AN OPTOELECTRONIC MOTION CAPTURE PROTOCOL FOR IN CLINIC ORTHOPAEDIC GAIT ANALYSIS

AN OPTOELECTRONIC MOTION CAPTURE PROTOCOL FOR IN CLINIC ORTHOPAEDIC GAIT ANALYSIS

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LAY ABSTRACT

Robotic assisted partial knee replacements have been gaining popularity in recent years due to the perceived benefits over a total knee replacement such as preserving more bone, faster recovery, and improved walking outcomes. A partial knee replacement can either replace one or both compartments of the knee joint, depending on the level of arthritis in the patient's knee. This thesis investigated the differences in walking ability before and after surgery using a specialized system installed in the hospital to collect data during regularly scheduled appointments. Patients in this study either received a partial knee replacement with the help of a surgical robot, or a regular total knee replacement. The results showed that there is a significant difference in how much the knee moves during walking between patients who had the robot surgery and those who had the usual surgery. However, the patient's experience and their perception of how well they were doing after surgery were not different between the two surgeries. This study provided valuable insight into the current surgical treatments available for knee arthritis.

ABSTRACT

Robotic assisted partial knee arthroplasty (PKA) has gained in popularity as a treatment for end stage knee osteoarthritis (OA) that involves only one or two compartments of the knee over total knee arthroplasty (TKA). PKA surgeries are known for their less invasive and more precise treatment of medial or lateral compartmental (+/- patellofemoral) arthritis, improved postoperative range of motion, greater ligament and bone preservation, and a more natural gait. The Robotic Arm Interactive Orthopedic MAKO Stryker (RIO; MAKO Stryker, Fort Lauderdale, Florida) Robot has significantly improved PKA implant alignment by providing real-time feedback during surgery and improving three-dimensional implant placement accuracy. To assess kinematic differences between robotic assisted PKA and manual technique TKA, a 14-camera optoelectronic motion capture system (Optitrack, NaturalPoint, Corvallis, OR USA) was designed and installed in a hospital hallway to collect patient gait outcomes directly after clinic appointments. This thesis investigates the feasibility and validity results from setting up a motion capture system and its associated reliability when using it in a high traffic clinical environment. The first objective of this thesis was to investigate a total of 26 patients (14 TKA, 12 PKA) that underwent a kinematic gait assessment at 4-time points; preoperatively, and postoperatively (3,6,12 months). At 3 and 6 months postoperatively, the TKA group had improved knee flexion range of motion (ROM) during walking compared to the PKA group. This result was statistically significant (3-month p value =0.042, 6-month p value= 0.048). At 6 months, changes in the knee adduction/abduction angles were also significantly different (p value= 0.023), showing less knee ROM in the frontal plane after a PKA comparable to healthy controls. Despite differences in improvements in joint kinematics during walking between the

two groups, these factors did not necessarily correlate with better perceived patient reported outcomes (PROMs). The results obtained from this pilot study display initial feasibility and suggest further research is required on a larger sample size to confirm if PKA surgeries are superior to TKA surgeries in terms of gait function. In conclusion, a repeatable, instrumented gait analysis was setup in a busy orthopedic hallway where reliable data can be collected.

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LIST OF ABBREVIATIONS AND SYMBOLS USED

%	Percent
°	Degrees
3D	Three Dimensional
AL	Anatomical Landmarks
AVG	Average
BiKA	Bicompartmental Knee Arthroplasty
CT	Computerized Tomography
CV	Change Value
DOF	Degree of Freedom
GC	Gait cycle
ICC	Intra-class correlation coefficient
LH	Left Hip
LK	Left Knee
m	Meters
m/s	Meters per second
Max	Maximum
Min	Minimum
OKS	Oxford Knee Score
PKA	Partial Knee Arthroplasty
PROM	Patient Reported Outcome Measure
RH	Right Hip
RK	Right Knee
ROM	Range of Motion
SD	Standard Deviation
SEM	Standard error of measure
TKA	Total Knee Arthroplasty
UKA	Unicompartmental Knee Arthroplasty

DECLARATION OF ACADEMIC ACHIEVEMENT

This thesis would not have been possible without the data collected over the last number of years at St. Joseph's Hospital in Hamilton ON. While I was not personally involved in the recruitment of this patient population, I took the lead on the data collection, analysis and writing for this thesis project.

