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Kinematic Analysis of Gait and Deep Knee Flexion for Pre- and Post-Operative Total Knee Arthroplasty

Samantha Collins

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Osteoarthritis (OA) is a form of arthritis that develops in the joint due to overuse and aging causing pain, discomfort, and disability. Total Knee Arthroplasty (TKA) is a surgical procedure performed when OA symptoms are severe with an estimated 600,000 patients in the United States currently receiving TKA. Studies have reported dissatisfaction of the knee for 14-39% of patients. This study collected knee kinematics before and after surgery using stereo radiography for precise measurement of gait and deep knee flexion activities. Results showed healthy knee kinematics were not restored and no significant changes could be seen from OA kinematics in all six degrees of freedom after TKA. An analysis of rotational and translational differences were made across all individual subjects. These results can be used to understand necessary surgical alignment and implant selection for improved patient specific outcomes.

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Kinematic Analysis of Gait and Deep Knee Flexion for Pre- and Post-Operative Total Knee Arthroplasty

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Title: Kinematic Analysis of Gait and Deep Knee Flexion for Pre- and Post-Operative Total Knee Arthroplasty
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1. Chapter One: Introduction

1.1 Introduction:

Osteoarthritis (OA) is a type of arthritis that can present with osteophytes, loss of cartilage, and inflammation in the affected joint. Symptoms can range from asymptomatic to severe with loss of function and pain during daily tasks. OA can present in articulating joints with the risk of knee OA being the most likely with a lifetime risk of 40% and 47% in males and females, respectively [1]. Risk factors that increase the incidence of OA range from age and gender to previous joint health and occupation. With the aging population and obesity epidemic, OA is expected to increase in the population. Females over the age of 60 are reported to have the highest risk; repeated use of the joint, unequal limb length and obesity can add to the likelihood of developing OA in the knee joint. When treatment options of physical therapy and medication no longer relieve symptoms, OA can be treated by arthroplasty.

Total Knee Arthroplasty (TKA) is a surgery performed to repair the damaged parts of the knee joint with implants. OA is the leading cause of TKA and accounts for 94-97% of surgeries performed [2,3]. It is estimated that the number of TKA will increase by 85% to 1.26 million by the year 2030 [4]. This projected increase is correlated to the rise in knee OA cases across the population. The current recipients of TKA report satisfactions between 75 and 92% [5]. With the goal of pain relief and improved function, such variance in satisfaction has resulted in research to understand what areas of TKA need to be improved.

Knee replacement implants can vary for each patient with implant factors like type, size, fixation method and alignment to consider. Studies have been conducted looking at the different implant and alignment combinations to find the kinematic results of the knee joint after surgery. Comparisons of the knee joint kinematics in studies looking at gait or deep knee flexion suggests that the function does not return to normal knee kinematics. However, there have only been few studies looking at both activities of gait and deep knee flexion for each subject in each pre- and post-operative conditions. When both activities are collected it requires the patient to perform movements that can capture the range of motion and function more accurately. When research is completed without looking at the same individual patients for each condition, there cannot be patient specific comparisons and data but rather averages and trends to be compared. Investigating these activities at the same time can provide valuable information on what specific factors of a TKA need to be adjusted for higher and more consistent patient satisfaction.

1.2 Thesis Objectives:

The objective of this thesis is to compare the pre-operative and post-operative knee kinematics for patients with OA receiving a TKA. It is hypothesized in this study that post-operative kinematics will not be significantly different from pre-operative kinematics in all six degrees of freedom. This will be determined by comparison of deep knee flexion, gait, and static standing activities at full extension and flexion. The data will be compared for all six degrees of freedom across averaged and individual pre- and post-TKA conditions.

1.3 Thesis Overview:

The purpose of this thesis is to provide detailed documentation on the results and methods of an original study along with information of previous studies looking at kinematics for TKA. Chapter 2 provides a literature review on topics of knee anatomy, OA, TKA, and review of previous research investigating similar research questions as this thesis. Chapter 3 outlines a study conducted at the University of Denver to analyze kinematic data of the knee joint before and after TKA. Chapter 4 provides concluding remarks to summarize the important findings for this thesis and recommendations for future work.

2. Chapter Two: Literature Review

2.1 Natural Knee Anatomy

The knee is a complex joint that consists of bones, ligaments, tendons, and muscles. It facilitates movement and stability to prevent falling or injury. There are three bones that make up the knee joint which are the femur, tibia, and patella (Figure 2.1). The distal end of the femur connects with the patella and proximal end of the tibia. The femur has medial and lateral condyles that articulate with the tibial plateau [6]. The knee is composed of two joints, the tibiofemoral joint and patellofemoral joint, which accommodate six degrees of freedom (DOF) during movement of the knee joint (Figure 2.2). The six degrees of freedom of the knee joint are broken into three translational movements: Medial-Lateral (ML), Anterior-Posterior (AP), and Superior-Inferior (SI) and three rotational movements: Flexion-Extension (FE), Internal-External (IE), and Varus-Valgus (VrVl). The tibiofemoral joint is classified as a hinge joint and is the region between the distal femur and proximal tibia. The patellofemoral joint is a plane, or gliding, joint between the femur and patella bone. These joints allow the rotations and translations that provide the function necessary for daily tasks.

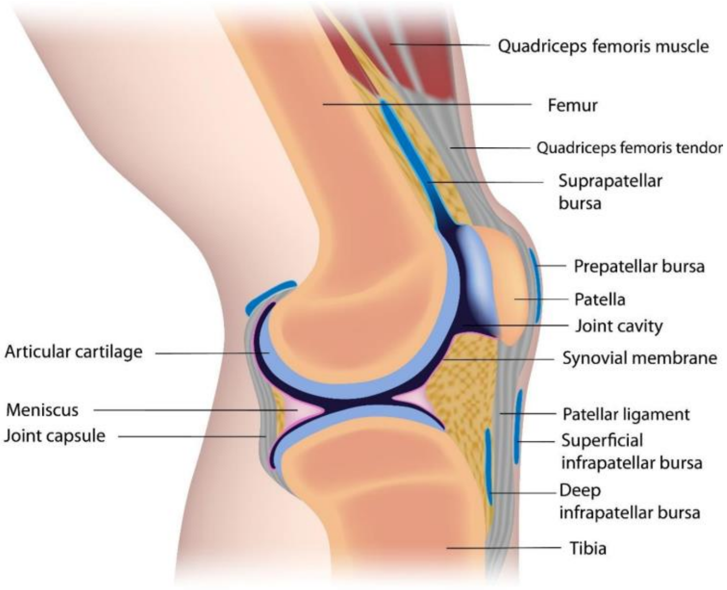


Figure 2.1: Knee Anatomy [7]

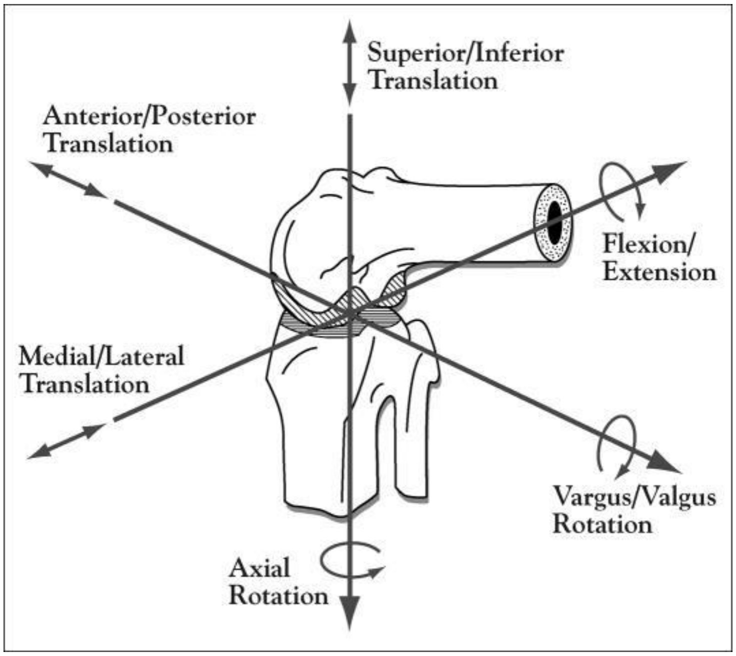


Figure 2.2: Degrees of freedom in the knee joint [8]

Medial translation is defined as movement towards the midline of the body and lateral translation is movement away from the midline. Anterior translation is defined as motion forward in the frontal plane and posterior translation is motion away from the frontal plane. Superior is directed upward, and inferior is downward from the head as seen by the vertical translation line in Figure 2.2. Flexion is defined as the bending motion that reduces the angle in the sagittal plane, whereas the extension is the straightening of the joint into a resting position [9]. The knee joint specifically would be extended during standing and flexed during a seated position. IE (axial) rotation is described when the femur is rotated inwards towards or away from the midline of the body [9]. Varus-valgus can be described by the alignments in Figure 2.3, with varus (bow-legged) rotations having the lateral condyle of the femur move further from the tibial plateau and the opposite for valgus alignments [10].

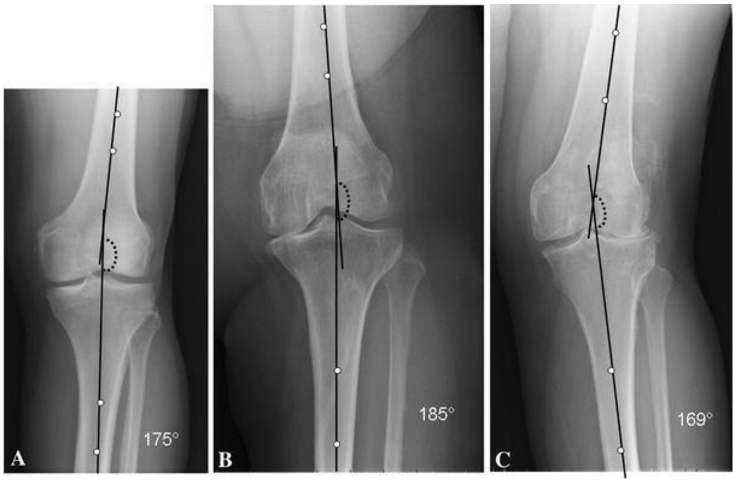


Figure 2.3: Left knee scans of normal (A) varus (B) and valgus (C) [10]

The VrVl rotation is limited to only a few degrees in each direction, but there are also congenital conditions that allow for different permanent alignments in the knee such as varus or valgus alignments. There can still be VrVl rotation with the presence of varus or valgus alignments, however, the function of the joint can be impacted. There are many knee disorders that alter the alignment and ultimately the function of the knee joint.

Understanding the difference between normal knee anatomy and the various disorders is important for understanding the significance of total knee arthroplasties and the role it has on improving knee joint function.

2.2 Osteoarthritis

Arthritis refers to joint tissue disorders that alter the healthy joint anatomy and results from tissue inflammation. Osteoarthritis (OA) is a specific type of arthritis that is caused by overuse and wearing of a joint as people age. OA affects the articulating surface of the joint with the presence of osteophytes, loss of cartilage, and inflammation of the joint. The difference between a normal knee's anatomy and an osteoarthritic knee is seen in Figure 2.4 [11]. OA can occur in all articulating joints, such as hands and hips, with the most common joint being the knee (Figure 2.5). This literature review will focus on OA of the knee joint specifically.

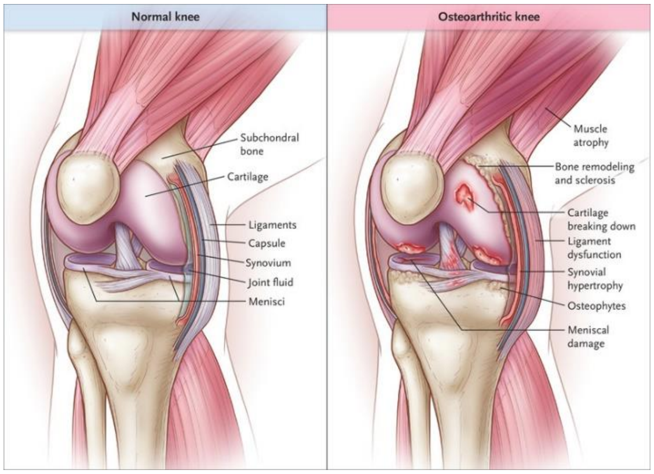


Figure 2.4: Anatomy of normal and OA knee joint [11]

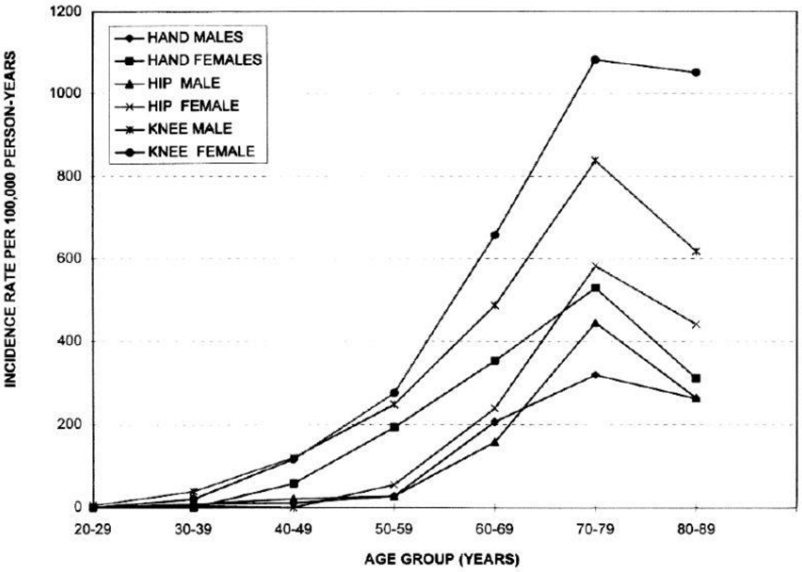


Figure 2.5: OA of hip, knee, and hand joints per gender in age group [12]

It is currently estimated that there are 27 million US citizens with clinical OA, which will continue to grow in the coming years [13,14]. An expected increase in the frequency of this disorder is attributed to the aging population and global obesity crisis [15]. Gender was also identified as a demographic risk factor for OA [16], disproportionately affecting females when compared to males, occurring in 10% and 18% in males and females, respectively [16]. Other risk factors such as joint alignment, muscle strength, and ethnicity have been identified, both inherently unavoidable and modifiable, as showcased in Figure 2.6 [17]. These unavoidable risks are often inherited genetic causes, whereas the modifiable risks can be reduced with a healthy active lifestyle and taking precautions in maintaining good joint health.

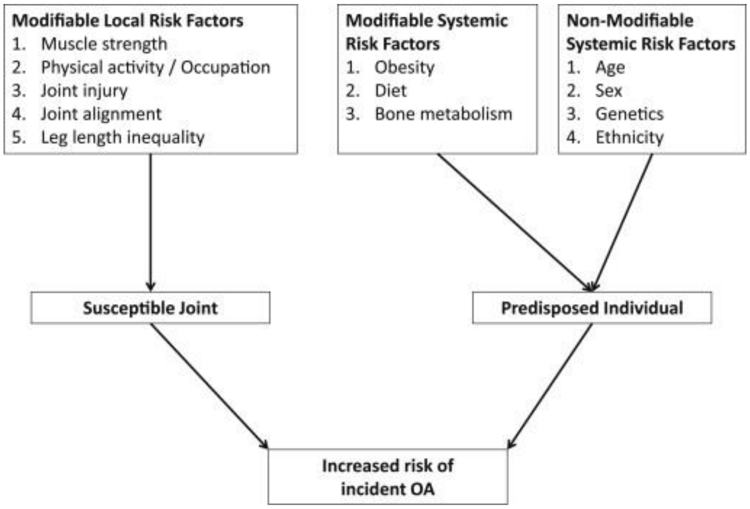


Figure 2.6: Risk factors that impact likelihood of OA [17]

OA is commonly known as a "wear and tear" disorder. Thus, as a result of cartilage degradation and potential femur and tibial bone-on-bone interactions, repeated knee injuries or consistent use without proper recovery can rapidly increase the chances of having OA at an older age. Other avoidable risk factors are obesity, diet, and occupation, which if managed can maintain good joint health. Knee OA has a lifetime risk of 40% and 47% in males and females respectively, which increases by 20% with obesity as a risk factor [1]. The unavoidable risk factors of age and gender make females aged 60 and over the highest risk category of OA [12]. Patients that develop OA can be asymptomatic while others can experience a decline in quality-of-life. OA of the knee can limit movements such as gait and bending of the leg, but pain is primarily managed with physical therapy, medication, and other conservative treatment methods. When conservative treatments fail, OA can be treated with knee arthroplasty surgery.

2.3 Total Knee Arthroplasty

Knee arthroplasties are common surgeries that replace damaged bone with implanted components to improve function and lower pain of the knee joint during normal activities. A Total Knee Arthroplasty (TKA) replaces the entire distal end of the femur and proximal tibial plateau with implants (Figure 2.7). Whereas the partial knee arthroplasty replaces only the medial, lateral, or patella-femoral compartments of the knee joint [18]. TKA is expected to increase by 3.5 million surgeries each year by 2030, with a 143% increase by the year 2050 [19,20,21]. Osteoarthritis is the leading cause for knee replacements and can account for 94 to 97% of TKA surgeries [2,3,22]. The surgery is done only during end-stage arthritis when other treatment options are not available or providing pain relief for patients [2,3]. TKA is the best form of treatment when pain caused by tasks of daily living is severe and functionality of the knee joint is limited. There are a variety of surgical parameters, especially with the implant type and alignment, that vary for each TKA.

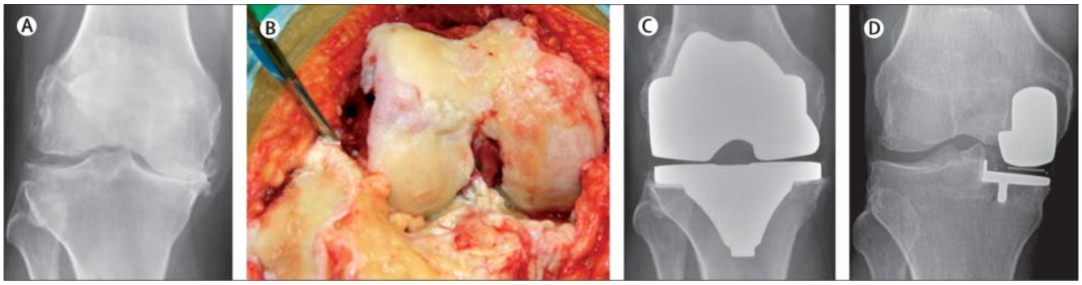


Figure 2.7: OA Knee scan (A), OA Knee anatomy (B), Total Knee Arthroplasty (C), Partial Knee Arthroplasty (D) [18]

2.3.1 Types of Implants

There are many implants that surgeons can use for patients requiring a TKA. The main categories that sperate implants are material, design, and fixation, each of which can affect the outcome of the surgery. The resected tibial and femoral bone is replaced with an implant that is made of metal. These are often referred to as the tibial tray and femoral components. A plastic spacer between the femur and tibia is used to replace the function of the cartilage and prevents metal contact for smooth interactions during movement (Figure 2.8) [23].

