)

O yes, a little bit (2 pts)

O yes, somewhat (3 pts)

O yes, a moderate amount (4 pts)

O yes, a lot (5 pts)

2- Do you expect your surgery will help you carry out your normal activities of daily living? **(5 points)**

O no, not at all (1 pt)

O yes, a little bit (2 pts)

O yes, somewhat (3 pts)

O yes, a moderate amount (4 pts)

O yes, a lot (5 pts)

3- Do you expect you surgery will help you perform leisure, recreational or sports activities? **(5 points)**

O no, not at all (1 pt)

O yes, a little bit (2 pts)

O yes, somewhat (3 pts)

O yes, a moderate amount (4 pts)

O yes, a lot (5 pts)

Maximum total points (15 points) ☐

5216569408

FUNCTIONAL ACTIVITIES (To be completed by patient)

WALKING AND STANDING (30 points)

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

○ Yes ○ No

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

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

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

○ other

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

○ Yes ○ No

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

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

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

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

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

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

Maximum points (30 points)

0541569404

STANDARD ACTIVITIES (30 points)

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

Maximum points (30 points)

ADVANCED ACTIVITIES (25 points)

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

Maximum points (25 points)

7470569402

DISCRETIONARY KNEE ACTIVITIES (15 points)

Please check 3 of the activities below that you consider *most important* to you.

(Please do not write in additional activities)

Recreational Activities

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

Workout and Gym Activities

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

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

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

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

Maximum points (15 points) ☐

Maximum total points (100 points) ☐

KNEE SOCIETY SCORE: POST-OP

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

1- Today's date
☐☐ / ☐☐ / ☐☐☐☐

Enter dates as: mm/dd/yyyy

2- Date of birth
☐☐ / ☐☐ / ☐☐☐☐

3- Height (ft' in")
☐ ☐☐

4- Weight (lbs.)
☐☐☐

5- Sex
○ Male ○ Female

6- Side of this (surgically treated) knee
○ Left ○ Right

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

7- Ethnicity
○ Native Hawaiian or other Pacific Islander ○ American Indian or Alaska Native ○ Hispanic or Latino
○ Arab or Middle Eastern ○ African American or Black ○ Asian ○ White

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

Date
☐☐ / ☐☐ / ☐☐☐☐
Enter dates as: mm/dd/yyyy

Name of Surgeon
☐

9- Was this a primary or revision knee replacement?
○ Primary ○ Revision

To be completed by surgeon

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

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

OBJECTIVE KNEE INDICATORS (To be completed by surgeon)

ALIGNMENT

1- Alignment: measured on AP standing Xray (Anatomic Alignment) **25 point max**

Neutral: 2-10 degrees valgus (25 pts)
Varus: < 2 degrees valgus (-10 pts)
Valgus: > 10 degrees valgus (-10 pts)

INSTABILITY

2- Medial / Lateral Instability: measured in full extension **15 point max**

None (15 pts)
Little or < 5 mm (10 pts)
Moderate or 5 mm (5 pts)
Severe or > 5 mm (0 pts)

3- Anterior / Posterior Instability: measured at 90 degrees **10 point max**

None (10 pts)
Moderate < 5 mm (5 pts)
Severe > 5 mm (0 pts)

JOINT MOTION

4- Range of motion (1 point for each 5 degrees)

Deductions

Flexion Contracture **Minus Points**

1-5 degrees (-2 pts)
6-10 degrees (-5 pts)
11-15 degrees (-10 pts)
> 15 degrees (-15 pts)

Extensor Lag **Minus Points**

<10 degrees (-5 pts)
10-20 degrees (-10 pts)
> 20 degrees (-15 pts)

SYMPTOMS

(To be completed by patient)

1- Pain with level walking **(10 - Score)**

0	1	2	3	4	5	6	7	8	9	10

none **severe**

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

0	1	2	3	4	5	6	7	8	9	10

none **severe**

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

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

Maximum total points (25 points)

PATIENT SATISFACTION

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

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

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

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

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

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

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

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

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

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

Maximum total points (40 points)

PATIENT EXPECTATION (To be completed by patient)

Compared to what you expected before your knee replacement:

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

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

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

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

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

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

Maximum total points (15 points) [ ]

FUNCTIONAL ACTIVITIES (To be completed by patient)

WALKING AND STANDING (30 points)

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

O Yes O No

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

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

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

O other

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

O Yes O No

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

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

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

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

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

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

Maximum points (30 points)

5272547316

STANDARD ACTIVITIES (30 points)

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

Maximum points (30 points)

ADVANCED ACTIVITIES (25 points)

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

Maximum points (25 points)

4511547311

DISCRETIONARY KNEE ACTIVITIES (15 points)

Please check 3 of the activities below that you consider *most important* to you.

(Please do not write in additional activities)

Recreational Activities

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

Workout and Gym Activities

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

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

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

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

Maximum total points (100 points)

SF-12 Health Survey

This survey asks for your views about your health. This information will help keep track of how you feel and how well you are able to do your usual activities. **Answer each question by choosing just one answer**. If you are unsure how to answer a question, please give the best answer you can.

1. **In general, would you say your health is**:

□1 Excellent □2 Very good □3 Good □4 Fair □5 Poor

The following questions are about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much?