CHAPTER 1 INTRODUCTION

1.1 Introduction

Arthritis is a joint disease that affects 6 million Canadians, with half of those affected over the age of 65[1]. Osteoarthritis (OA) is the most common type of arthritis, and is characterized by the deterioration of cartilage, subchondral bone, and the surrounding musculature, tendons, and ligaments[2]. OA leads to pain, reduced range of motion, and impaired mobility, most commonly affecting the hips and knees[2].

Knee OA specifically has affected over 650 million individuals globally, with a higher prevalence among women compared to men[3][4]. While there is currently no cure for OA, treatments for mild to moderate OA often include physiotherapy, bracing, medical intervention such as injections, or pharmacology[5]. For advanced OA, surgical options such as a total knee arthroplasty (TKA) can provide significant pain relief and improve function[4]. TKA is one of the most common surgeries performed in Canada, with over 65,000 surgeries performed yearly and increasing over the past decade[6].

There are currently two types of surgeries offered: TKA and partial knee arthroplasty (PKA). In a TKA, all compartments of the knee are replaced with an artificial joint. In contrast, in a PKA, a unicompartmental knee arthroplasty (UKA) or bicompartmental knee arthroplasty (BiKA) can be performed, with only the damaged compartments in the knee getting replaced[7][8]. In Canada, the current standard of care for advanced knee OA is a TKA due to the perception of durability, surgeon preference/experience and clinical standards[9][10].

Between 2019 and 2020, 8% of knee replacements performed in Canada were UKA[11]. Early reviews of UKA reported poor results[8] leading to the belief that TKA was a more reliable and durable procedure. However, more recent studies have shown improved outcomes due to better patient selection, improved surgical techniques, more advanced component design, and improved instrumentation[12][13]. These advances have helped to increase the durability of UKA, making it a more popular surgical option for isolated medial compartmental knee OA in younger patients (ages 40-60 years)[7][14]. Recent studies on UKA have reported several potential advantages over TKA, including lower rates of complications[15], lower risk of infection[15], less blood loss[16], faster recovery[14], and improved range of motion[14].

To improve the success rates of these procedures, researchers are examining variables that can be controlled by the surgeon during surgery, such as lower leg alignment, joint line maintenance, and the alignment, size, and fixation methods of the tibial and femoral components[9]. To control these variables more accurately and reliably, several computer-assisted surgery systems have been developed, including robotic-assisted systems[17]. Robotic-assisted surgeries have been shown to improve the alignment and positioning of implants in PKA and show a high survival rate and a high level of patient satisfaction of 92%[13] at a short-term follow-up with minimal technical errors. However, there is currently limited data on the long-term success and functional outcomes of robotic-assisted surgery, and more research is needed to determine if the increased accuracy of these systems leads to better long-term success of robotic-assisted PKA[9][18]. In addition, prospective comparative studies with a longer follow-up period and a higher follow-up rate are needed to compare the long-term survival and satisfaction rates of robotic-assisted PKA compared to manual PKA and TKA[13].

Traditionally, the success of a surgery is evaluated using radiological assessment, functional assessment, and patient-reported outcome measures (PROMs)[19]. Radiological assessment ensures correct component alignment based on the patients' joint surfaces. Kinematic assessment is used to observe static range of motion and PROMs are used to understand the effects of postoperative pain, daily function, and overall affect on the quality of life based on self-reported questionnaires[20]. However, PROMs only provide a broad overview of surgical outcomes and may not accurately capture functional limitations[21]. Performance-based measures, such as gait parameters obtained through instrumented gait analysis, can provide objective, quantitative information about the patient's functional abilities and have been shown to be related to patient satisfaction after TKA surgery[22]. Specifically, marker- based motion capture systems have been used in orthopaedic research for decades to track continuous motion in 3D space and are currently considered the gold standard in gait analysis[23]. Motion capture technology can be used to assess the success of a knee replacement surgery by measuring the range of motion, alignment, and function of the knee joint[24]. Although motion capture functional assessments are typically not utilized in clinical settings due to the high cost and specialized equipment required for the analysis, their routine use within a clinical setting could enhance the reporting of outcomes in the field[25].