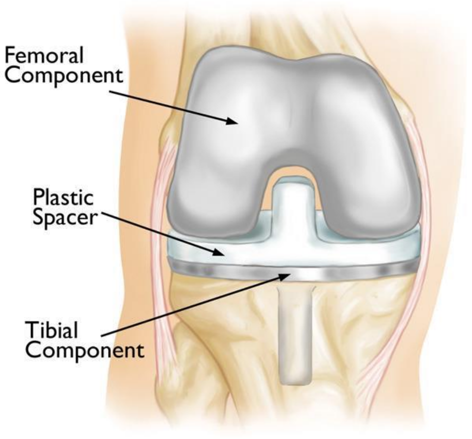


Figure 2.8: Components that make up TKA implant [23]

Both the tibial tray and femoral components are made of titanium or cobalt-chromium alloy, which is durable for the loading conditions of the knee joint and biocompatible with a polyethylene spacer to prevent metal component interaction and enable smooth movements [23]. These components are implanted and fixed into the prepared bone by methods of cementless, cemented or hybrid techniques. Cemented fixation uses a polymethylmethacrylate bone cement to secure the implant to the bone. Cementless implants have a rough and porous exterior that encourages bone on-growth to promote fixation and osteointegration (Figure 2.9). Finally, hybrid fixation uses a combination of both cemented and cementless fixation techniques to secure the metal implants to the prepared bone. Hybrid fixation uses cemented fixation for one component while cementless fixation is used on the other component.

Figure 2.9: ATTUNE Cementless Knee System (left) ATTUNE Cemented Knee System (right)

There are sufficient implant options for any fixation techniques that the surgeon chooses, however, debate still exists around the optimal method of fixation. Cemented fixation has been the gold standard for implantation with historic performance of low revision rates related to short- and long-term implant loosening compared to the cementless fixation. Both fixation methods have the ability to deliver antibiotics and limit chances of infection which could lead to revision surgery along with prevention of osteolysis [25,26,27]. For specific patients, cementless fixation can be more reliable in longer lifespans of implant components. Studies have found that younger patients with faster bone regeneration, active lifestyles or obesity can benefit from cementless fixation [28]. In some studies, the survivorship of cemented implants were shown to be reduced over time while the survivorship of cementless implants stabilize two years after surgery (Figure 2.10) [28,29,30].

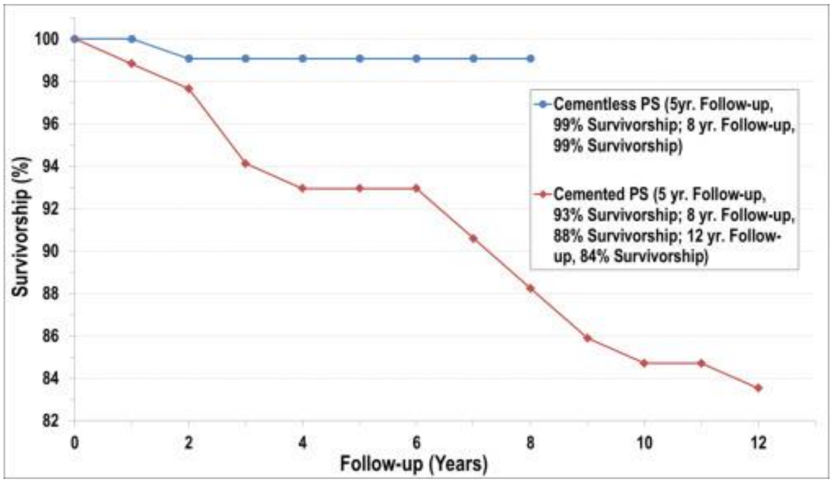


Figure 2.10: Lifespan of Implant for cemented and cementless fixation [28]

The type of implant used is primarily based on the surgical approach and remaining ligaments in the knee joint. Two common types of implants are Posterior-Stabilized (PS) and Cruciate-Retaining (CR), which each have different design elements to accommodate the posterior cruciate ligament (PCL). In cases where the PCL is healthy enough to stabilize the knee, CR implants can be used. Use of a CR implant only requires surgical removal of the ACL [23]. On the other hand, PS implants are used in cases of severe deformity, insufficient ligaments, and history of trauma and surgeries [31]. The PS includes a cam and spine mechanism to replace the role of ligaments (Figure 2.11) [23]. Despite the geometrical and design differences between CR and PS implants, there are still advantages and disadvantages to using both such as implant stability, ligament balancing, and post-operative kinematics (Figure 2.12) [31]. Furthermore, while the PS and CR implants both have advantages after TKA, there is no significant difference in studies looking at the functionality, survival of implant, and range of motion to determine a superior design type for TKA [31]. These implant factors of implant design, size, fixation, and material can all impact the function and stability of the joint which can directly impact post-operative patient satisfaction outcomes.

Figure 2.11: Posterior-stabilized (left) and Cruciate retaining (right) designs [23]

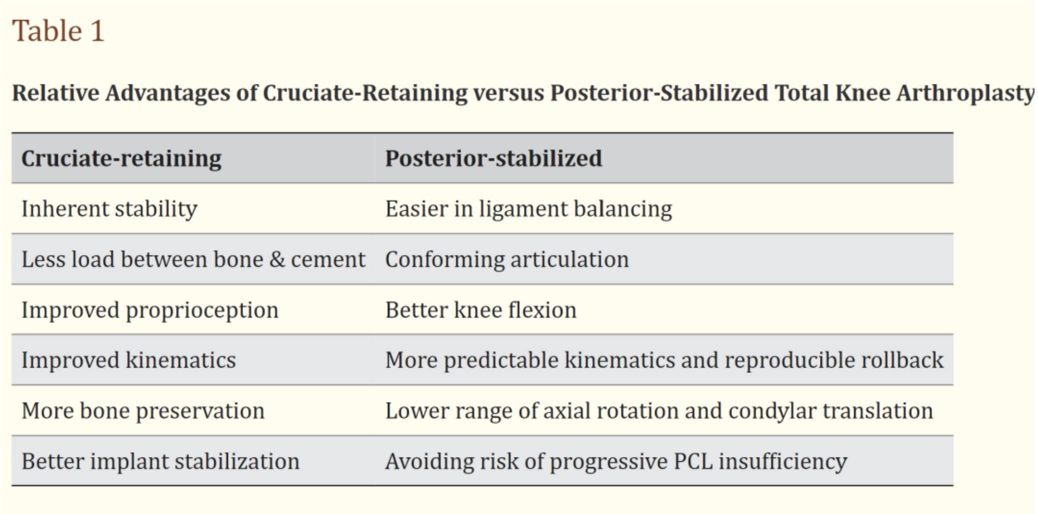


Table 1

Relative Advantages of Cruciate-Retaining versus Posterior-Stabilized Total Knee Arthroplasty

Cruciate-retaining	Posterior-stabilized
Inherent stability	Easier in ligament balancing
Less load between bone & cement	Conforming articulation
Improved proprioception	Better knee flexion
Improved kinematics	More predictable kinematics and reproducible rollback
More bone preservation	Lower range of axial rotation and condylar translation
Better implant stabilization	Avoiding risk of progressive PCL insufficiency

Figure 2.12: Table for comparing advantages between CR and PS TKA implants [31]

2.3.2 Alignment of Implants

Once an implant type is selected, the surgeon must align the tibial tray and femoral component in the joint. There are a few alignment techniques that surgeons can choose from, but there is not a gold standard for alignment of implants during TKA. Every patient has different anatomical alignments and conditions. Thus, it is not yet known which method produces the best results, restoring the alignment for more standard loading conditions or keeping the natural alignment within the safe zone. Patient specific, systematic and hybrid techniques can be used when implants are aligned to either correct or restore this alignment based on surgeon preference. Specifically, these include anatomic (AA), mechanical (MA), adjusted mechanical (aMa), kinematic (KA), or restricted kinematic (rKA) alignment techniques as seen in Figure 2.13 [32].

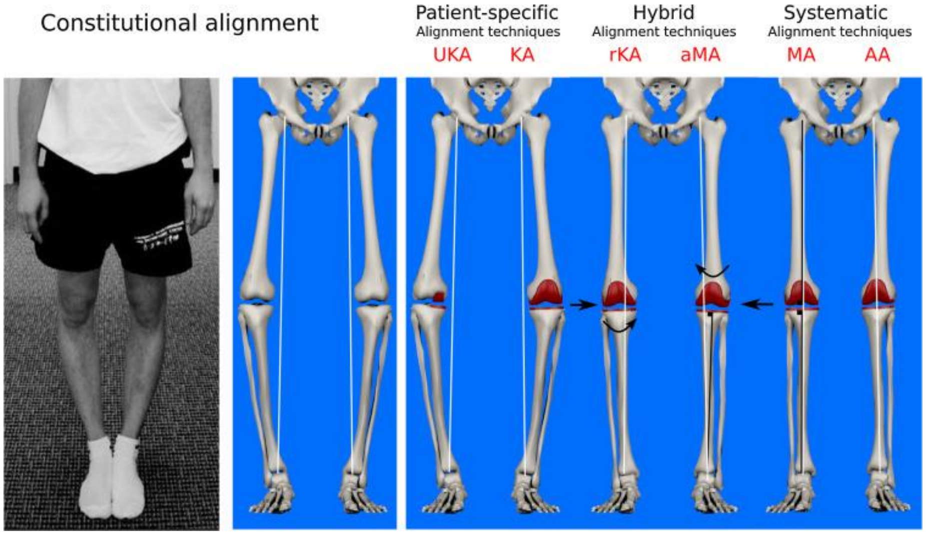


Figure 2.13: Knee joint alignment techniques [32]

MA does not restore patient specific alignments and instead aims for a systematic alignment between the femoral and tibial implants with equal positioning around the joint line. This is done with the tray and femur component implanted perpendicular to the mechanical axis in the frontal plane. Surgeons frequently use MA alignments on the tibia to protect the medial tibia from excess loading and allowing for even distribution of weight. The AA technique uses a systematic approach that offsets the joint line from the mechanical axis by an average 3° varus cut on the tibia and 3° valgus cut on the femur to match the average patient joint line [33]. There is also the aMA technique that was adopted from MA but under-corrects the frontal VrVl deformity and is a better technique for knees with varus-valgus deformities [32]. The tibia will remain mechanically aligned while the femur is adjusted to preserve some deformity with severe sections reduced [32]. The KA and rKA techniques strive to keep as much of the native joint alignment as possible and preserve the ligaments. The KA technique is good for patients that do not have severe deformities thus needing less preoperative planning. When patients have more severe deformities of the coronal limb, rKA is the best option [32]. This technique uses bone cuts that align the implants within a safe zone of alignment while keeping as much of the natural alignment as possible [34].

The different alignment techniques between MA and KA have resulted in different implant alignments but both have returned relatively low complication rates [32]. Complications of alignment, loading, and implant survivorship can arise in patients when ligaments around the knee are not balanced properly during the alignment of implants.

Misalignment of implants is a common cause for revision surgery due to symptoms of instability or implant facture after TKA [35]. Revision surgery is a second surgery that can address issues that have arisen from the initial TKA with work being done to resurface the bone and replace the implants. Other complications to cause the need for revision can include implanted component wear, aseptic loosening, instability, or infection. With the evolution of TKA there are fewer revisions required, however younger patients or patients receiving partial replacements have a higher percentage of revisions after surgery [36,37,38,39].

2.3.3 Patient Reports Outcome Measures

Complications requiring revision surgery, along with general post-operative complications as discussed in this literature review, can directly impact the patient’s satisfaction with their TKA. Patient satisfaction is measured primarily through surveys that ask patients to rank the ability to complete tasks, functionality for specified activities and improvement of pain relief [5,40,41]. When pain relief and ease of completing specified tasks were analyzed, it was found that patient satisfaction ranged from 75% to 92% [5]. Surveys for pain and function directly showed that pain relief and functionality varied from 72-86% and 70-84%, respectively [40]. Simple movements, like standing or walking, resulted in higher satisfaction than complex movements such as going up and down stairs, kneeling and squatting [40,41]. These complex movements require more loading and flexion of the knee which could be compromised for TKA patients [40,41].

Factors including age, previous health conditions, and rehabilitation after surgery can affect post-operative performance and consequently the level of patient satisfaction. Although the level of patient satisfaction is uncertain for arthroplasties due to these factors, with the expected increase in TKA volume there is a need for more reliable outcomes of functionality and pain relief to improve satisfaction. Surveys are a great way to measure pain relief after implantation, however, functionality and range of motion after surgery can be tested in a multitude of ways. Function can be directly measured with indications for areas of improvement using a variety of methods. Specifically, the functional improvement for TKA can be assessed by looking at implant factors such as type, size and fixation method. While function can be measured directly, surveys for patient satisfaction infrequently correlate with function. This is due to patient’s perceptions on how they believe they are doing and can have variability or bias present in results while function is a consistent measurement between individuals. Measuring knee kinematics to quantify the functional outcome of TKA can give specific results to improve patient specific care in regard to TKA and severe OA.

2.4 Methods of Measuring Knee Joint Kinematics

Measuring knee kinematics is an essential step towards understanding variations between healthy natural knee anatomy, arthritic knees, and implanted knees. When studying kinematics, coordinate systems are assigned to each bone to describe the relative position between them. Specifically, TKA can have knee kinematics recorded to quantify the outcome of the surgery and the patient’s improvement in functionality from pre-operative conditions. Several methods are used to measure 6-DOF knee movement that can be used for further analysis. Collecting knee kinematics can be done through tracking bone pins, motion capture, and bi-plane fluoroscopy.

2.4.1 Bone Pins

Intra-cortical bone-pins are a method of measuring the femoral and tibial kinematics using surgically placed pins that have either passive or active markers attached. The markers attached to the outside of the bone pins are used to form a connection between the bone, pins, and markers during imaging by the camera system (Figure 2.14-2.15) [42,43]. High speed cameras can be placed in the collection environment to record movement of the pins and provide the kinematic relationship between the bones and joints of interest. This is the optimal method for tibiofemoral joint kinematic data collection as the markers are placed in the exact landmarks needed for data collection, without any interference of misplaced markers, extra movement during activities, or markers falling off during collections. However, this method is not commonly used in vivo because of the need for the bone pins to be placed surgically. Instead, this method is commonly used to collect true kinematic data during cadaveric testing, intraoperative computer assisted and robotic surgery for high accuracy results as the markers are set in exact locations of interest.

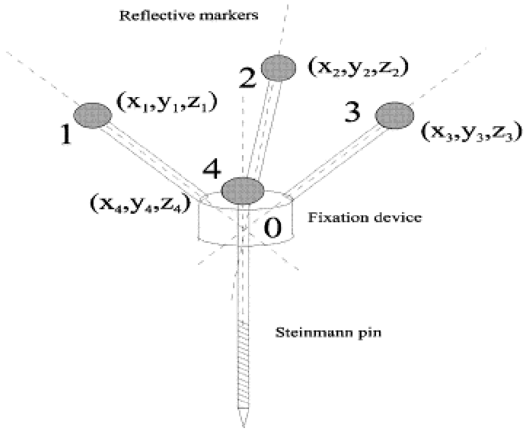


Figure 2.14: Diagram of bone pin with markers attached [42]

Figure 2.15: Bone pins after insertion in the leg [43]

2.4.2 Motion Capture

Motion capture kinematics are recorded using small infrared-reflecting marker beads similar to those attached to the exterior of the pins in bone-pin tracking. These markers are attached to the skin using removable adhesive approximately where bone landmarks of interest are located. The markers are captured by a cluster of infrared cameras that triangulate the kinematics in a 3D space. This method is safe and easier for subjects to participate in, however, there is less accuracy compared to bone-pin kinematics. With respect to tibiofemoral joint kinematics, the skin under markers were shown to produce less accuracy for motion capture compared to bone-pin tracking [44]. Specifically, the rotation and translation of the knee can have an error up to 4.4° of rotation and 13mm of translation during walking as found in a study by Benoit et al. [44]. Error of this magnitude makes marker motion capture not an ideal method for kinematic data of the joint due to the extra tissue movement, markers falling off during data collection, and inconsistent placement between subjects of the markers on the skin. However, it remains widely used in research as the trends and comparisons can still be measured within reason.

2.4.3 Biplane Radiography

High-Speed Stereo Radiography (HSSR) uses a pair of offset cameras to capture static or dynamic joint motions over a series of frames. Geometries are created for objects of interest, such as bones and implants, and assigned coordinate systems. These geometries and coordinate systems are used to recreate the objects in 3D space by matching digitally reconstructed radiographs (DRR) of bones or implants of interest with the 2D images collected from the X-rays. Biplane radiography is helpful in the kinematic analysis of motions such as gait and deep knee flexion activities. A specific apparatus for HSSR was developed for measuring joint motion with sub-millimeter accuracy in 6 degrees of freedom (Figure 2.16) [45].

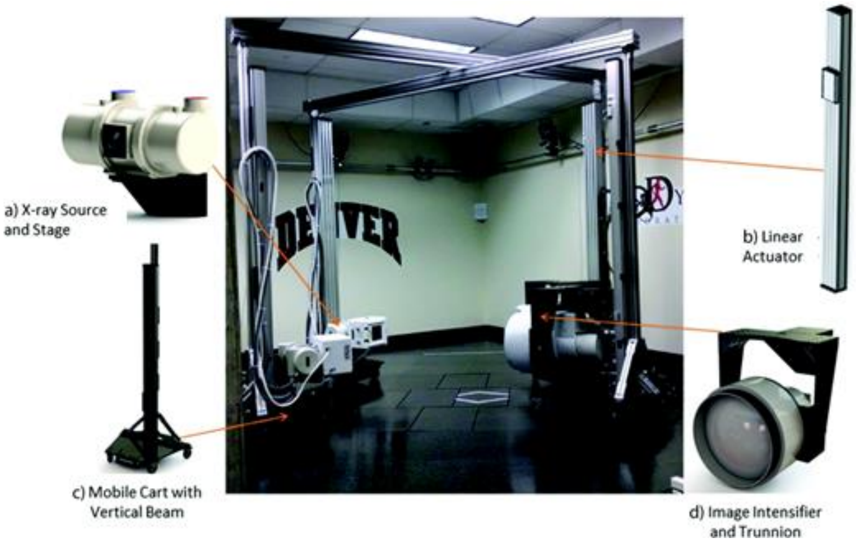


Figure 2.16: HSSR apparatus components and set up at the University of Denver [45]

The HSSR system is configured to allow for subject-specific alignment in the field of view of both cameras. Similar to previous radiography systems, the HSSR collects data at high speeds (100Hz) and resolution while having low radiation emitted due to its ‘pulsing radiography’ method [45]. Capturing knee kinematics, the HSSR error of 0.2mm and 4° for bone tracking in translation and rotation, respectively was reported [45]. This accuracy makes HSSR one of the most accurate methods of data collection for joint kinematics outside of bone pins. A disadvantage of this method is that it requires a longer setup time for system calibration and the bones require manual tracking after collection. However, with the high accuracy, there can be fewer subjects and trials required for collection since the data processed will yield lower standard deviations and errors.

Specifically, studies looking at pre- and post-operative TKA can use this method to track native bone and implants for accurate measurement of 6 DOF kinematics.

2.5 Kinematic Results of TKA

Previous studies have been conducted to better understand relationships between knee kinematics and TKA outcomes. Previous work in this space can provide insight into anticipated changes in knee kinematics from the current study. Each previous study reviewed has unique experimental setups, movements, and TKA procedures that make interstudy comparisons difficult. Differences between studies include the activities measured and post-processing of the kinematic data. However, the trends and findings in each paper provide insight to consider for improved study designs.

2.5.1 Normal Kinematics of the Knee Joint

To restore normal knee function with TKA, it is important to quantify healthy knee kinematics. Gale et al. analyzed gait mechanics for healthy subjects during treadmill walking to find the average range of motion (ROM) of the knee joint using HSSR (Figure 2.17) [46]. This study enrolled younger subjects than typically seen among TKA patients (i.e., 60-70 years old) [48]. This younger patient population can serve as a comparison for post-TKA kinematics as the likelihood of any underlying conditions or abnormalities is low.