	YES, limited a lot	YES, limited a little	NO, not limited at all
2. **Moderate activities** such as moving a table, pushing a vacuum cleaner, bowling, or playing golf.	□1	□2	□3
3. Climbing **several** flights of stairs.	□1	□2	□3

During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of your physical health?

	YES	NO
4. **Accomplished less** than you would like.	□1	□2
5. Were limited in the **kind** of work or other activities.	□1	□2

During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)?

	YES	NO
6. **Accomplished less** than you would like.	□1	□2
7. Did work or activities **less carefully than usual**.	□1	□2

8. **During the past 4 weeks, how much did pain interfere with your normal work (including work outside the home and housework)?**

□1 Not at all □2 A little bit □3 Moderately □4 Quite a bit □5 Extremely

These questions are about how you have been feeling during the past 4 weeks.
For each question, please give the one answer that comes closest to the way you have been feeling.

How much of the time during the past 4 weeks…

	All of the time	Most of the time	A good bit of the time	Some of the time	A little of the time	None of the time
9. Have you felt calm & peaceful?	□1	□2	□3	□4	□5	□6
10. Did you have a lot of energy?	□1	□2	□3	□4	□5	□6
11. Have you felt down-hearted and blue?	□1	□2	□3	□4	□5	□6

12. **During the past 4 weeks, how much of the time has your physical health or emotional problems interfered with your social activities (like visiting friends, relatives, etc.)?**

□1 All of the time □2 Most of the time □3 Some of the time □4 A little of the time □5 None of the time

Patient name: Date: PCS: MCS:

Visit type (circle one)
Preop 6 week 3 month 6 month 12 month 24 month Other:________

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?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

2. … when you are sitting on a chair for more than 1 hour?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

3. … when you are walking for more than 15 minutes?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

4. … when you are taking a bath/shower?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

5. … when you are traveling in a car?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

6. … when you are climbing stairs?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

7. … when you are walking on uneven ground?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

8. … when you are standing up from a low-sitting position?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

9. … when you are standing for long periods of time?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

10. … when you are doing housework or gardening?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

11. … when you are taking a walk/hiking?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

12. … when you are doing your favorite sport?

○ never ○ almost never ○ seldom ○ sometimes ○ mostly

Under each heading, please tick the ONE box that best describes your health TODAY.

MOBILITY

I have no problems in walking about	☐
I have slight problems in walking about	☐
I have moderate problems in walking about	☐
I have severe problems in walking about	☐
I am unable to walk about	☐

SELF-CARE

I have no problems washing or dressing myself	☐
I have slight problems washing or dressing myself	☐
I have moderate problems washing or dressing myself	☐
I have severe problems washing or dressing myself	☐
I am unable to wash or dress myself	☐

USUAL ACTIVITIES *(e.g. work, study, housework, family or leisure activities)*

I have no problems doing my usual activities	☐
I have slight problems doing my usual activities	☐
I have moderate problems doing my usual activities	☐
I have severe problems doing my usual activities	☐
I am unable to do my usual activities	☐

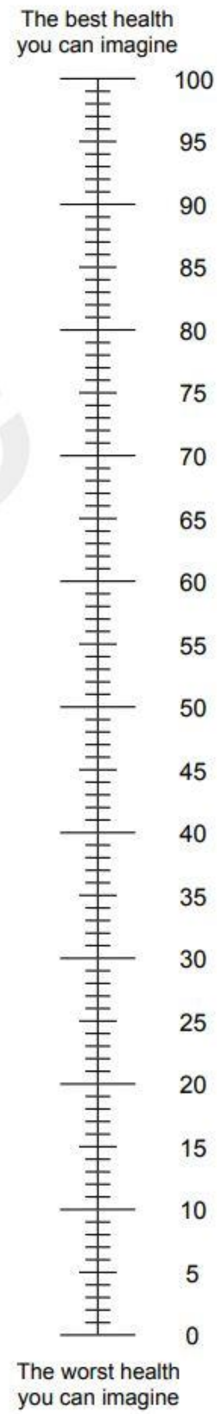
PAIN / DISCOMFORT

I have no pain or discomfort	☐
I have slight pain or discomfort	☐
I have moderate pain or discomfort	☐
I have severe pain or discomfort	☐
I have extreme pain or discomfort	☐

ANXIETY / DEPRESSION

I am not anxious or depressed	☐
I am slightly anxious or depressed	☐
I am moderately anxious or depressed	☐
I am severely anxious or depressed	☐
I am extremely anxious or depressed	☐

- We would like to know how good or bad your health is TODAY.
- This scale is numbered from 0 to 100.
- 100 means the <u>best</u> health you can imagine.
  0 means the <u>worst</u> health you can imagine.
- Mark an X on the scale to indicate how your health is TODAY.
- Now, please write the number you marked on the scale in the box below.



YOUR HEALTH TODAY = [ ]

Height: *Weight:* *Age:* *Time: Pre-OP Post-1-month 6-month*

Left Knee	
Extension Active	
Extension Passive	
Flexion Active	
Flexion Passive	
ROM Active	
ROM Passive	
Right Knee	
Extension Active	
Extension Passive	
Flexion Active	
Flexion Passive	
ROM Active	
ROM Passive	

Left Knee	
Extension Active	
Extension Passive	
Flexion Active	
Flexion Passive	
ROM Active	
ROM Passive	
Right Knee	
Extension Active	
Extension Passive	
Flexion Active	
Flexion Passive	
ROM Active	
ROM Passive	