1.2 Objectives

1.2.1 Objective 1: In-Clinic Marker Based Optoelectronic Motion Capture

The aim of Objective 1 is to install and establish the feasibility and reliability of a marker-based optoelectronic motion capture system in a hallway within the Fracture and Orthopaedics Outpatient Clinic at St. Joseph's Healthcare in Hamilton, ON.

1.2.2 Objective 1 Hypothesis

i) A motion capture system and protocol will be installed and deemed feasible to collect patient data in a hallway of St. Joseph's Hospital fracture clinic.

ii) A motion capture system and protocol will provide knee joint kinematic outcomes that are reliable and within average values of lab-based systems.

1.2.3 Objective 2: Knee Joint Gait Outcomes Between Manual Total Knee Replacements vs Robotic Assisted Partial Knee Replacements

The aim of Objective 2 is to compare knee kinematic gait outcomes as change values between preoperative and postoperative knee kinematics for patients receiving robotic-assisted PKA and those receiving manual TKA. A secondary aim is to compare patient reported outcomes between the surgeries.

1.2.4 Objective 2 Hypothesis

i) There will be significant differences in knee kinematic outcomes between robotic assisted PKA and manual TKA, with PKA surgeries having better kinematic outcomes.

ii) PROMs between robotic-assisted PKA and manual TKA will be significantly different significantly, with PKA surgeries hypothesized to have better outcomes.

1.3 Structure of Thesis

The chapters of this thesis are organized in the following manner: Chapter 2 provides background information related to knee osteoarthritis, normal human gait and knee movement, gait analysis for knee osteoarthritis and an in-depth review of the current literature available for both total knee replacements, partial knee replacements, robotic assisted surgeries, the clinical and gait outcomes of the surgeries. Chapters 3 and 4 each address *Objective 1* and *Objective 2* respectively. Lastly, Chapter 5 offers a summary of the thesis outcomes and their practical implications, along with a discussion of any limitations and recommendations for future research directions.

CHAPTER 2 BACKGROUND

2.1 Knee Osteoarthritis

Arthritis affects approximately one in five people, with prevalence increasing to one in two individuals for those over the age of 65[26]. Osteoarthritis (OA) is the most common joint disease, predominantly affecting the knees and is a leading cause of disability among older adults[26]. There are two common forms of OA: primary and secondary OA. Primary OA is the most common type and is associated with degenerative risk factors such as age, obesity, and genetics[2]. Secondary OA occurs in the presence of pre-existing joint abnormalities or following trauma or injury[2]. Knee OA can affect any of the three compartments of the knee joint and is caused by the progressive overload of the cartilage leading to its degeneration [4]. This process can result in a loss of cartilage in the affected compartments, leading to bone-on-bone contact, pain, and difficulty with mobility[4]. Clinical presentation of OA includes gradual onset of knee pain that worsens with activity requiring analgesics, swelling, stiffness and pain after prolonged rest, and loss of function/mobility[26]. End-stage OA is commonly diagnosed by means of physical examination and radiographic imaging. A study revealed that only 15% of patients with radiographic evidence of knee OA exhibited symptoms and women are more frequently affected by OA[3][4][26]. Progressive gait changes can be seen including sagittal plane changes at the knee creating successively smaller knee flexion angles during the stance phase and less total range of motion[27]. Knee kinematics during walking can significantly influence the initiation and progression of osteoarthritis as biomechanical changes in the knee are related to differing stages of clinical OA severity[28]. Presently, there is no cure for OA, and the focus is on mitigating symptoms and impeding progression. Conservative approaches such as physiotherapy and intra-articular injections are first pursued, followed by joint-preserving measures such as arthroscopy, before resorting to joint replacement[26].