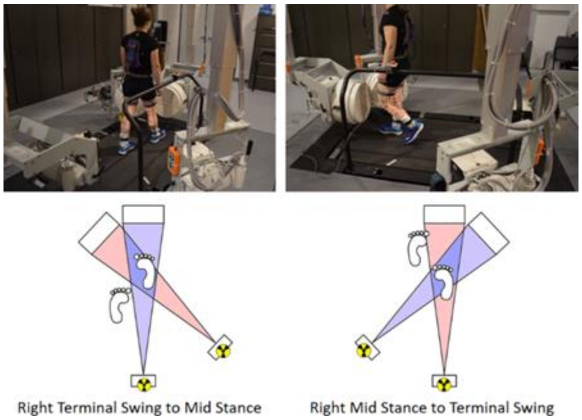


Figure 2.17: Biplane radiography angled to capture full gait movement [46]

The findings from Gale et al. show the average range of motion during gait for 39 healthy subjects was 3.2mm, 7.0mm and 2.9mm in ML, AP, and SI translations, respectively. The rotational kinematics were also found to be 67.3°, 11.5°, and 3.7° in the FE, IE and VrVl directions, respectively. These ROM values for healthy subjects are important for having baseline numbers and ranges to compare kinematic data of pathologic joints. The study also found the ROM to be smaller in all degrees of freedom during stance phase (Figure 2.18) [46]. Having a large population of subjects is helpful in normalizing the trends, however the age and BMI is not ideal for comparison to OA patients.

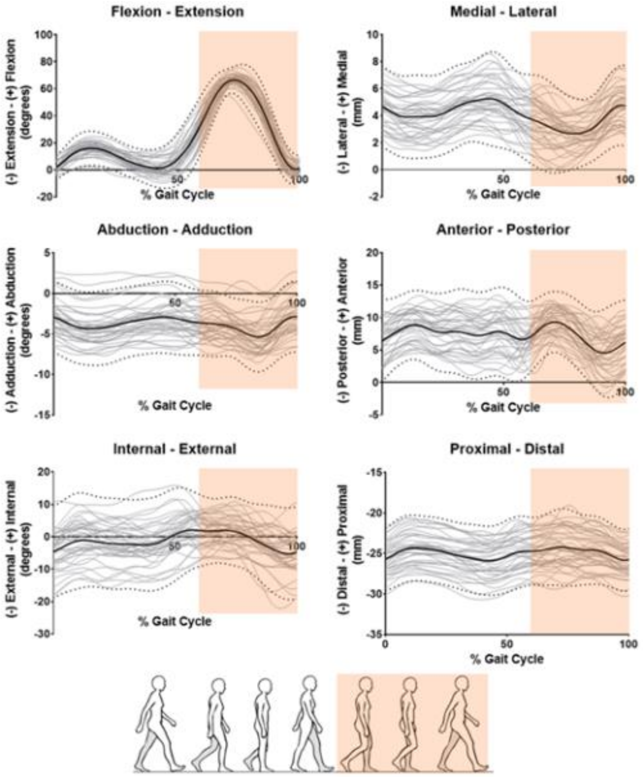
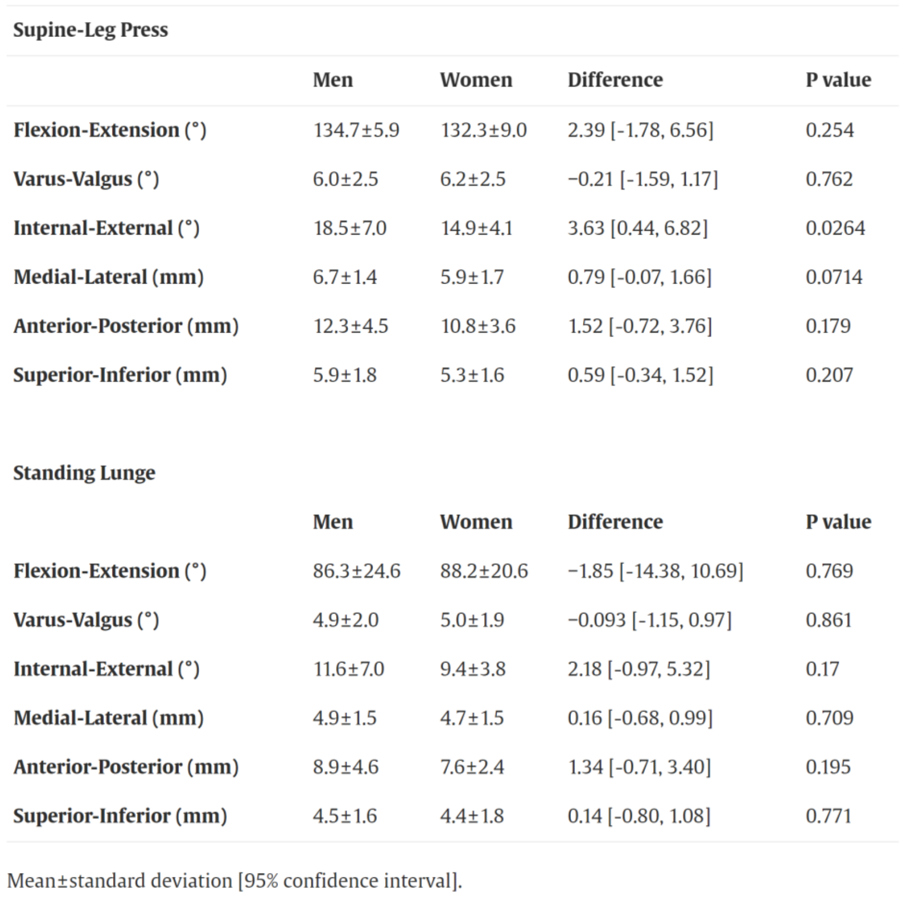


Figure 2.18: Results of rotation and translation degrees of freedom normalized from heel strike to toe off [46]

Another study measured age matched subjects to the TKA patient population. Hamilton et al. used 53 healthy participants during activities of supine leg press and a standing lunge captured by HSSR imaging [47]. The goal of this study was to verify the leg press captures the same knee ROM as the standing lunge activity. While the purpose of this study was to validate a complementary activity to lunging; the data provided a large cohort of healthy knee kinematics for all 6-DOF that use subjects similar to the age of individuals receiving a TKA. The averages between male and female participants for each translation and rotation were compared and shown in Figure 2.19 below [47].



Supine-Leg Press

	Men	Women	Difference	P value
Flexion-Extension (°)	134.7±5.9	132.3±9.0	2.39 [-1.78, 6.56]	0.254
Varus-Valgus (°)	6.0±2.5	6.2±2.5	−0.21 [-1.59, 1.17]	0.762
Internal-External (°)	18.5±7.0	14.9±4.1	3.63 [0.44, 6.82]	0.0264
Medial-Lateral (mm)	6.7±1.4	5.9±1.7	0.79 [-0.07, 1.66]	0.0714
Anterior-Posterior (mm)	12.3±4.5	10.8±3.6	1.52 [-0.72, 3.76]	0.179
Superior-Inferior (mm)	5.9±1.8	5.3±1.6	0.59 [-0.34, 1.52]	0.207

Standing Lunge

	Men	Women	Difference	P value
Flexion-Extension (°)	86.3±24.6	88.2±20.6	−1.85 [-14.38, 10.69]	0.769
Varus-Valgus (°)	4.9±2.0	5.0±1.9	−0.093 [-1.15, 0.97]	0.861
Internal-External (°)	11.6±7.0	9.4±3.8	2.18 [-0.97, 5.32]	0.17
Medial-Lateral (mm)	4.9±1.5	4.7±1.5	0.16 [-0.68, 0.99]	0.709
Anterior-Posterior (mm)	8.9±4.6	7.6±2.4	1.34 [-0.71, 3.40]	0.195
Superior-Inferior (mm)	4.5±1.6	4.4±1.8	0.14 [-0.80, 1.08]	0.771

Mean±standard deviation [95% confidence interval].

Figure 2.19: ROM averages for translation and rotation of healthy age matched cohort for TKA comparison.

2.5.2 Osteoarthritic Kinematics

Many studies analyze knee kinematics when patients had severe OA prior to TKA surgery. Patients that have OA of the knee generally belong to an older age range with a higher BMI than healthy individuals. The pre-operative kinematics of the joint vary for each patient as the inflammation and pain can affect translations and rotations in relation to healthy joints. However, there is still differentiation between the stages of OA severity that is based on the age of the patient, joint health and can continue to progress after diagnosis. Understanding the different kinematic patterns for varying levels of OA can give insight into how functionality reduced with disease progression.

A study by Nagano et al investigated gait variability between three stages of OA (early, moderate, and severe) with comparisons between the groups and a controlled (healthy) group [48]. The different stages of OA for these groups are determined by the symptoms and changes in joint anatomy. Early-stage patients have recently been diagnosed with little inflammation and without the presence of osteophytes, whereas severe patients have large inflammation and osteophytes present with pain that is hard to manage. The study collected data for angular displacements of the knee, muscle strength, and ROM using a motion capture system. Nagano et al. found that knee flexion and abduction was smaller in the severe group than the control group. The moderate group also showed significantly smaller flexion than the healthy control group (Figure 2.20, [48]).

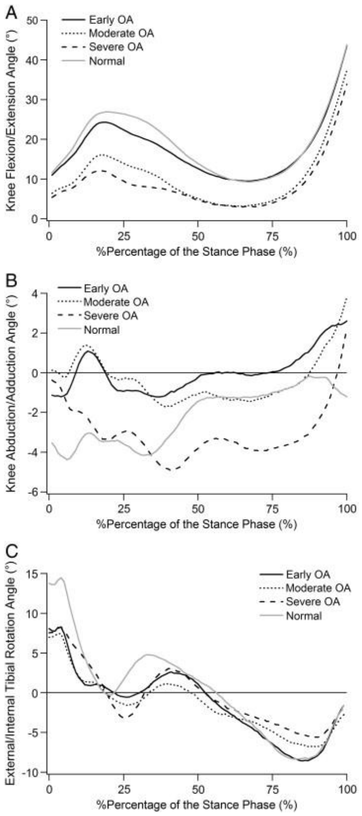


Figure 2.20: Comparison between OA groupings and normal for rotational degrees of freedom during stance phases of gait (A) Flexion-Extension (B)Abduction-Adduction (C) External-Internal [48]

These results are as expected with the severe group having large differences in rotations compared to healthy individuals. A significant finding from this study is the early group having kinematic data that is most like the healthy and a big jump in differences for the moderate [48]. These findings suggest that improved function and pain reduction can be achieved with kinematics closer to early-stage groups than only healthy values.

The data by Nagano et al. is valuable to make relationships between each stage of OA to the function; it can also provide information on if early OA kinematics can be reached when symptoms of pain and functionality are not as severe following TKA rather than kinematic values seen by healthy groups. Using these values, researchers and medical professionals have a baseline on typical OA stages and can aid in classifying the severity of each individual diagnosis and the progression.

2.5.3 Kinematics of Pre- and Post-Operative TKA

Pre- and post-operative studies have been conducted to compare differences in kinematics for patients before and after surgery. These studies use cohort data from OA and post-surgical participants that are not consistent between patients. The data collected in each condition for one study can allow for comparison and a measurement of improvements in function for specified activities. Each study has a unique protocol that can provide advantages and disadvantages for interpretations of the results. A significant takeaway for this literature review is the results of previous studies analyzing patient outcomes pre- and post-TKA to understand which factors need to be examined further for improved patient outcomes.

A common motion for the knee joint is a deep knee bend that is used in daily tasks like stair ascent, sitting and lunges. Deep knee bend movements can be affected by the symptoms of OA and demonstrate changes in maximal knee flexion after TKA. Yue et al. looked at a deep knee bend activity for Posterior Cruciate Retaining TKA (CR-TKA) with patients that had medial compartment OA [50]. The experiment used biplane fluoroscopy (Figure 2.21) to capture weight bearing quasi-static knee bending from full extension to flexion at 15° increments [50].

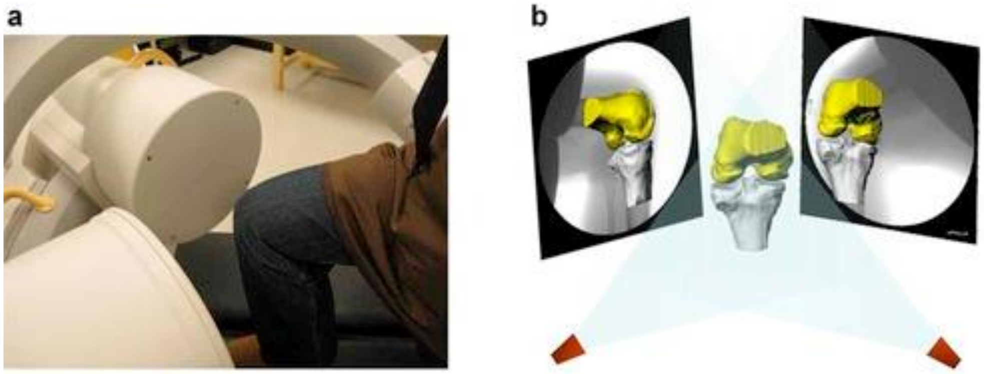


Figure 2.21: (A) Set up of radiography for patient lunging activities (B) View of femur and tibia from angle of cameras [50]

Three groups consisting of healthy, OA and post-TKA subjects were collected. Differences in IE and VrVl knee rotations and ML and AP knee translations were calculated between groups. In summary, the CR-TKA kinematics did not restore healthy kinematics in any degree of freedom. Knee I–E rotations were more similar between the OA and healthy cohorts than the TKA cohort, with less internal tibial rotation during flexion after TKA (Figure 2.22) [50]. The OA and healthy groups had the femur located medially to the tibia, while the femur tracked more laterally after CR-TKA (Figure 2.23) [50]. This suggests that the alignment was adjusted during TKA across all subjects in the lateral direction. While these findings are valuable, dynamic lunging was not collected (only quasistatic positions) and there was no investigation into the actual implant kinematics for post-operative data, just the relative position of the native bones.

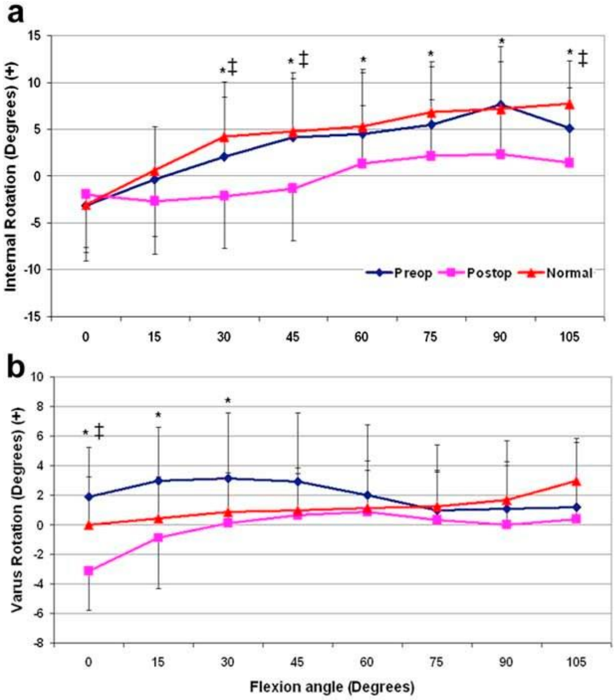


Figure 2.22: (A) Internal rotation of each group during flexion with preop and Normal groups having similar values (B) Varus rotation during flexion with all groups having similar values during high flexion [50]

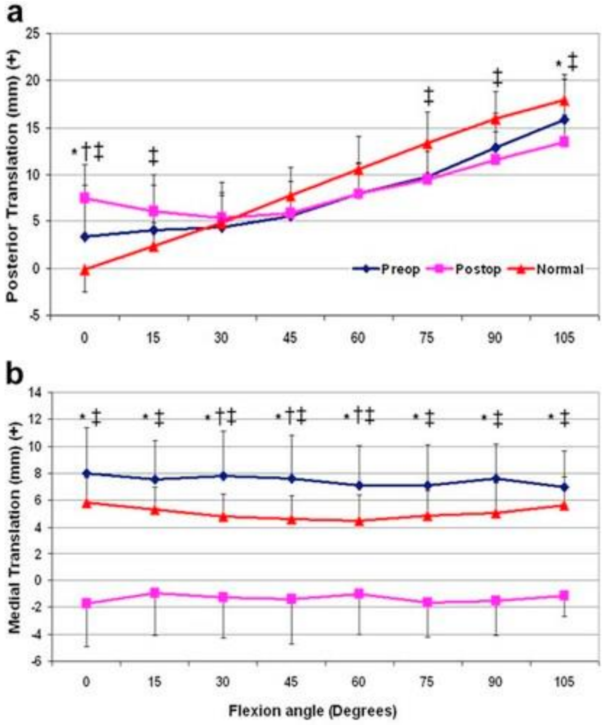


Figure 2.23: (A) Posterior translation for all groups during flexion showing close results between preop and postop categories (B) Medial translation during flexion with postop values different from other categories [50]

Another study analyzed deep knee flexion pre- and post-operatively in subjects implanted with a “flexion-enhanced” CR-TKA [51]. Subjects in the study underwent TKA for medial OA with varus knee deformities to understand if flexion was improved after surgery. Results of this study were pre-operative kinematics persisted during post-operative translations and rotations for all degrees of freedom [51]. The key finding was that subjects achieved the same average 130° of maximum flexion after TKA, but the contact position was more posterior after surgery, particularly in early and mid-flexion (Figure 2.24-2.25) [51].

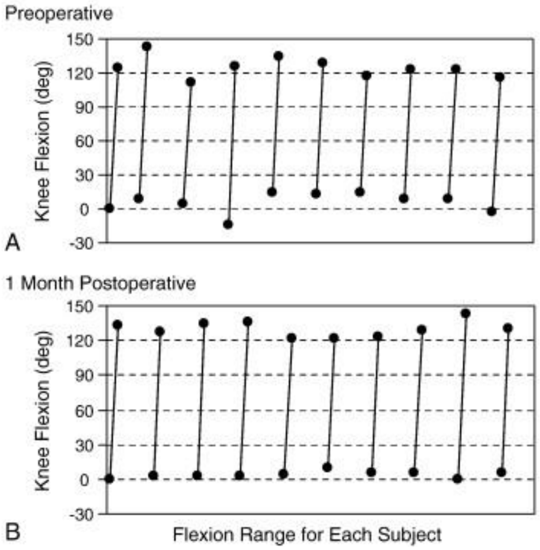


Figure 2.24: (A) Preoperative maximum and minimum flexion angles for each subject (B) Postoperative range of flexion for each subject which retained maximum angles from preoperative data [51]

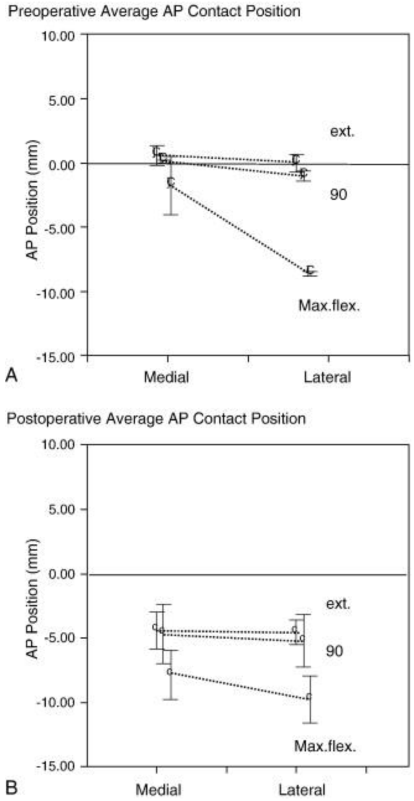


Figure 2.25: (A) Medial and lateral AP preoperative positioning (B) AP positioning postoperatively that has shifted posteriorly compared to preoperative contact [51]

Deep knee lunge is only one approach to finding knee kinematics for TKA; another activity that is often investigated is gait. Gait can be compared between pathological groups to the normal knee and is an activity that can be reliably done for subjects that have severe pain. Even with the variety of gait patterns in pathological conditions (e.g. stride lengths, paces, loading, ROM, etc.) gait patterns after TKA were consistent with patterns prior to surgery. In a study by Levinger et al., TKA patients walked on a 12-meter walkway for comparison of the hip, knee, and ankle joints to an age matched control group using motion capture cameras [52]. Stride length, cadence and speed of gait trials were significantly smaller than the control group and persisted over time [52]. There is not a specific cause for these differences in results, however, it suggests that there is a reduction in the functionality due to the pain and inflammation. While there is a higher peak flexion moment in the knee joint, no major kinematic differences could be seen pre- and post-operatively for the knee specifically (Figure 2.26) [52]. The most important findings were that the ankle joint had the largest kinematic changes after TKA. This suggests that studies viewing only the knee joint may not be collecting all the necessary information to understand the difference in functionality and the possibility the gait prior to the onset of OA cannot be captured with severe OA due to compensation by other joints.

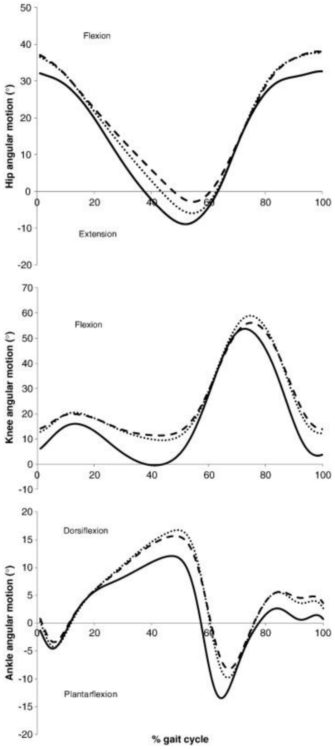
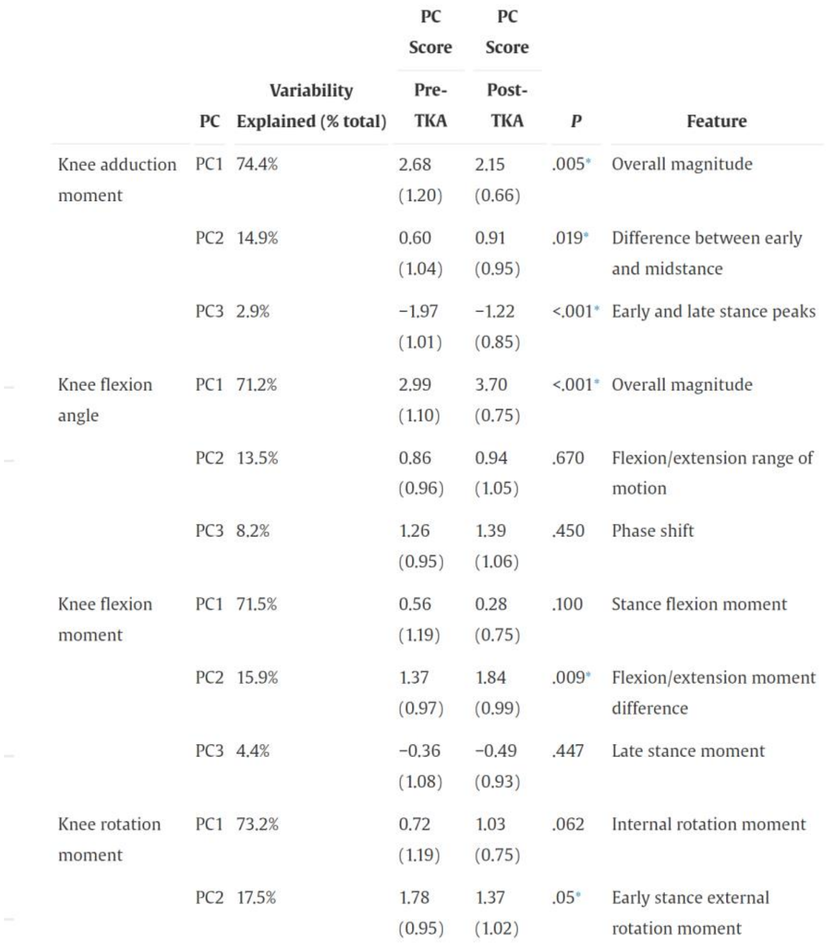


Figure 2.26: Hip, knee, and ankle rotation during normalized gait trials. No difference seen between pre-operative (dashed line) and post-operative (dotted line) flexion-extension in the knee [52]

Hatfield et al. also studied variability in gait waveforms from TKA patients [53]. They performed a Principal Component (PC) analysis to show differences in knee moments and flexion angles pre- and post-TKA; each PC is described in Figure 2.27 [53]. The difference in PC scores pre- and post-operatively can be used to explain which features of gait contribute to the variability.



	PC	Variability Explained (% total)	PC Score Pre-TKA	PC Score Post-TKA	*P*	Feature
Knee adduction moment	PC1	74.4%	2.68 (1.20)	2.15 (0.66)	.005*	Overall magnitude
	PC2	14.9%	0.60 (1.04)	0.91 (0.95)	.019*	Difference between early and midstance
	PC3	2.9%	−1.97 (1.01)	−1.22 (0.85)	<.001*	Early and late stance peaks
Knee flexion angle	PC1	71.2%	2.99 (1.10)	3.70 (0.75)	<.001*	Overall magnitude
	PC2	13.5%	0.86 (0.96)	0.94 (1.05)	.670	Flexion/extension range of motion
	PC3	8.2%	1.26 (0.95)	1.39 (1.06)	.450	Phase shift
Knee flexion moment	PC1	71.5%	0.56 (1.19)	0.28 (0.75)	.100	Stance flexion moment
	PC2	15.9%	1.37 (0.97)	1.84 (0.99)	.009*	Flexion/extension moment difference
	PC3	4.4%	−0.36 (1.08)	−0.49 (0.93)	.447	Late stance moment
Knee rotation moment	PC1	73.2%	0.72 (1.19)	1.03 (0.75)	.062	Internal rotation moment
	PC2	17.5%	1.78 (0.95)	1.37 (1.02)	.05*	Early stance external rotation moment

Figure 2.27: Table outlining different angles and moments with PC features defined, p-values, and variability due to corresponding PC [53]

The results of this study differ from those previously discussed in that the pre- and post-TKA data had significant differences which were indicated by p-values below 0.05. Differences were observed in knee adduction, flexion, and rotation moments, along with knee flexion angle [53]. Knee adduction moment results described the changes post-operatively for overall magnitude (PC1), difference between early and midstance in gait (PC2), and difference in early and late stance peaks of the gait cycle (PC3). This study observed that after TKA patients had a lower PC1 indicating a decreased adduction moment in a majority of the stance phase (Figure 2.28) [53]. It was also determined that there was a larger unloading during midstance than early stance as seen by the higher PC2 post-operatively than pre-operatively. These PC scores and waveforms provide detailed results on specific features of gait in each subject. The changes in PC scores are significant in identifying where large differences occur to help pinpoint what features could be driving the limited function and furthermore used in comparisons with other studies.

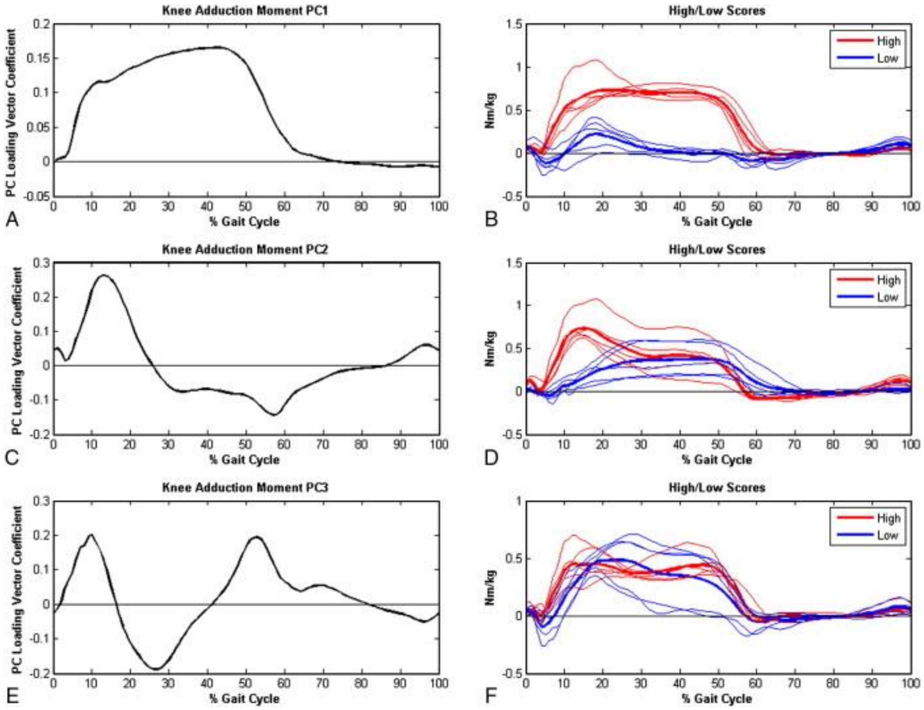


Figure 2.28: PC1, PC2, and PC3 adduction moments during gait with lower PC1 adduction post-operatively [53]

The post-TKA joint moments and flexion angles were more similar to the normal knee for patients with improved function [53]. However, this study used strict inclusion criterion and there are no reported changes in other knee kinematics after TKA. The findings by Hatfield et al. are relevant to this literature review as it shows that the variability can only be explained partly by alignment and therefore the loading during activities of daily living is also important. As previously discussed in this review, it is known that loading conditions can impact incidence of OA and is validated by this study that both peak loading and overall loading during full gait cycle plays a role in the severity of OA.

Other studies looked at kinematic measurements using different methods than traditional motion capture or HSSR. Matsuzaki et al. used a surgical navigation system that recorded measurements with patients under anesthesia for flexion, extension, and range of motion, however, the navigation system reports larger values than data recorded by fluoroscopic analysis [54]. The range of motion and kinematics persisted before and after surgery with only VrVl rotation showing improvement post-operatively [54]. Even with a different method the results are consistent with most of the previous studies that have been reviewed.

2.6 Summary

The studies in this literature review show that there is a need for more research in this field. Different studies have noted changes in AP translation and VrVl rotations after TKA. Other studies noted changes in gait characteristics and knee moments before and after TKA. Currently, there has yet to be a 3D radiography-based 6-DOF comparison of knee movement and implant alignment in the same patients before and after TKA surgery. A study using HSSR collection methods for high accuracy, as outlined previously, can provide valuable information to aid in improving patient specific care for patients with OA and receiving a TKA.

3. Chapter Three: Does Total Knee Arthroplasty Restore Native Knee Kinematics?

3.1 Introduction

Osteoarthritis (OA) alters normal knee anatomy through the loss of cartilage, formation of osteophytes, and inflammation of the surrounding soft tissue. The knee is most commonly affected by OA with a lifetime risk of 40% in males and 47% in females [1]. In the United States, it is estimated that OA affects 27 million people, and the occurrence will increase every year due to the aging population [13,14]. Development of OA can be attributed to previous injuries, occupation, and age as this disorder is commonly caused by overuse of the joint. Females above the age of 60 are the highest risk group, with 13% of this demographic affected by OA [16].

When OA becomes severe, patients experience pain, limited function, and stiffness of the joint that restricts knee rotations and translations. Total knee arthroplasty (TKA) is performed when less invasive treatments are no longer effective at mitigating pain. The goal of TKA is to reduce pain and restore the healthy knee’s functionality. OA accounts for 94% to 97% of TKA surgeries and is only done during end-stage arthritis to improve quality of life during daily tasks [2,3,22]. TKA procedures are expected to increase by 3.5 million cases each year by 2030, with a 143% increase by the year 2050 [19,20,21].

Knee implant design factors such as size, fixation method, and articular constraint can impact post-operative knee kinematics and could play a role in patient satisfaction. Currently, patients report between 75% and 92% satisfaction with performing daily tasks [5]. With such a wide disparity in satisfaction among TKA patients, it is important to study how to more reliably improve outcomes.

Changes in knee kinematics due to OA progression and restoration of healthy knee kinematics during TKA may affect patient satisfaction. Knee kinematics are routinely measured using marker-based motion capture systems, but these systems can have large errors in relative bony positions due to soft tissue artifacts. High-Speed Stereo Radiography (HSSR) enables measurement of precise joint positioning in both native and implanted knees, with errors of 0.2 mm and 0.4° for translations and rotations, respectively [45]. This level of accuracy makes HSSR an ideal modality for detecting small changes in joint positioning caused by implant design factors and alignment after TKA.

Previous studies have analyzed knee kinematic differences between healthy, OA, and TKA cohorts. These studies primarily focus on deep knee flexion and gait, two common movements used during activities of daily living. In both activities, post-TKA knee kinematics were found to be more similar to pre-operative OA knee kinematics than the healthy normal knee [50,51,54]. A study of TKA alignment by Yue et al. found a more lateral position of the femur across all subjects [50]. Another study using “flexion-enhanced” implants resulted in the same average maximum knee flexion of 130° before and after TKA with the TKA contact position located more posteriorly than in the native knee [51].

While previous studies have measured knee kinematics in both OA and TKA cohorts, no studies have measured the same patients before and after TKA using HSSR. Studying separate OA and TKA cohorts can identify general differences in kinematics, but they are unable to account for the effects that patient specific anatomy, implant alignment, and pre-op kinematics have on detailed post-operative knee mechanics. The objective of this study was to measure detailed knee kinematics in individual patients with severe OA prior to and 6 months after their primary TKA. Kinematics were measured in standing, gait, and deep knee flexion activities. It was hypothesized that the post-operative kinematics would remain consistent with the pre-operative movements and no significant differences would be measured in each degree of freedom in the articulating knee joint.

3.2 Methods

3.2.1 Participants

Subjects with severe OA and that were scheduled to receive TKA were recruited for this study. The inclusion criteria for study participation were:

1) Severe unilateral or bilateral OA of the knee
2) Age between 40 and 80 years
3) No history of cancer, tumors, or malignancies
4) No injuries to ligaments or muscles in the lower extremities
5) Non-antalgic gait during the data collection time period

Subjects were excluded from this study if they had persisting lower extremity injuries, were not healthy enough to complete the required activities, or participated in other studies involving radiation exposure within the past year. This study was approved by the University of Denver Institutional Review Board (IRB #1556634-4) and all participants signed informed consent prior to collection of data.

A total of five subjects were recruited for this study who underwent six TKA surgeries (i.e. five subjects undergoing unilateral TKA and one subject undergoing bilateral TKA). All subjects received a cruciate retaining total knee arthroplasty from the same implant family (ATTUNE^{TM}, Depuy Synthes Inc.), although the exact design varied between cementless and cemented fixation and between fixed-bearing and rotating platform designs (Table 3.1).

Table 3.1: Subject demographics for participants in the study. K05R and K05L are the right and left side for the same subject.

Subject	Age	Sex	Knee	Femur Size	Femur Type	Tibia Type	Tibia Size	Fixation
1	58	Male	Right	6	CR	FB	5	Cemented
2	65	Male	Left	8	CR	FB	7	Cemented
3	47	Female	Left	7	CR	RP	6	Cementless
4	71	Female	Right	5	CR	RP	4	Cementless
5R	62	Male	Right	7	CR	FB	6	Cemented
5L	62	Male	Left	7	CR	FB	6	Cemented

3.2.2 Procedure

Subjects underwent a detailed hip to ankle pre-operative computed topography (CT) scan of both lower extremities for use in subsequent data analysis. All data collections were performed in the Human Dynamics lab at the University of Denver. The pre-operative data collection occurred during a 2-hour protocol within 1 week prior to the TKA procedure.

Subjects were outfit with reflective markers attached to both surgical and non-surgical lower legs to enable marker-based motion-capture during the movement trials (100 Hz sampling frequency; VICON, Centennial, CO). Simultaneously, a HSSR system consisting of two image intensifiers with high-speed, high-definition digital cameras set approximately 70 degrees offset from each other was used to capture detailed biplanar knee joint images (50 Hz imaging frequency). Four force platforms were embedded into the lab floor beneath the field of view of the HSSR system to record ground reaction forces (1000 Hz sampling rate; Bertec, Columbus, OH). Subjects performed three activities during the protocol in view of both imaging systems: 1) standing, 2) gait at a self-selected pace, and 3) leg press from full flexion to full extension.

Static trials were collected in pre- and post-operative conditions with a total of three trials collected for each condition. The subjects stood in a neutral pose within the HSSR field of view for a frontal image and again for an oblique image (Figure 3.1). The pre-operative condition collected a third trial during the leg press activity with a static shot of the knee in deep flexion. This was not done in the follow-up collection; instead, the third trial was done for a standing position at another angle in the field of view. The pre-operative static images were used to establish knee alignment and optimize the image quality when tracking. Post-operative standing trials were taken to establish implant positioning relative to the native bone.

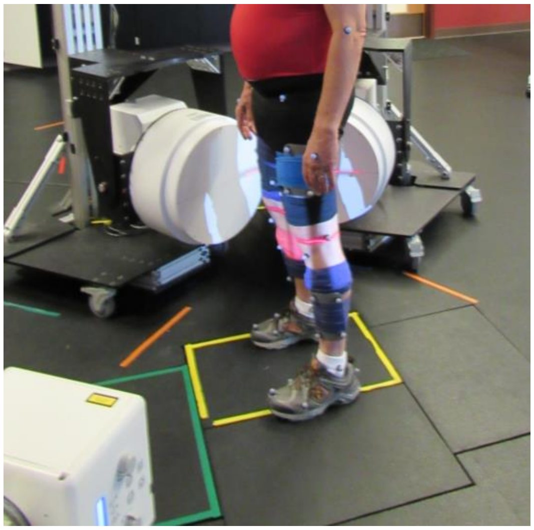


Figure 3.1: Static standing trial capturing the right knee joint.

During the gait trials, subjects were instructed to walk at a comfortable pace starting from a position that ensured the knee was in the HSSR field of view during heel strike (Figure 3.2). Practice trials were completed as necessary to adjust the starting position until images could be successfully collected without disruption of the gait cycle. Trials were collected for both the affected surgical joint and the non-affected/contralateral knee joints during pre-surgical data collections.

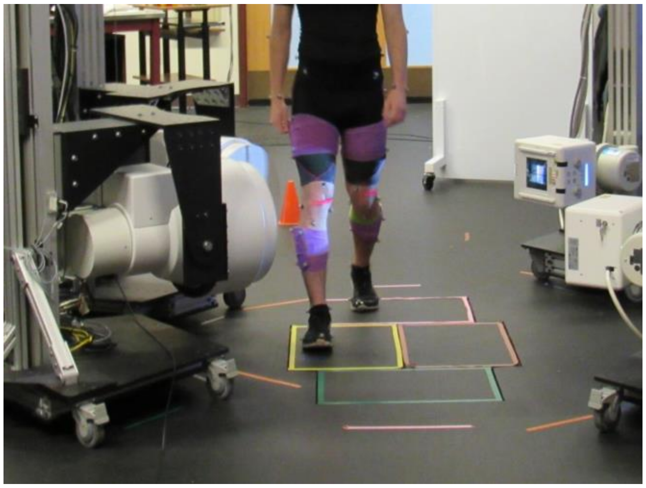


Figure 3.2: Gait trial with joint of interest striking in the field of view. Orange cone used to time the trial.