2.2 Biomechanics

2.2.1 Human Gait Cycle

A healthy human gait cycle is one in which a person can walk smoothly and efficiently. It is a repetitive process that involves the use of both legs to provide support and propulsion, and it requires a coordinated and balanced sequence of movements to maintain stance stability[29]. During walking, one limb acts as a source of support while the other limb moves forward to a new support site. Then, the roles of the limbs are reversed, and this process is repeated and each sequence of these movements by one limb is called a gait cycle[30]. Each gait cycle is divided into two phases: stance phase and swing phase[29]. Stance phase occurs from 0-60% of the gait cycle where the foot is on the ground can be further divided into loading response (0-10% of gait cycle), midstance (10-30% of gait cycle), terminal stance (30-50% of gait cycle) and pre-swing (50-60% of gait cycle)[29]. The stance phase can also be broken down into double support and single support where double support starts at initial contact and loading response then transitions to single support for midstance and terminal stance then back to the second double support for pre-swing[29]. Toe off is the transition between stance and swing phase. Swing phase applies to the time the foot is in the air for limb advancement which can be divided into initial swing (60-70% of gait cycle), mid-swing (70-85% of gait cycle) and terminal swing (85-100% of gait cycle)[29][30]. A figure of the gait cycle can be seen in Figure 2.1

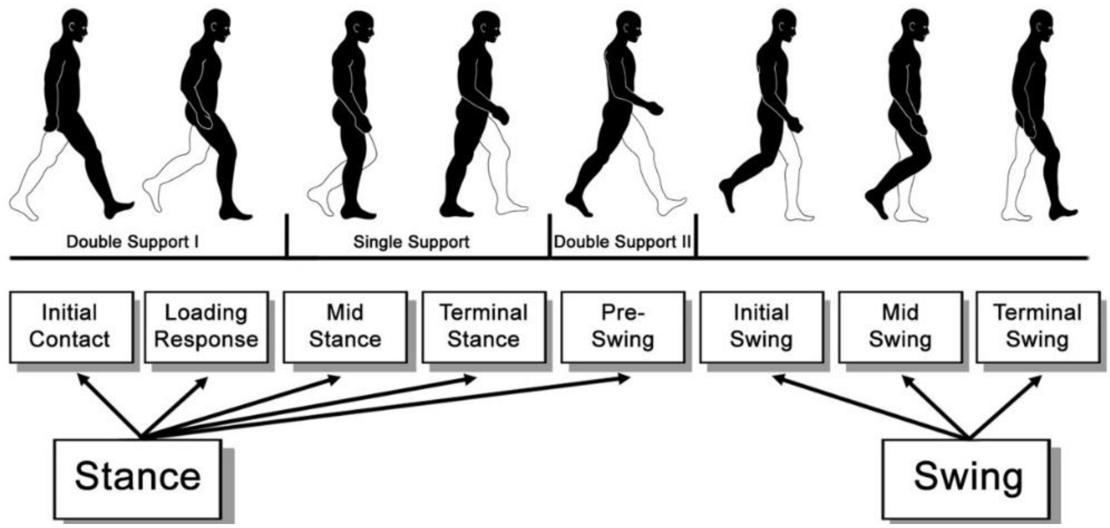

Figure 2.1: Breakdown of the gait cycle based on previous literature[31][32].

A healthy gait pattern relies on a range of biomechanical features that are coordinated by the central nervous system for efficiency and stability. When these features are altered by injuries or pathologies, it can lead to significant gait impairments that can have negative consequences for mobility and overall health[33].

2.2.2 Gait Biomechanics

Kinematics is the study of body motion, excluding the forces responsible for body movements during gait [34][35]. Kinematics analyzes the positions, angles, velocities, and accelerations of body segments and joints[35]. The knee joint is typically described in three rotational degrees of freedom in the sagittal (flexion/extension), coronal (adduction/abduction), and transverse (internal/external rotation) planes for clear clinical interpretation (Figure 2.2)[31][32].

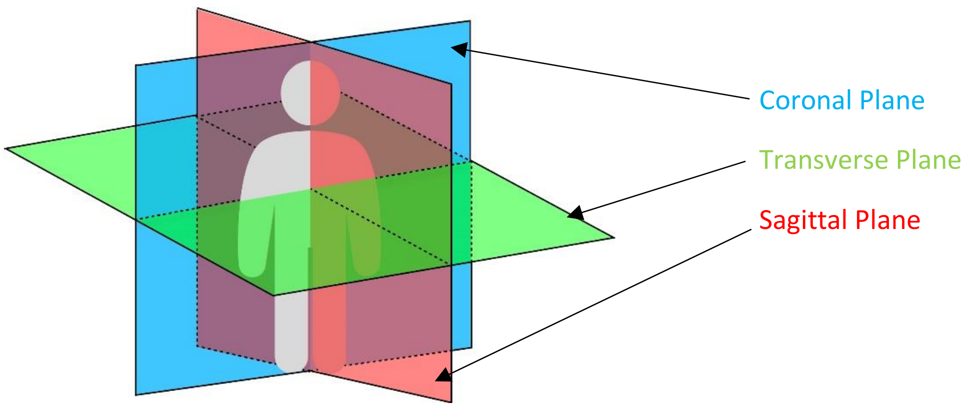

Figure 2.2: Planes of the body; Blue describes the coronal plane, Green represents the transverse plane and Red represents the sagittal plane