A leg press apparatus was used to facilitate imaging the knee through the full flexion range. Subject were positioned supine on a rolling sled with their foot in a neutral position pressing against a stable vertical platform resisting a 10lb weight and the knee in the most flexed position without severe pain. The leg press activity was recorded in two trials to ensure the full range of motion occurred within the field of view of the HSSR system (Figure 3.3). The height of leg press apparatus was adjusted so that the flexed knee was centered in the HSSR field of view, and the first knee extension movement trial was imaged from deep- to mid-flexion. The apparatus was then repositioned to center the HSSR field of view on the extended knee, and the activity was repeated imaging from mid-flexion to terminal extension. Methods previously used in Hamilton et al. were performed to combine the two imaging sequences during data analysis to form a single trial [47]. Trials were performed on both affected and non-affected knees.

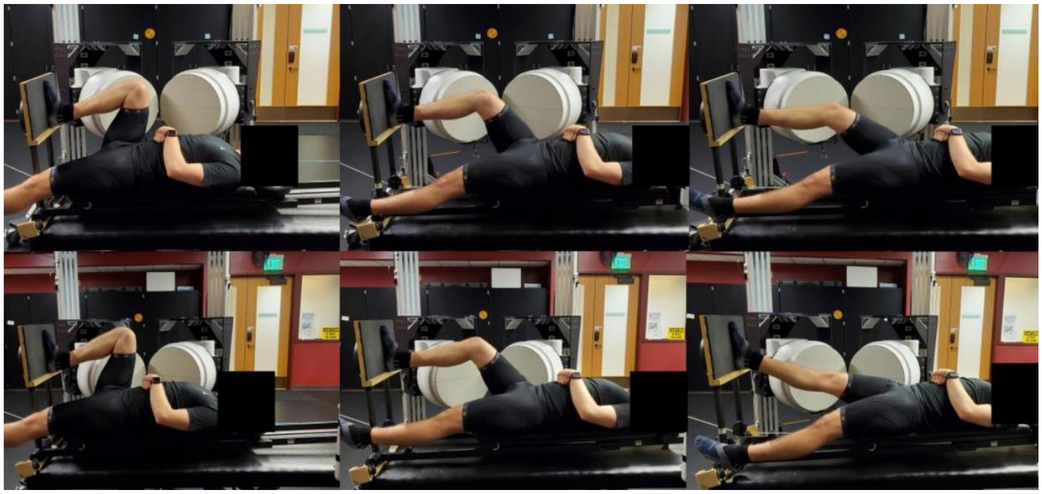


Figure 3.3: Leg press apparatus and trials captured in two parts. (Top) Flexion during leg press (Bottom) Extension during leg press.

All subjects returned to the lab a minimum of 4 months after surgery to measure the post-TKA knee kinematics. The same testing protocol was completed with measurements only taken of the implanted knee(s).

3.2.3 Data Processing

The CT scans were segmented to create subject-specific bone geometry of the native femur, tibia, and fibula (Simpleware ScanIP, version 02018.12). Local anatomic coordinate systems were created for subject's bones following the notation by Grood and Suntay (1983).

The femur anatomic coordinate system had the superior-inferior (SI) axis from the midpoint of medial and lateral epicondyles to the center of the femoral head. The anterior-posterior (AP) axis was the cross-product of SI axis and a temporary vector connecting the epicondyles. The ML axis was the cross-produce of the AP and SI axis. A similar process was done for the anatomic coordinate system of the tibia (Figure 3.4). The femoral and tibial implant models were reconstructed from geometries provided by the manufacturer and implant coordinate systems were assigned (Figure 3.5).

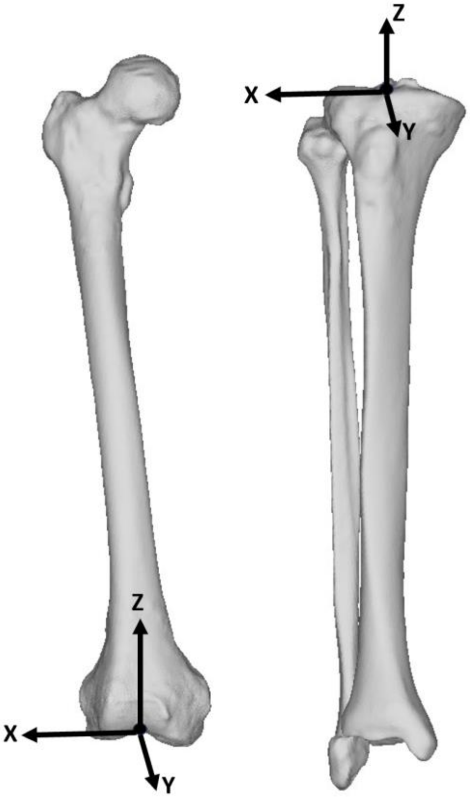


Figure 3.4: 3D model of femur and tibia with anatomic coordinate systems.

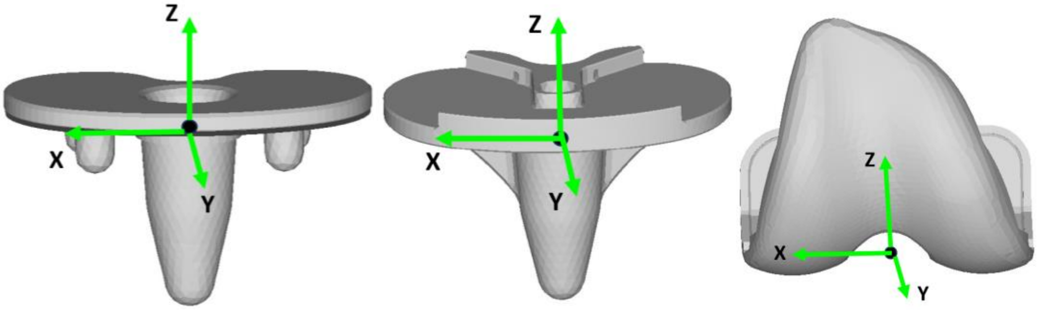


Figure 3.5: Implant component 3D geometry and coordinate systems.

Tracking of the bone and implant geometries were manually performed for the two HSSR imaging planes in DSX software (DSX, C-Motion, Germantown, MD, USA). The

3-dimensional models were aligned with the 2-dimensional radiography images to recreate subject-specific translations and rotations. The implant alignment relative to the bony anatomic coordinate systems were established by independently tracking the femur and tibia bones and implants in the three post-operative static standing trials. The average implant alignment was averaged across the three static trials. Post-operative tracking was performed using the implant geometry in the local implant coordinate systems and then transformed into the native bone coordinate system using the averaged implant positions from the static trials.

Either cementless or cemented tibial trays were used during tracking based on the subject's implant type. However, cemented femur implants were used for tracking both cemented and cementless components. The surgical notes were provided for each subject with details on implant information, alignment, resection and tissue release (Appendix, Table A.0.1). Once the bones and implants were accurately positioned for the frames in each trial, transformation matrices were exported for each bone or implant and analyzed using a custom MATLAB script (Matlab, Mathworks, Natick, MA, USA) to calculate knee kinematics using Grood and Suntay (1983) conventions.

3.2.4 Data Analysis

Trials for the leg press that were collected in two parts were combined into a single cycle by finding the average of overlapping regions or interpolating between flexion angles where no data was collected. A smoothing spline filter was applied to reduce noise in the combined trials. The post-operative leg press trials were analyzed using the same process which was also used in Hamilton et al. [47].

Once knee kinematics were obtained for both pre- and post-operative conditions for each of the activities, comparisons were made between pre- and post-operative results for individual subjects and across all participants. The maximum common knee extension and flexion angles achieved by the subject during the leg press in both pre- and post-operative conditions was found. The leg press kinematics for the pre- and post-operative conditions, as well as the contra-lateral knee were averaged across the subject population. To highlight changes between the pre- and post-operative leg press kinematics, the pre-operative knee kinematics were subtracted from the post-operative kinematics at each flexion angle. Changes in the contralateral joint were also analyzed with the pre-operative kinematics subtracted from the pre-operative contralateral data collected. Statistical analysis was performed to determine statistically significant differences between the pre-TKA and post-TKA kinematics in the form of paired t-tests ($\alpha = 0.05$) for all 6-DOF at both maximum knee extension and flexion.

Gait trials used the point of heel strike for comparison. Heel strike was determined by using the difference of frames from the force plate impulse during heel strike and when the camera was shut off in VICON (100 Hz sampling frequency; VICON, Centennial, CO). The difference was then subtracted from the last frame in DSX (DSX, C-Motion, Germantown, MD, USA) to determine the frame of heel strike for each patient. This was completed across all subjects before and after surgery.

3.3 Results

The five subjects in this study had six pre- and post-operative knee joints for analysis. Static standing trials were used to quantify the mean position of the femur and tibia implants in the implant coordinate systems to the respective pre-surgical native bone coordinate systems. Standard deviations across the trials for all subjects were less than 3° for rotations and 3 mm for translations (Tables 3.2 and 3.3).

Table 3.2: The average position of the femur implant component and standard deviation. Positions of the implants were taken from the femur coordinate system for each subject.

Femur Implant Alignment

Subject	FE (°)	VrVl (°)	IE (°)	ML (mm)	AP (mm)	SI (mm)
1	-1.6 ± 0.5	0.6 ± 0.2	-2.2 ± 1.3	3.8 ± 0.4	8.7 ± 0.2	11.4 ± 0.7
2	-2.8 ± 1.3	1.5 ± 1.3	1.2 ± 1.3	2.5 ± 1.6	5.1 ± 2.0	10.9 ± 0.6
3	3.0 ± 1.9	1.5 ± 0.3	5.0 ± 1.4	2.8 ± 0.1	11.3 ± 2.4	11.1 ± 1.6
4	-0.2 ± 0.0	-0.1 ± 0.7	3.6 ± 2.4	3.8 ± 0.5	9.3 ± 0.4	12.9 ± 0.6
5R	1.0 ± 2.4	5.1 ± 1.9	7.5 ± 0.7	4.2 ± 1.7	1.0 ± 2.7	9.9 ± 1.9
5L	-4.7 ± 0.4	0.6 ± 1.9	-1.5 ± 2.1	1.1 ± 1.7	6.8 ± 0.8	8.6 ± 1.7

Table 3.3: The average position of the tibial tray implant component and standard deviation. Positions of the implants were taken from the tibial coordinate system for each subject.

Tibial Implant Alignment

Subject	FE (°)	VrVl (°)	IE (°)	ML (mm)	AP (mm)	SI (mm)
1	3.8 ± 1.2	-1.4 ± 0.3	-3.1 ± 1.9	0.7 ± 0.9	-25.3 ± 0.3	4.2 ± 0.9
2	6.8 ± 1.7	-2.6 ± 1.6	-5.7 ± 1.5	-0.8 ± 0.5	-30.9 ± 1.9	9.1 ± 0.8
3	7.4 ± 0.4	-0.1 ± 0.1	-10.8 ± 2.3	-3.1 ± 0.2	-27.5 ± 0.5	3.7 ± 1.5
4	7.1 ± 1.3	4.0 ± 0.7	-13.9 ± 1.7	-2.0 ± 1.0	-29.1 ± 0.1	11.1 ± 0.9
5R	4.2 ± 2.9	-3.7 ± 1.2	-7.8 ± 1.2	3.0 ± 0.9	-23.4 ± 2.1	9.8 ± 1.5
5L	3.2 ± 2.5	-2.9 ± 0.3	2.1 ± 3.0	1.7 ± 1.0	-26.0 ± 1.1	7.5 ± 1.3

The implant VrVl alignments were compared with the post-operative hip-knee-ankle (HKA) angle. The implant VrVl alignments were indicative of the HKA at full extension (Table 3.4). This was seen in the strong correlation between the HKA and Post-operative VrVl alignment which reported a correlation coefficient of 0.94 (Figure 3.6). The tibial trays were aligned in varus for each subject except Subject 4 which showed a 4° valgus alignment (Table 3.4, Figure 3.7).

Table 3.4: HKA and Implant Alignments for verification of correct post-operative tracking.

Subject	Pre-Op Vr-Vl(+)	Contralateral Vr-Vl(+)	Post-Op Vr-Vl(+)	Femur Vr(+)-Vl	Tray Vr-Vl Vr-Vl(+)	HKA (Implant) Vr-Vl(+)
1	-3.5 ±	-1.0 ±	-3.0 ± 0.3	0.6 ± 0.2	-1.4 ± 0.3	-1.9
2	-9.4 ± 0.7	-4.3 ± 0.1	-2.1 ± 0.3	1.5 ± 1.3	-2.6 ± 1.6	-4.1
3	11.1 ±	1.6 ±	-1.4 ± 0.5	1.5 ± 0.3	-0.1 ± 0.1	-1.6
4	4.5 ± 0.6	3.7 ±	3.8 ± 1.0	-0.1 ± 0.7	4.0 ± 0.7	4.1
5R	-8.4 ±	-5.1 ±	-8.2 ± 2.3	5.1 ± 1.9	-3.7 ± 1.2	-8.8
5L	-5.1 ±	-8.4 ±	-3.9 ± 2.4	0.6 ± 1.9	-2.9 ± 0.3	-3.5

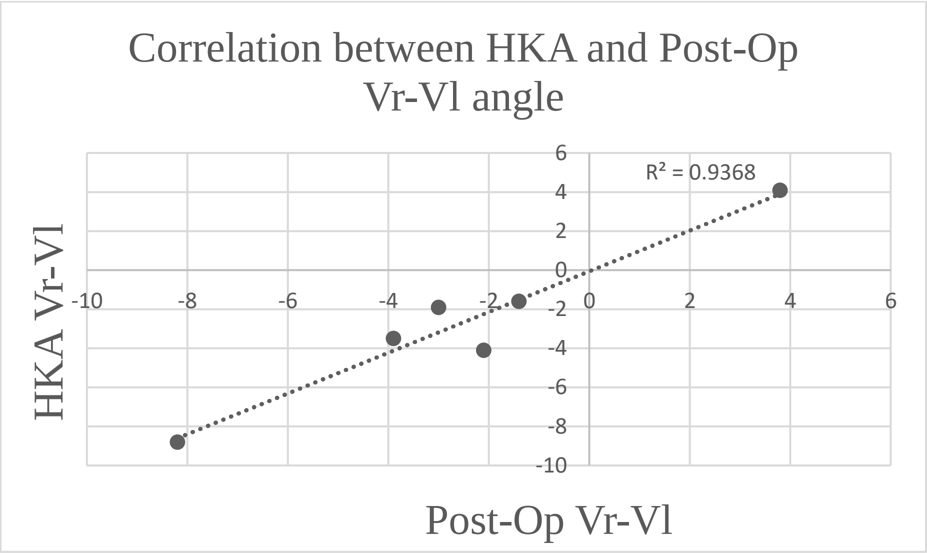


Figure 3.6: Correlation plot

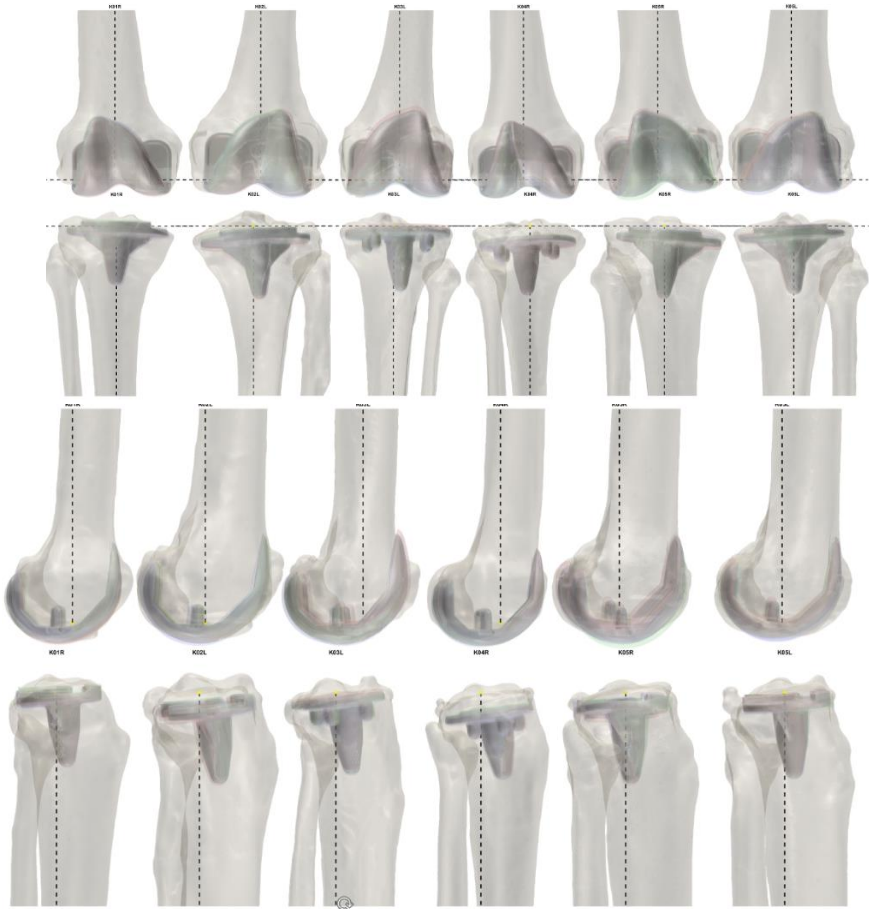


Figure 3.7: Implant alignment in coronal (top) and sagittal (bottom) planes.

3.3.1 Extension

Knee kinematics were recorded in the most extended position during standing and leg press. All kinematics except VrVl rotation were reported as the difference with the pre-operative pose to the pre-operative standing pose (Figure 3.8 - 3.9). The largest change in VrVl kinematics was seen in Subject 3 with a valgus shift of 10.3° during leg press trials.

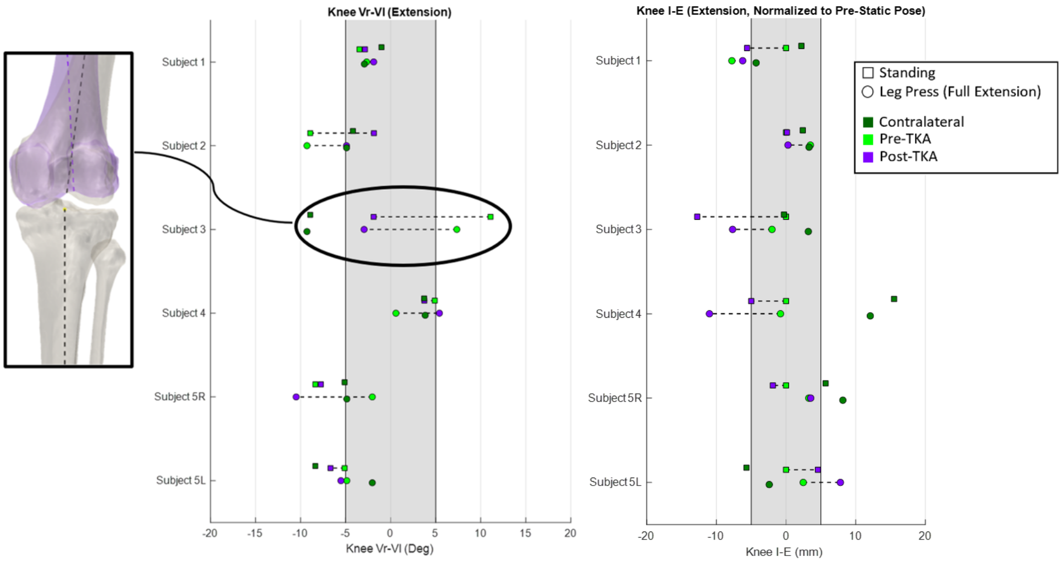


Figure 3.8:Varus-Valgus rotation (left) and Internal-External rotation (right) at the highest extension point. The grey band represents ± 5 degrees or mm.

Mean pre-operative I-E rotation during leg press was -5.0° ± 3.9° and was -6.9° ± 8.5° post-operatively, which were not significantly different (p=0.424, CI [-3.8,7.8]). The mean leg press VrVl rotations were -1.8° ± 5.6° and -3.4° ± 5.2° before and after TKA, respectively, which were not significantly different (p = 0.577, CI [-5.2,8.3]).

The FE angle for activities of leg press at full extension and static standing were averaged in both pre-TKA and post-TKA conditions. There was no significant difference in either activity with similar averages (Table 3.5).

Table 3.5: Flexion-Extension data during highest extension point for standing and leg press trials.

Activity	Pre-Operative	Post-Operative	P-Value	Confidence Interval
Leg Press	7.9°±5.9°	7.7° ± 5.7°	0.723	[-1.2, 1.6]
Standing	8.6°±4.5°	5.8° ± 2.8°	0.093	[-0.7, 6.3]

All subjects exhibited a lateral femoral shift from the pre-operative OA state during leg press and static standing activities (Figure 3.3). This lateral shift was statistically significant (p = 0.003, CI [2.9,8.2]) with averages of 1.4mm ± 2.7mm and -4.2mm ± 1.5mm in the pre- and post-operative conditions, respectively. The mean AP translations were -8.7mm ± 5.1mm and -5.9mm ± 3.8mm in the pre- and post-operative conditions, respectively. Mean SI translations were -11.7mm ± 2.1mm and -13.4mm ± 2.4mm in the pre- and post-operative conditions, respectively. SI translations in four of five subjects were within 3mm of the pre-operative knee. The paired t-test showed no significant difference between pre- and post-operative leg press translations in the AP (p = 0.086, CI [-6.1,0.6]) and SI (p=0.151, CI [-0.9,4.4]) directions.

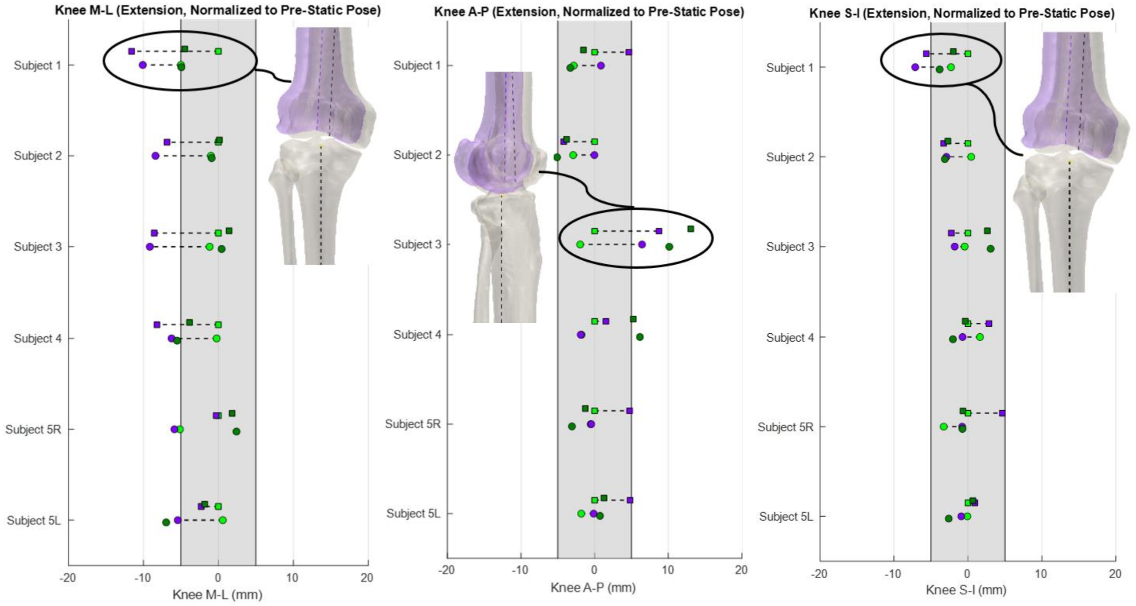


Figure 3.9: Translations at maximum knee extension for each activity.

3.3.2 Flexion

The knee flexion angle was recorded during the supine leg press activity. The post-operative and contralateral knee kinematics were reported as the difference between the pre-operative and post-operative knee position. The change in VrVl rotations during flexion was small, with the largest change with Subject 5L moving varus after TKA (Figure 3.10). The contralateral knee for Subject 3 was aligned over 10° varus compared to the surgical knee. The rotational degrees of freedom for VrVl (p = 0.976, CI [-4.3, 4.4]) and IE (p = 0.916, CI [-4.8, 5.2]) were not significantly different with averages of 1.1° ± 4.7° (VrVl) and -10.3° ± 3.6° (IE) pre-operatively and 1.0° ± 5.8° (VrVl) and -10.5° ± 4.5° (IE) post-operatively.

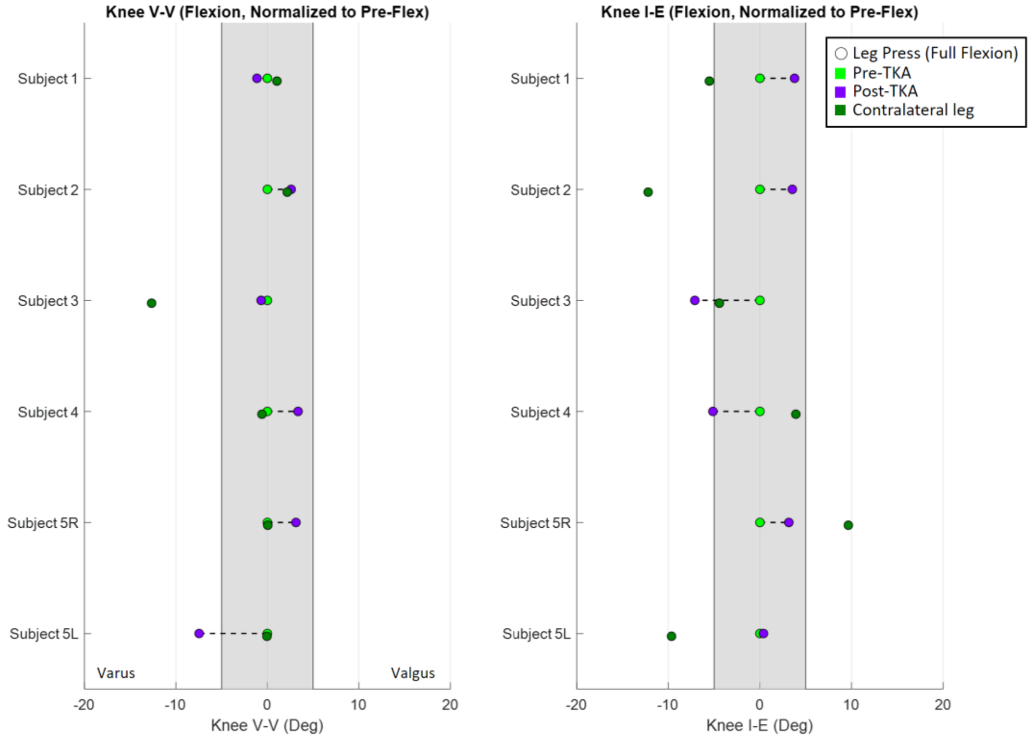


Figure 3.10: VrVr and IE rotation for maximum flexion during leg press.

The FE angle for full flexion was calculated during the leg press activity in both conditions of severe OA and after TKA. The FE angles reported were not significantly different when using an alpha of 0.05 (Table 3.6).

Table 3.6: Flexion-Extension data during highest flexion for the leg press trial.

Activity	Pre-Operative	Post-Operative	P-Value	Confidence Interval
Leg Press	112.7° ± 3.2°	113.7° ± 4.5°	0.23	[-3.5, 1.1]

The largest change in knee translations seen between pre- and post-operative conditions is for Subject 5L with a femoral anterior shift of 18.8mm (Figure 3.11). There was a significant difference in the post-operative AP translations with mean translations of 4.7mm ± 2.9mm pre-operatively and -2.9mm ± 4.2mm post-operatively (p=0.025, CI [1.4, 13.8]). The leg press trials for ML averaged 1.1mm ± 3.4mm and -1.8mm ± 2.9mm before and after TKA, respectively, which were not significantly different (p = 0.089, CI [-0.6, 6.4]). This was also the result for SI translations (p = 0.318, CI [-2.0, 5.1]) with average translations of -41.0mm ± 5.0mm and -42.5mm ± 5.6mm before and after TKA.

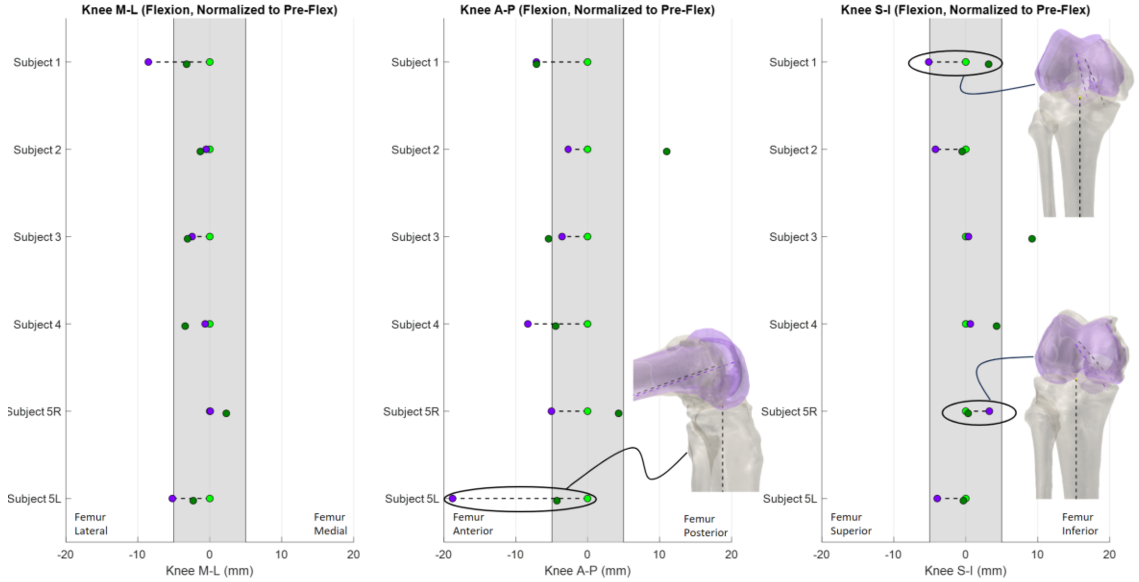


Figure 3.11: ML, AP, and SI translations maximum flexion during leg press.

3.3.3 Heel strike

The gait trials for each subject had a specific instance of heel strike that was calculated for comparison. The point of heel strike for rotation and translations were compared pre-TKA and post-TKA. The VrVl kinematics did not show any significant differences (p = 0.488, CI [-9.0, 4.9]) between conditions with an average of -2.1° ± 6.9° pre-operatively and -0.08° ± 0.8° post-operatively. However, the IE rotational degree of freedom reported significant differences (p = 0.018, CI [-18.0, -2.7]) between conditions during statistical testing with an average -7.8° ± 6.7° pre-operatively and 2.6° ± 2.9° post-operatively (Figure 3.12).

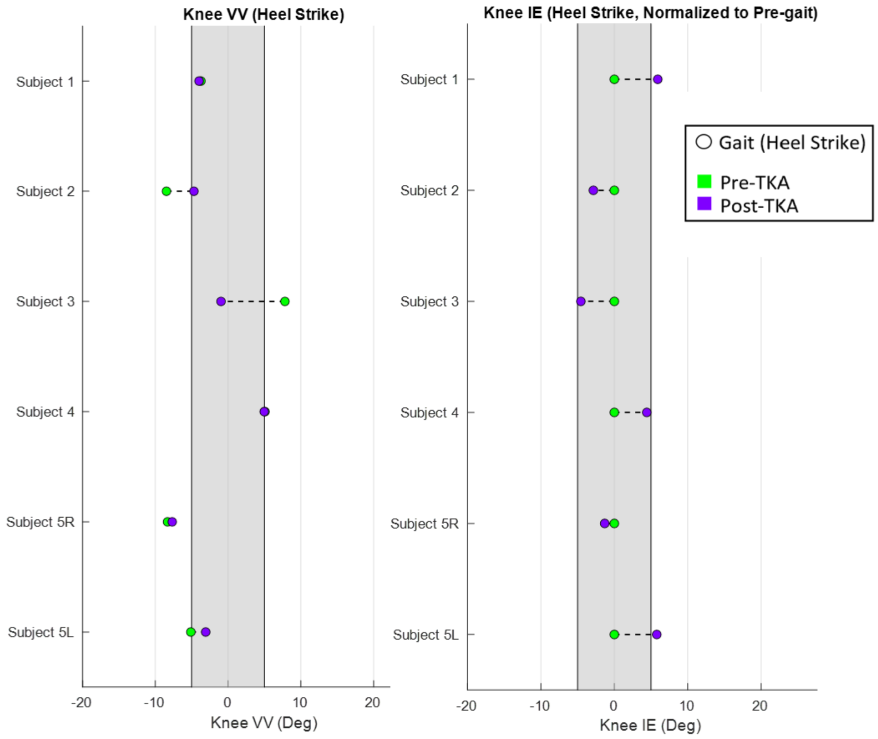


Figure 3.12: VrVl and IE rotation kinematics for heel strike during gait. IE degree of freedom was normalized to the pre-gait heel strike.

The ML translations for each subject were measured to move laterally except for subject 5L which had a slight shift medially. The average pre-operative ML translation was 1.4mm ± 2.3mm and 1.8mm ± 1.0mm post-operatively which did not report a significant difference (p = 0.739, CI [-3.5, 2.6]). The AP (p = 0.0, CI [-40.5, -30.7]) and SI (p = 0.038, CI [-3.1, -0.1]) translational degrees of freedom were significantly different between conditions. The AP translation averaged -9.2mm ± 4.3mm pre-operatively and 26.4mm ± 3.8mm post-operatively while the SI translation had a pre-operative average of -13.2mm ± 1.2mm and -11.6mm ± 1.7mm post-operatively. All subjects shifted posteriorly during the heel strike phase in gait trials (Figure 3.13).

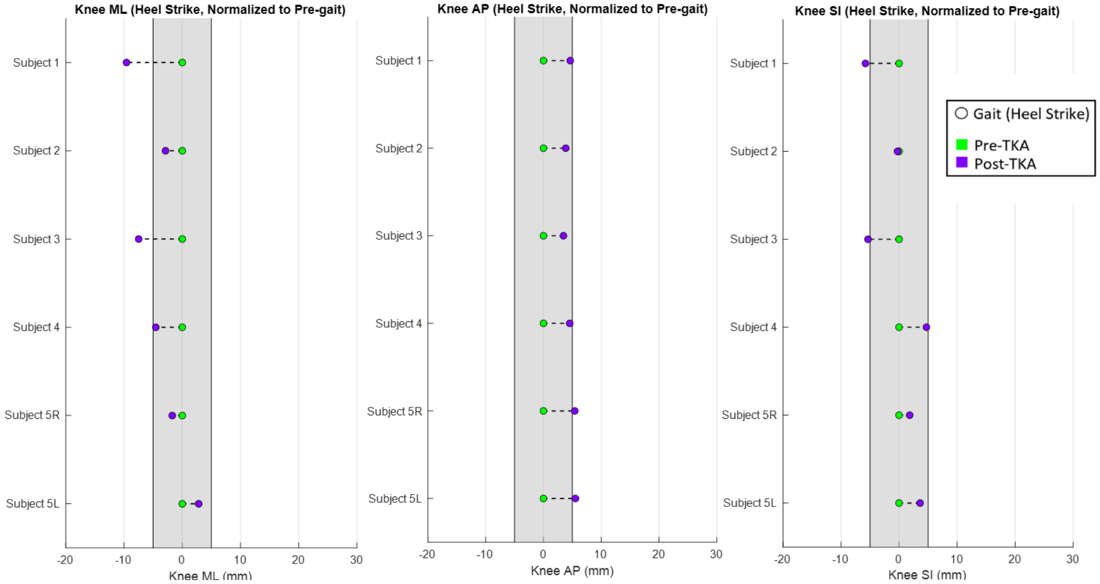


Figure 3.13: ML, AP, and SI translation kinematics at heel strike during gait. All translational degrees of freedom were normalized to the pre-gait heel strike.

The FE angle was measured for each subject at the point of heel strike during their gait cycle. The FE angles reported were significantly different when using an alpha of 0.05 (Table 3.7).

Table 3.7: FE kinematic averages before and after surgery. P-value and confidence interval for statistical analysis.

Activity	Pre-Operative	Post-Operative	P-Value	Confidence Interval
Gait	16.4° ± 5.9°	5.3° ± 5.7°	0.041	[0.7, 21.7]

3.3.4 Leg Press Kinematics

Changes in VrVl and IE rotations before and after TKA through the range of flexion in the leg press showed no consistent trends across subjects (Figure 3.14). However, the ML translation had a consistent lateral shift with the implanted femur lateral to the native. This was observed for Subjects with both pre-operative varus and valgus knee deformities. The change in AP kinematics showed the implanted femur on average is posterior to the native femur in extension and anterior to native femur with increasing flexion.

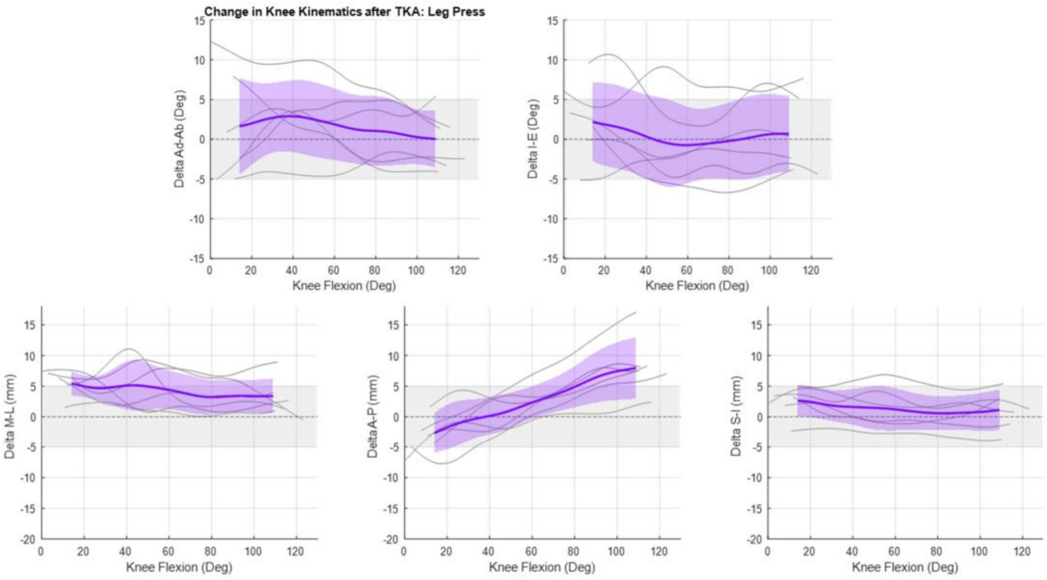


Figure 3.14: Change in kinematics during supine leg press with averages shown by the purple line and one standard deviation indicated by the purple shaded region.

The contralateral leg did not have any notable differences to the OA leg (Figure 3.15).