Mathematically describing clinical hip, knee, and ankle joint angles during gait is a challenge to accurately capture. The joint coordinate system developed by Grood and Suntay[36] was used to describe the 3D motion of the knee about three axes. The flexion/extension axis is defined by the medial and lateral epicondyles of the femur, while the internal/external rotation axis is about the long axis of the shank from the lateral malleolus to the head of the fibula [36]. The ab/adduction axis is a floating axis defined by the cross product of the flexion/extension and internal/external rotation axis vectors[36].

2.2.2.1 Knee Kinematics

The knee's functions include providing limb stability, supporting body weight, deceleration, and flexibility to allow limb movement during the swing phase[34][35].The knee angle is determined by the movement of the thigh and shank in three-dimensional (3D) space. The knee moves in three planes: the coronal, transverse, and sagittal plane as the knee is capable of flexion/extension, abduction/adduction, and rotation[37]. The coronal plane divides the body into front and back halves and measures the side-to-side movement (also called adduction and abduction)[37]. The transverse plane runs horizontally and divides the body into upper and lower halves and looking at rotation. Lastly, the sagittal plane runs front to back and looks at the knee during flexion and extension[34][35]. The knee has two flexion/extension peaks during the gait cycle. During initial contact, the knee is fully extended (0°), and during loading response, it flexes around 15°[34][35]. In single support, the knee is fully extended and while transitioning to the second double support, there is passive knee flexion (around 35°), preparing for swing phase[34][35]. Throughout the stance phase the knee also undergoes adduction and external rotation as the leg moves towards the midline of the body[38]. At the beginning of the swing phase, the knee is flexed around 60° for limb advancement reaching the peak flexion angle[34][35]. During mid-swing, the knee extends passively to facilitate limb advancement reaching the peak flexion angle during the initial swing phase[34][35]. At terminal swing, the knee remains in extension in preparation for the next initial ground contact[34][35]. The knee's movement is critical for maintaining stance stability, absorbing shock, and is associated with foot and ankle movements[34][35]. During the swing phase the knee also undergoes abduction, and internal rotation as the leg swings forward[38]. A normal gait has a knee joint range of motion of around 60° in the sagittal plane, with minimal frontal plane movement[34][35].

2.2.3 Motion Capture

Motion analysis aims to collect information about the musculo-skeletal system during walking through kinematic and kinetic data. This can be achieved using various forms of image processing, floor sensors or sensors placed on the body[39]. The current gold standard for gait analysis is marker-based motion capture[25]. This system works by installing a group of cameras along the periphery of a space as seen in Figure 2.3. Using 3D motion analysis, the joint motion is modelled in three Degrees of Freedom (DOF) with each rigid body segment assigned a 3-dimensional axis system, originating at the joint centre[40][41]. In order to obtain numerical information for reconstructing joint movement, motion and morphological data is required[41]. To describe segment morphology, it is broken down into a series of points that are located in relation to a set of perpendicular axes. This set of axes is called the local frame[40]. Vector transformation calculates the position vectors of a segment's points using a local and global frame[40]. The position vector and orientation matrix of each bony segment are determined relative to a global frame of reference[40]. The global frame of reference is established using marker position coordinates provided by the system, which are defined relative to the system's calibration.

Figure 2.3: Standard marker-based motion capture setup[42]

A cluster non-collinear markers affiliated with the bony segment is used to demonstrate joint motion[41]. Clusters are typically made up of 3 or more non-collinear markers to identify the clusters in each axis[41]. The number of clusters required for a motion capture system may vary based on camera views and the data to be collected. Depending on the system restrictions, the marker clusters can be added or removed to optimize data collection for a space. Previously published work has shown the most used cluster placement[43]. To ensure repeatability, calibration is performed on each subject, as the position of marker clusters is arbitrary and non-repeatable[40]. Anatomical Landmarks (AL) are used for calibration, which are specific and repeatable points on the subject's anatomy[44]. These landmarks are identified through palpation and located with individual makers[41]. The movement of the clusters can then be defined relative to these AL which is similar to global frame calibration [41].