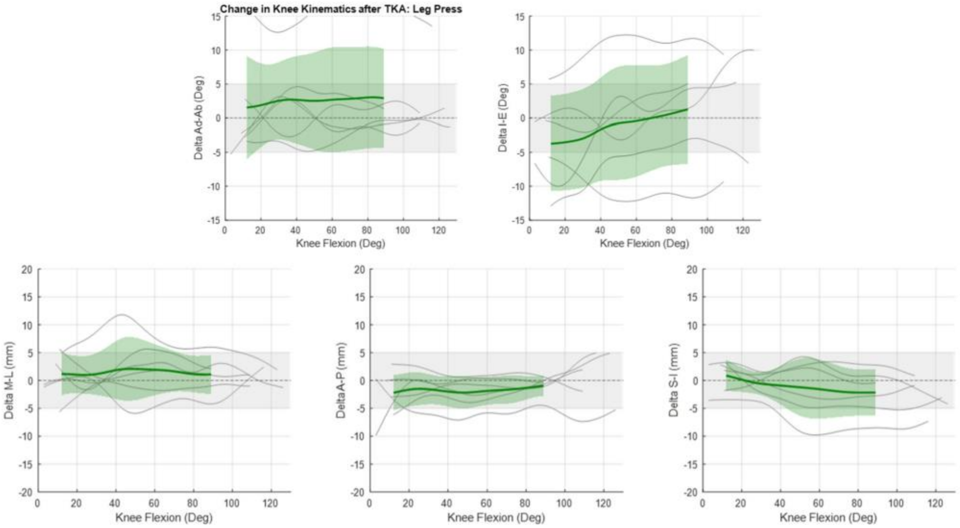


Figure 3.15: Contralateral knee kinematics during supine leg press. Averages indicated by the green line and one standard deviation within the shaded green region.

3.4 Discussion

The rising number in TKA each year and varying satisfaction has suggested a need for improved outcomes of knee replacements. Authors believe the kinematics of the implanted knee are not restored to healthy function but there is a reduction in pain reported by patients. Studies have looked at kinematics of the knee joint with patients of severe OA or have undergone TKA surgery during activities of deep knee flexion or gait. This study looked at subjects before and after receiving TKA with activities of deep knee flexion, static standing, and gait being collected. The study measured deep knee flexion with an apparatus that used a pulley system to allow for greater ranges of motion and consistent loading for each patient compared to a body weight lunge used in previous studies. Our results showed that each degree of freedom in the joint had changes from pre-operative conditions that were specific for each individual subject.

The averages our study reported showed that in maximum extension the only significant change in kinematics between the pre- and post-operative conditions was in ML translation. All other kinematics during the supine leg press for extension were similar to the kinematics collected pre-operatively with the severe OA. Each individual had pre-operative HKA deformities noted during pre-operative collections. The varus-valgus rotation for each patient was corrected towards a neutral alignment for the first 4 patients while the last subject maintained their pre-operative HKA angle. Factors such as male or female sex can impact the native HKA alignment in the joint prior to onset of OA symptoms; the native positioning can greatly impact post-operative limb alignment and requires further analysis. The findings of implant component positions relative to bone coordinate systems were significant for accuracy between manual tracked trials and comparison of implant location between subjects.

During extension in supine leg press trials, the only degree of freedom that had a significant difference after TKA was ML translation. The femur shifted to a lateral position post-operatively which was consistent with the findings by Yue et al. [50]. This post-TKA response is also consistent with native knee anatomy. The implant femur component has equal sized medial and lateral condyles; however, the medial condyle is wider than the lateral in native bone. This anatomical difference can be driving the shift laterally seen in this study. The other rotations and translations in extension were unchanged after TKA. In flexion, all 3 rotations were similar between pre-TKA and post-TKA conditions along with ML and SI translations. AP kinematics at maximum knee flexion during the leg press activity were significantly different after TKA with the femur shifting anteriorly. This is not consistent with the findings in Kitagawa et al., who observed a shift posteriorly [51]. However, Kitagawa et al. found this to be true during early and mid-flexion while the results in this study show anterior shifts during deep flexion from an initial posterior position in early flexion.

While this data was used for comparison to previous literature, results from the current study should be used with caution due to the limited sample size. The HSSR has high accuracy but a target sample size of 10 was not met in our study. Another limitation in the current study was recording the leg press in two trials rather than one. Steps were taken to minimize this effect such as marking the foot positioning and instructing them to remain as consistent as possible; subjects may have adjusted the foot positioning or changed the knee position between collections resulting in inaccurate overlapping or interpolated regions. There should also be collections that use methods that only require one trial for the leg press rather than collection in two trials to obtain full range of motion. Future research should be done with a larger sample size and analyzed for sex differences.

4. Chapter Four: Conclusion

4.1 Key Findings

The goal of TKA is to reduce pain and improve function for patients experiencing severe OA. The work presented throughout this thesis investigated the kinematic outcomes of TKA and compared it to the pre-operative severe OA joint function. The methods established in this thesis contribute to the orthopedic biomechanics research community with knowledge of function before and after TKA along with values of implant component positioning in anatomic coordinate systems. As discussed in Chapter 2, previous studies have been conducted with limited degrees of freedom captured leading to insight on gaps in research that this thesis aimed to address.

The work from Chapter 3 showed results for a variety of tasks in all degrees of freedom possible in the knee joint and implant positioning relative to native bones of participants. The overall average values did not show significant improvements towards restoring pre-OA knee joint function. Results show the kinematic results remained consistent with the pre-operative data collected. The study provided data for positioning, kinematics and comparisons between subjects for points in activities with the joint and full extension and flexion. The procedure in Chapter 3 demonstrates methods that can be used in future research to capture meaningful data for patient specific results. The findings in this thesis can be used for further analysis to find the specific factors that need to be adjusted for better TKA outcomes.

4.2 Future Work and Limitations

There were many limitations in the current work that can be used to guide future studies. There was a lack of subjects recruited for participation in the study that caused results to be used with caution as the sample size cannot confidently represent the true population. Another limitation was the use of only ATTUNE CR Knee System implants being considered when there are other cruciate retaining implants that could be analyzed and used for comparison. This made it difficult for recruitment of patients as the potential subjects in the area with this implant were severely limited. The absence of other implant systems made it difficult for implant factors that affect outcomes to be reported from the current results.

Although this thesis provides valuable in-depth results, there should be a focus on quantifying the difference between pre- and post-surgical functionality. Future studies should increase the number of subjects with a large enough cohort to have measurements separated by “poor” and “good” patient reported satisfactions. There should also be inclusion criteria to have healthy contralateral joints for subjects for individualized comparisons of joints within the same bone and joint history as the surgical knee. With a large sample size, subject specific cohorts can be made for sperate varus and valgus pre-operative alignments. There should also be considerations in the surgical techniques used which can be eliminated if only one surgeon is used to minimize any differences in surgical decisions.

While the methods outlined in this study can be used in other studies, these recommendations for future work should be considered for enhancing the significance of key findings. With access to more resources and time, future work can continue the work that was started in this study.

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Appendix

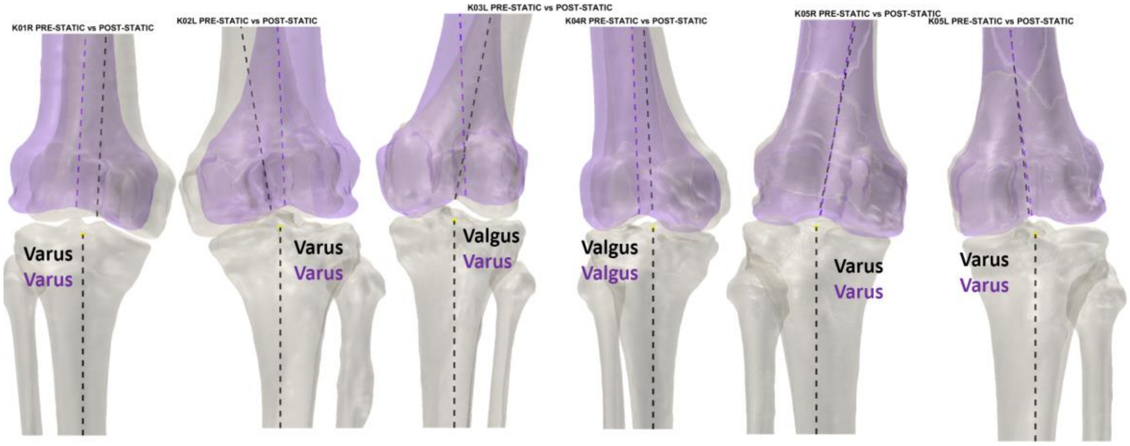

Figure A.0.1: pre- and post-operative VrVl alignment during static standing trials. Post-TKA is purple.

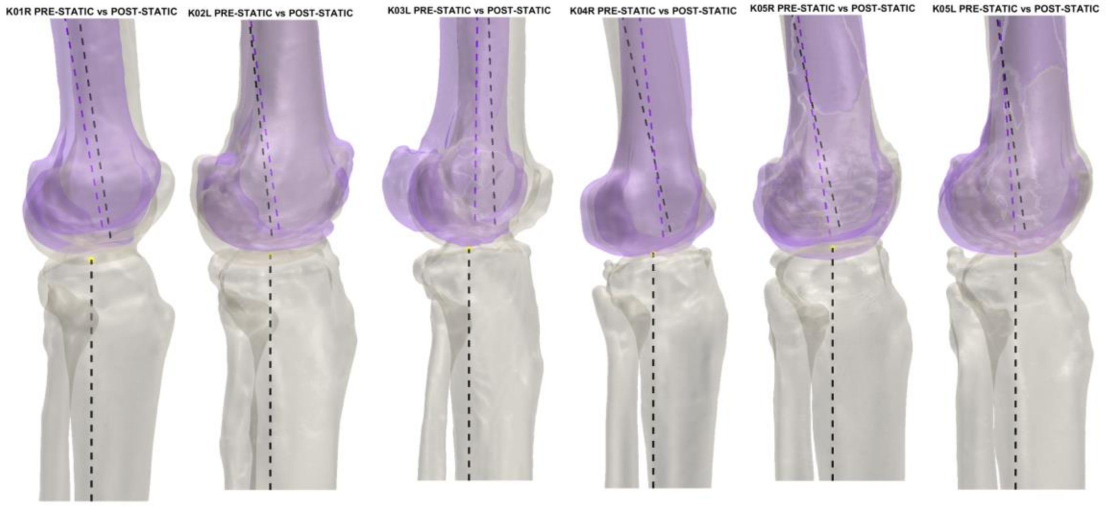

Figure A.0.2: Sagittal view of pre- and post-operative VrVl alignment during static standing trials.

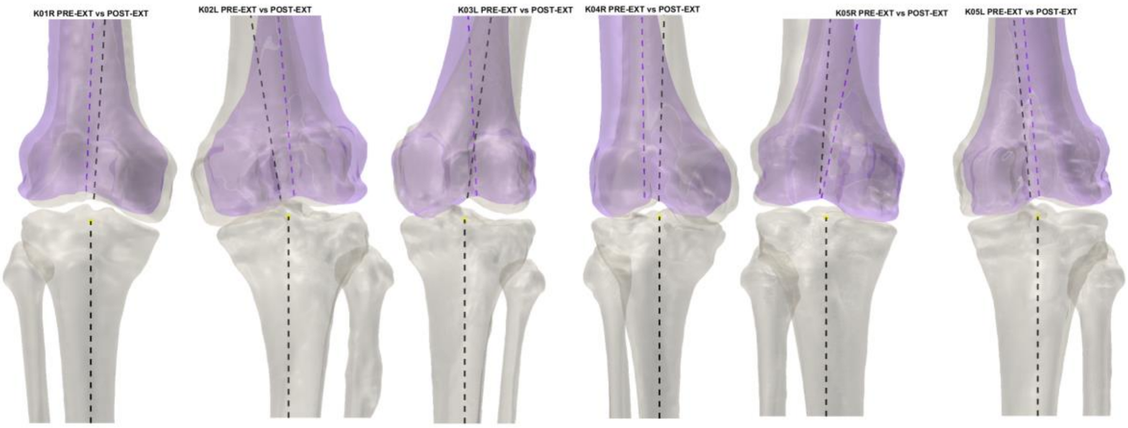

Figure A.0.3: Coronal view of VrVl alignment before and after TKA during leg press extension trial.

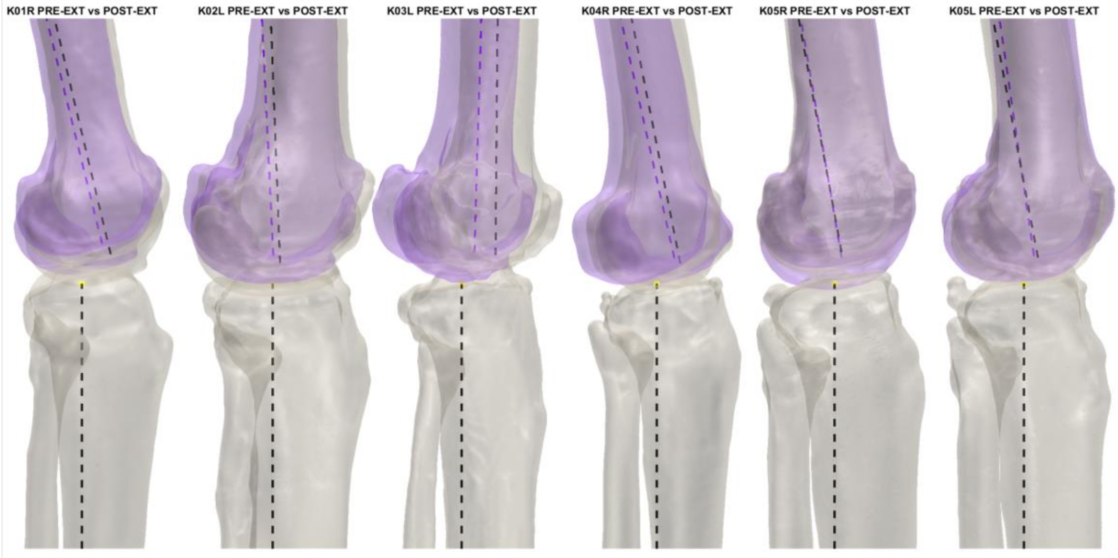

Figure A.0.4: Sagittal view of VrVl alignment before and after TKA during leg press extension trial.

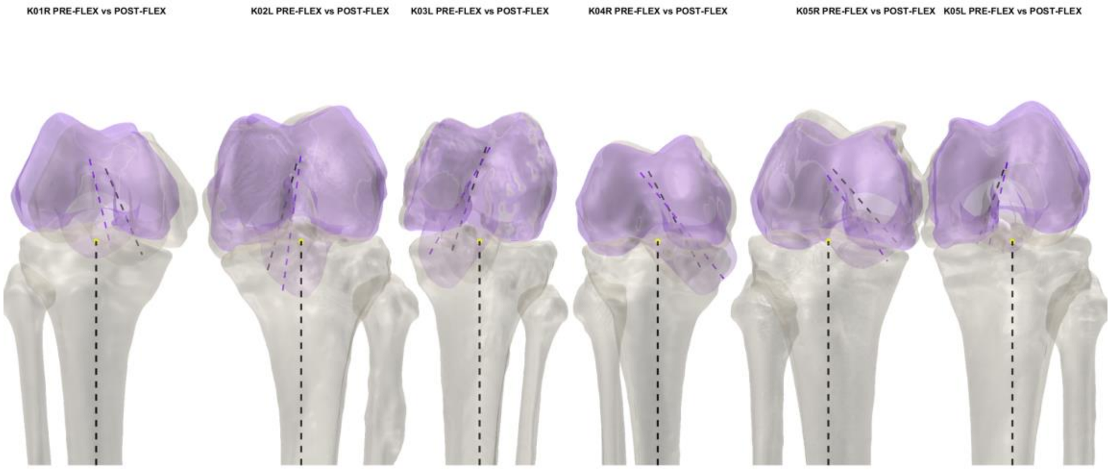

Figure A.0.5: Coronal view of VrVl alignment at flexion during leg press.

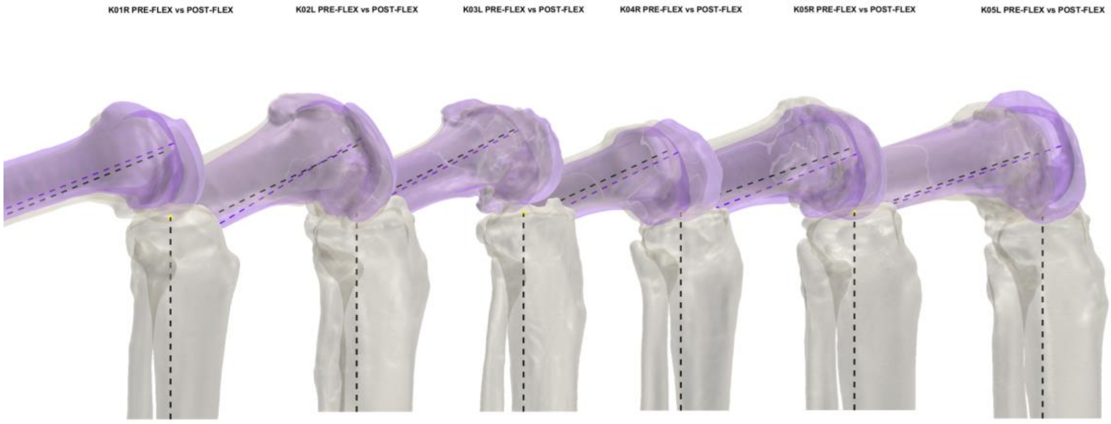

Figure A.0.6: Sagittal view of VrVl alignment at flexion during leg press.

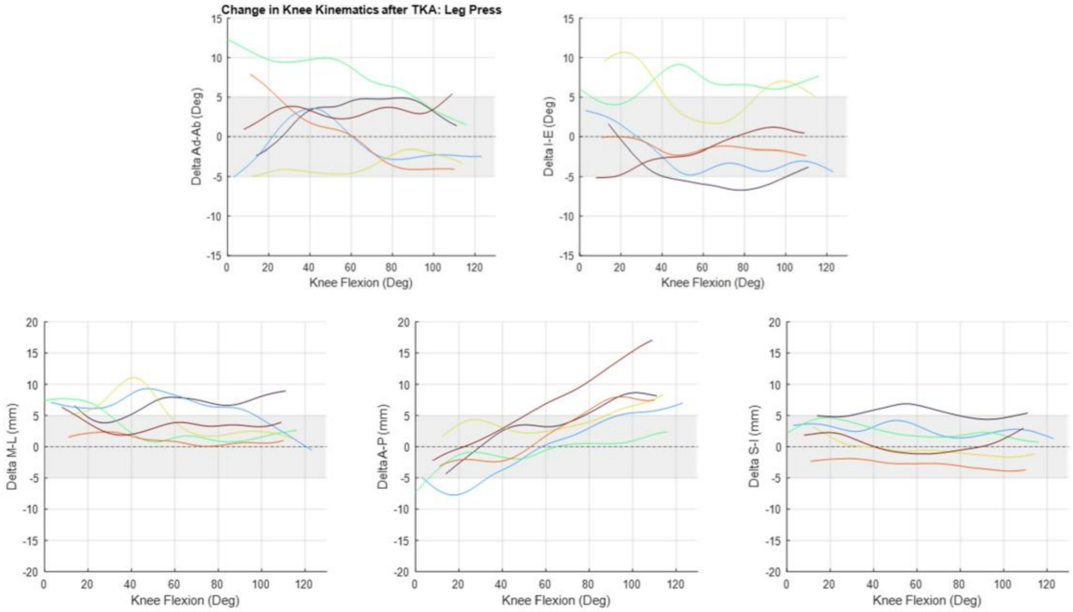

Figure A.0.7: Change in pre- and post-operative kinematics during FE in leg press trials.

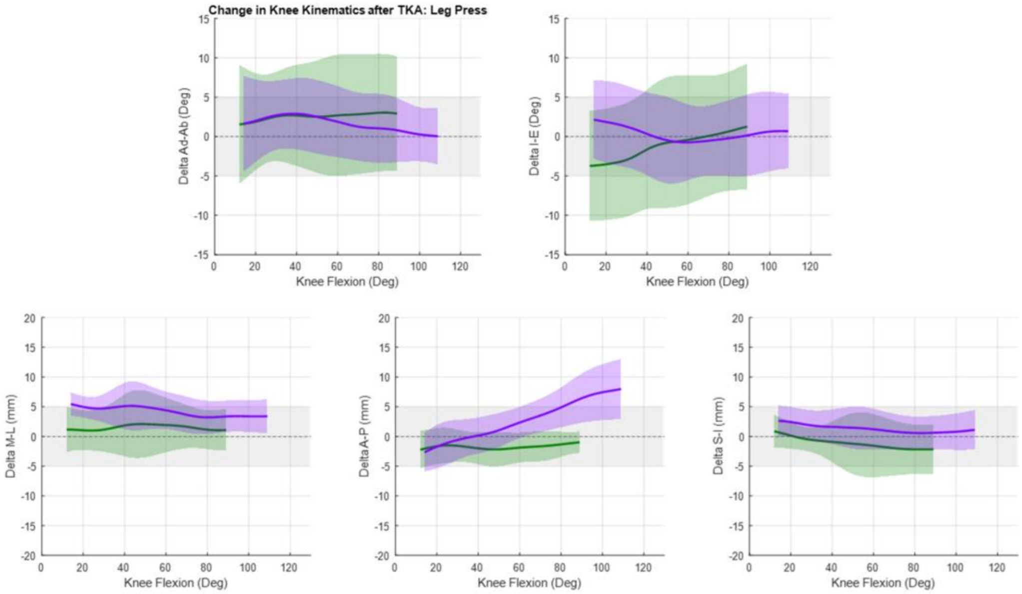

Figure A.0.8: Change in kinematics during supine leg press for surgical and contralateral knees. The contralateral is indicated with green and surgical knee by the purple.

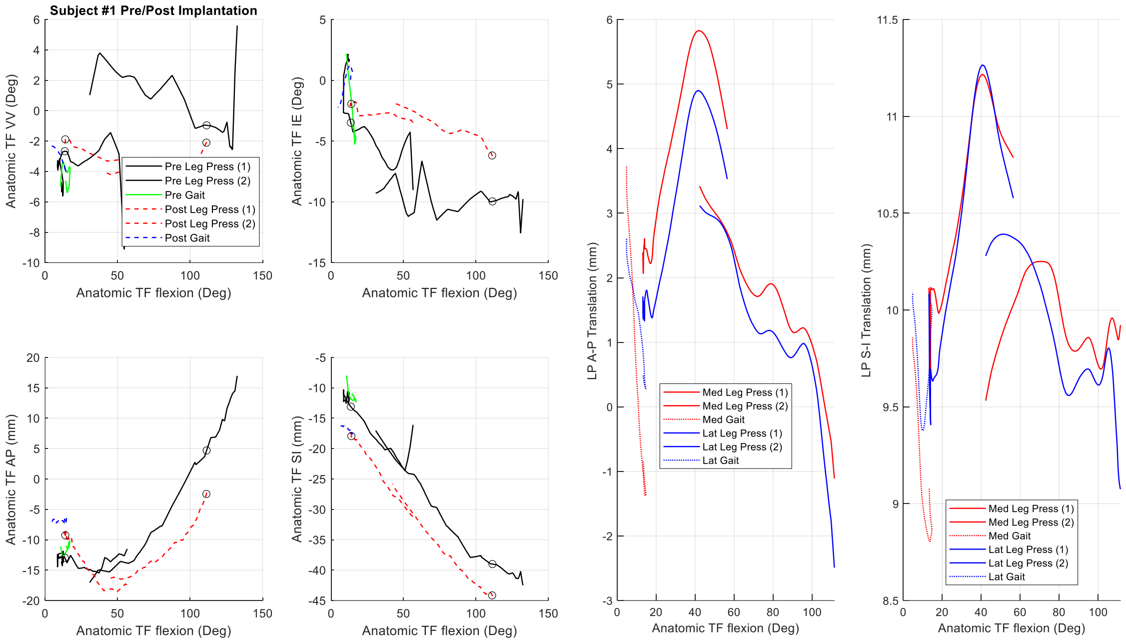

Figure A.0.9: Subject 1 kinematic data for leg press and gait trials before and after TKA. AP and SI low point kinematics for both gait and leg press.

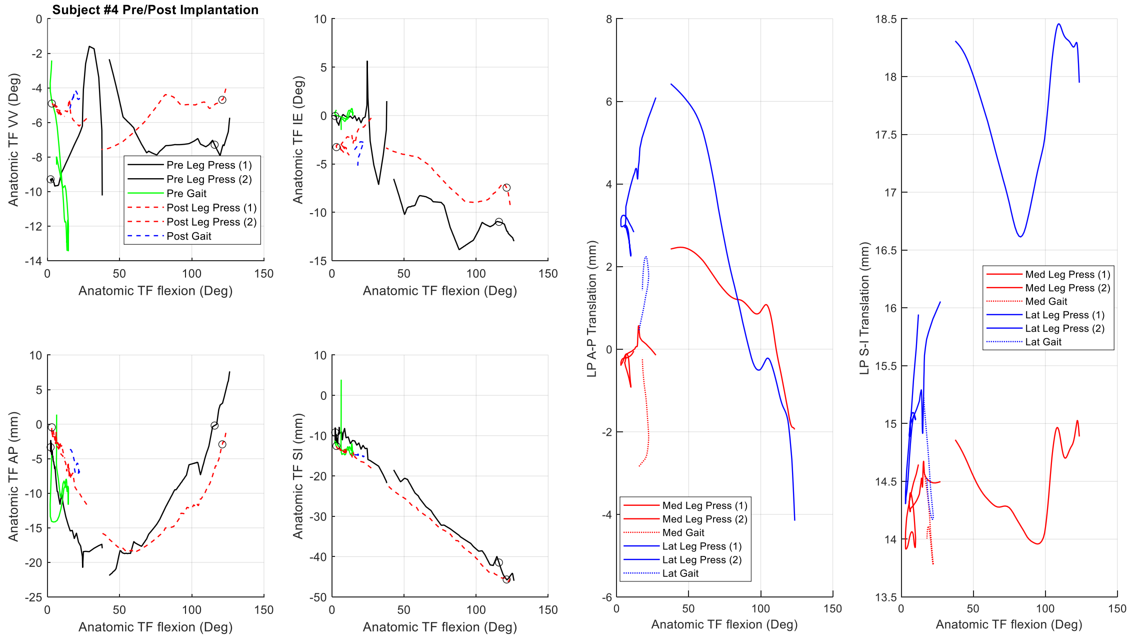

Figure A.0.10: Subject 2 kinematic data for leg press and gait trials before and after TKA. AP and SI low point kinematics for both gait and leg press.

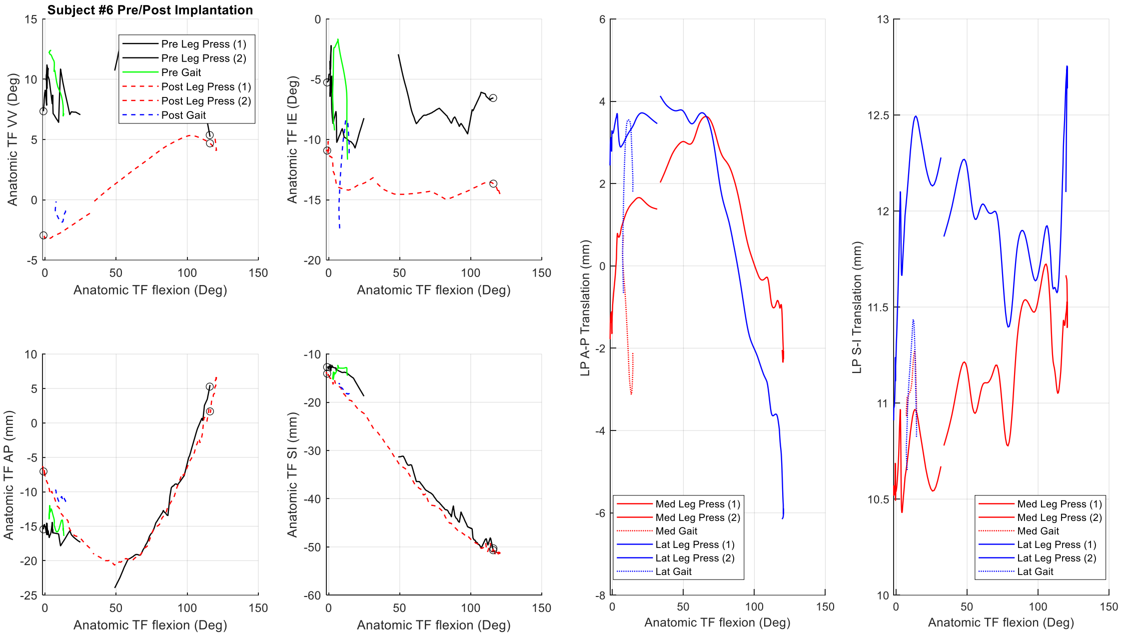

Figure A.0.11: Subject 3 kinematic data for leg press and gait trials before and after TKA. AP and SI low point kinematics for both gait and leg press.

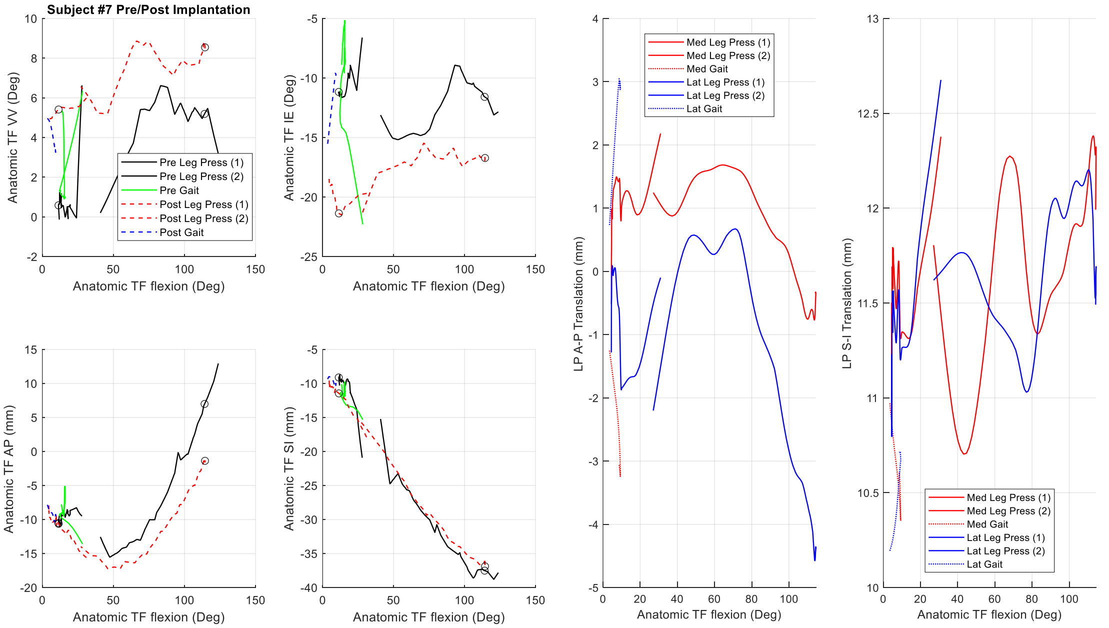

Figure A.0.12: Subject 4 kinematic data for leg press and gait trials before and after TKA. AP and SI low point kinematics for both gait and leg press.

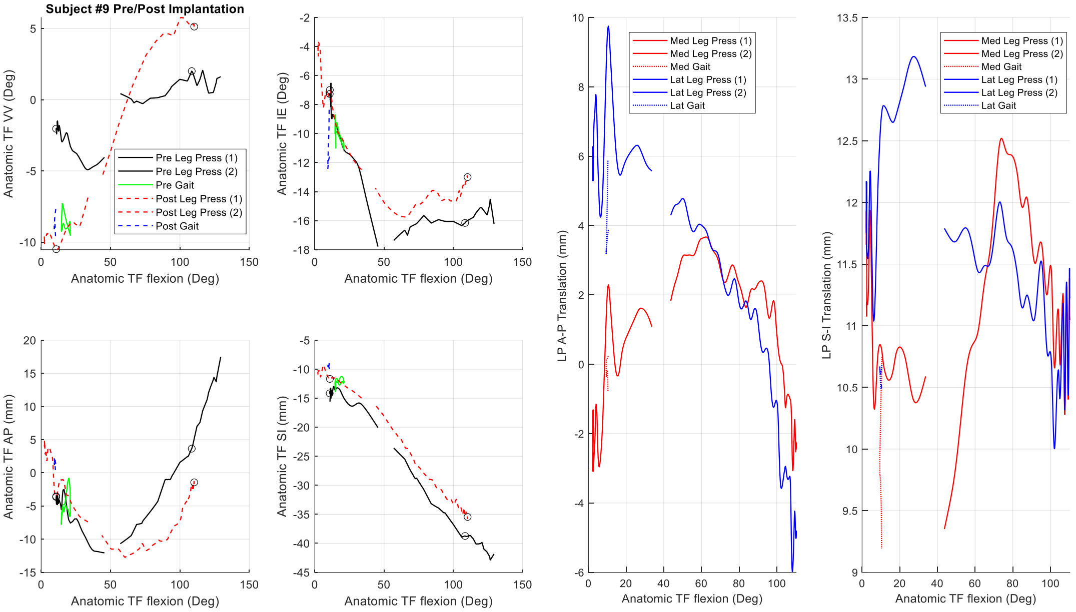

Figure A.0.13: Subject 5R kinematic data for leg press and gait trials before and after TKA. AP and SI low point kinematics for both gait and leg press.

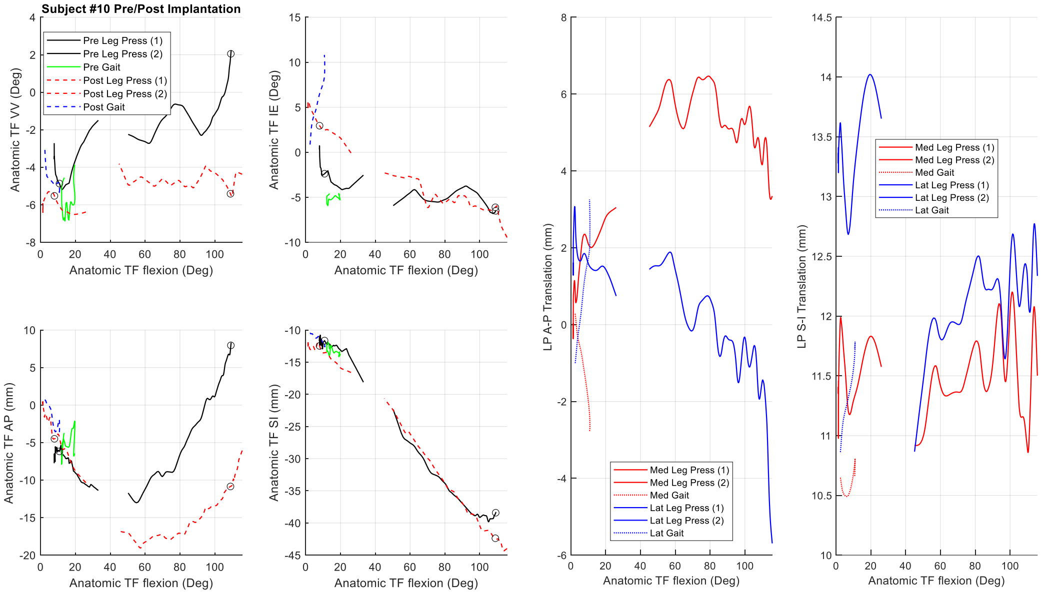

Figure A.0.14: Subject 5L kinematic data for leg press and gait trials before and after TKA. AP and SI low point kinematics for both gait and leg press.

Table A.0.1: Surgical notes for each patient. Showing consistency between surgeries for alignment technique and approach.

Subject	Date of Surgery	Age	Surgeon	Femur Implant	Tray	Insert Thickness	Intramedullary Rod	Approach	Patella	Tissue Release	Tibia Resection Alignment	Resection Depth
1	11/10/20	58	Jesse Chrastil	CR 6	FB 5	5mm	4° Valgus	Medial parapatellar	Free-handed	Deep MCL	Mechanical	9mm from high side
2	8/11/21	65	Jesse Chrastil	CR 8	FB 7	10 mm	4° Valgus	Medial parapatellar	Free-handed	Deep MCL	Mechanical	9mm from high side
3	12/29/21	47	Charlie Yang	CR 7	RP 6	7mm	4° Valgus	Medial parapatellar	Free-handed	Deep MCL	Mechanical	9mm from high side
4	2/2/22	71	Jesse Chrastil	CR 5	RP 4	7mm	4° Valgus	Medial parapatellar	Free-handed	Deep MCL	Mechanical	9mm from high side
5R	8/1/22	62	Jesse Chrastil	CR 7	RP 6	6mm	4° Valgus	Medial parapatellar	Free-handed	Deep MCL	Mechanical	9mm from high side
5L	3/7/22	62	Jesse Chrastil	CR 7	RP 6	7mm	4° Valgus	Medial parapatellar	Free-handed	Deep MCL	Mechanical	9mm from high side

Table A.0.2: Knee Injury and Osteoarthritis Outcome Score (KOOS) for each subject. Scores for each grouping and total score are reported.

Subject	Symptoms and stiffness	Pain	Function: Daily Living	Function: sports and rec activities	Quality of life total	KOOS SCORE
3	86%	100%	94%	55%	81%	**83%**
4	82%	81%	85%	80%	75%	**81%**
5R	25%	44%	60%	10%	31%	**34%**
5L	46%	64%	71%	20%	31%	**46%**

Table 0.3: Forgotten Joint Score-12 (FJS-12) for subjects 3-5L to measure joint awareness. This questionnaire was not completed by subjects 1 and 2.

Are you aware of your affected knee joint in everyday life…	Subject 3	Subject 4	Subject 5R	Subject 5L

In bed at night?	Almost never	Almost never	Mostly	Sometimes
when you are sitting on a chair for more than one hour?	Never	Sometimes	Sometimes	Seldom
when you are walking for more than 15 minutes?	Never	Sometimes	Sometimes	Sometimes
when you are taking a bath/shower?	Never	Sometimes	Sometimes	Seldom
when you are traveling in a car?	Almost never	Sometimes	Mostly	Sometimes
when you are climbing stairs?	Never	Sometimes	Mostly	Sometimes
when you are walking on uneven ground?	Almost never	Seldom	Mostly	Mostly
when you are standing up from a low sitting position?	Almost never	Sometimes	Mostly	Mostly
when you are standing for long periods of time?	Almost never	Mostly	Mostly	Mostly
when you are doing housework or gardening?	Never	Sometimes	Mostly	Mostly
when you are taking a walk/hiking?	Almost never	Mostly	Mostly	Mostly
when you are doing your favorite sport?	Almost never	Sometimes	N/A	N/A
FJS-12 Total score	**85**	**27**	**7**	**18**