Once all the clusters and individual markers have been captured, AL can be removed prior to data collection [34][41]. The cameras collect marker movements as the participant performs various exercises or activities. The collected data can then be used to compute various metrics, including the range of motion, joint alignment, and knee stability[23]. Optimal motion capture data collection is based on the estimated 3D positions of markers by triangulation from multiple cameras. Successful data collection relies on the marker visibility from at least two cameras at once and the triangulation accuracy[45][42]. Camera configuration has a significant impact on the quality of the 3D position estimation as the two-dimensional views of each camera to reconstruct 3D coordinates of the markers[45]. Based on the data collection environment, and the intended use, the number of cameras used can vary[42]. In common applications tracking a skeleton or a rigid body to obtain the 6 DOF data, it is beneficial to arrange the cameras around the periphery of the capture volume for tracking markers both in front and back of the subject[42][45].

Kinematic crosstalk is an occurrence that can cause errors in joint angles. This occurs when off-plane motions are projected onto the defined coordinate system due to misalignment between the coordinate system and in vivo motion[40]. This can result in errors in the measurement of motion, which can negatively impact the accuracy and precision of kinematic analyses[40]. To prevent kinematic crosstalk, it is crucial to align the coordinate systems with the directions of motion[40].The joint coordinate system has been tested for reliability in kinematic measurements, but they have been found to be less reliable in regions with high flexion, rotation, and adduction angles[40].

2.3 Knee Arthroplasty

2.3.1 Total Knee Arthroplasty

A total knee arthroplasty (TKA) is currently the standard of care for end stage knee OA. The primary aim of this surgery is to relieve pain, correct deformity and improve function. TKA is the most often performed surgery due to its consistent success, reliable outcomes, surgeon preference and surgeon experience[46][47]. Within a TKA, the entire knee joint including the damaged or diseased articular surfaces, and healthy components (femoral condyles and tibial plateau) of the knee joint are replaced with smooth metal and polyethylene plastic[47]. Despite being a dependable and reproducibly successful surgery for patients with debilitating advanced arthritic knees, approximately 20% of patients are dissatisfied with the results[47].

TKA complications can occur. Some of the most common complications include implant loosening, bearing surface wear, instability, malalignment, stiffness, reoperation, revision surgery as well as other complications typically related to most invasive operation such as vascular and tissue related adverse events[48]. Although patients who undergo TKA typically experience a significant reduction in knee pain and an improvement in knee function, functional performance one year postoperatively remains lower than that of healthy adults[49]. Studies have reported an 18% slower walking speed, 51% slower stair-climbing speed, and nearly 40% deficits in quadriceps strength among these patients. Additionally, they may have difficulty with kneeling, squatting, performing lower extremity strengthening exercises, and participating in various activities when compared to healthy adults[49].

2.3.2 Partial Knee Arthroplasty

Studies have reported up to 30% of TKA patients presenting with knee degeneration are limited to one compartment of the knee, predominantly the medial component[50]. Unicompartmental knee arthroplasty (UKA) is an alternative to a TKA for selected patients with severe single compartment knee OA (Figure 2.3)[50]. They are more susceptible to component malalignment and progression of arthritis in other parts of the knee which can result in early implant wear, bearing dislocations, suboptimal functional outcomes, and a higher revision rate[51][52].

UKA surgeries are more technically challenging than a TKA due to smaller surgical incisions resulting in reduced visibility of anatomical landmarks[51]. If a UKA fails, most often it must be converted to a TKA, which can increase surgical complexity and potentially lead to inferior outcomes compared to if a TKA was initially performed[53]. Initial UKA outcomes showed high rates of failures, with about 28% of patients requiring conversion to TKA within an average of six years of follow-up[47]. However, advancements in implant design and surgical techniques have improved upon the previous surgical shortfalls[47]. Proper patient selection criteria have also been adapted to better control postoperative outcomes. UKA is typically recommended for patients who have low pain at rest, more than 90 degrees of preoperative ROM, and not have an angular deformity over 15°[47]. Strict adherence to these criteria can be challenging, as one analysis showed that only 6.1% of cases met the anatomical indications and only 4.3% met the clinical indications for UKA[47]. On average, UKA patients are also more likely to undergo revision surgery showing a lower clinical threshold for UKA revisions[52].

Recent literature has shown that UKA can improve the quality of life in patients over 65 years of age due to increased bone and ligament preservation, better post-operative range of motion and improved gait with some studies suggesting normal knee kinematics can be preserved[54]. For patient suffering with patellofemoral OA in addition to medial compartmental OA, a bicompartmental knee arthroplasty (BiKA) can be performed (Figure 2.4). BiKA are an excellent alternative with advanced OA spreading past one compartment, but not enough to warrant the need for a TKA[8]. This surgical technique bridges the gap between a TKA and UKA allowing a bone and ligament sparing approach to help with end stage OA[8].

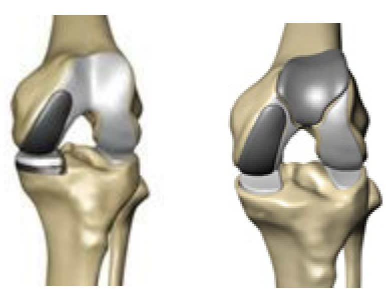

Figure 2.4: Medial UKA and medial BiKA[55]

Despite these advantages, PKA may be an underutilized procedure. This can be partly due to concerns about the long-term survival of the implant[8]. However, recent studies have shown that PKA performed in high-volume centers has a survivorship over 95% after 10 years, and revision and survivorship rates comparable to a TKA[54].

2.3.3 Robotic Assisted Knee Arthroplasty

Robotic assisted surgeries have recently gained in popularity to challenge the difficulties previously associated with UKA surgeries. Semiactive robotic systems provide the surgeon with active control of the robot during surgery. These systems use pre-operative computerized tomography (CT) scans to create a surgical plan and enable the surgeon to actively control the preplan the surgery and control the cutting process. Additionally, they incorporate features designed to reduce the risk of complications during surgery with the use of tactile feedback [9].Surgeons can accurately control lower leg alignment, balance soft tissue and assess component alignment, size and fixation [9]. However, these systems require the use of an invasive frame that must be applied to he patient so that the robotic arm will know where the knee is in space, and the system has exclusive compatibility with a prosthesis[17]. The use of robotic technologies for controlling UKA surgical techniques has the potential to improve survivorship for treating isolated medial compartment degenerative joint disease[17].

The use of robotic-assisted surgery may benefit surgeons in the earlier stages of their training, by providing intraoperative monitoring and control of critical parameters such as precise implant placement and leg alignment [56]. Specifically, the Robotic Arm Interactive Orthopedic MAKO (RIO; MAKO Stryker, Fort Lauderdale, Florida) robot allows frontal plane mechanical alignment during a robotic PKA is accuracy within 1.6°, soft tissue balancing within 0.53 mm of all flexion angles, femoral implant positioning within 0.8 mm and 0.9° and tibial component alignment within 0.9 mm and 1.7° of the preoperative plan in all directions[56]. This is currently the most used surgical robot for TKA and UKA making up 20% of the market[57].

The MAKO RIO system is a CT-based technology that features a navigation module for preoperative planning and computer-assisted positioning of implants[46][48]. A 3D model is generated based on the patient's preoperative CT scan to plan the implant position (Figure 2.1). The surgeon determines the optimal implant position within the system, and the software then defines the bone resection areas and boundaries for the cutting instrument[46][48]. The distal end of the robot is connected to a high-speed bur, which provides audio feedback as the surgeon cuts bone [55][56]. If the surgeon approaches the predefined boundaries of the implant position, haptic feedback is provided via active stiffness of the robotic arm. If the cutting instrument encounters excessive pressure or if the patient's anatomy moves rapidly, the instrument immediately stops [55][56]. Once the components are inserted, the surgeon performs a complete flexion-extension arc of the patient's knee to receive feedback about the current leg alignment and knee kinematics [55][56]. After accepting the implant position, both implant components are cemented, and a final range of motion is measured to compare implant kinematics, as well as the knee alignment[55][56].

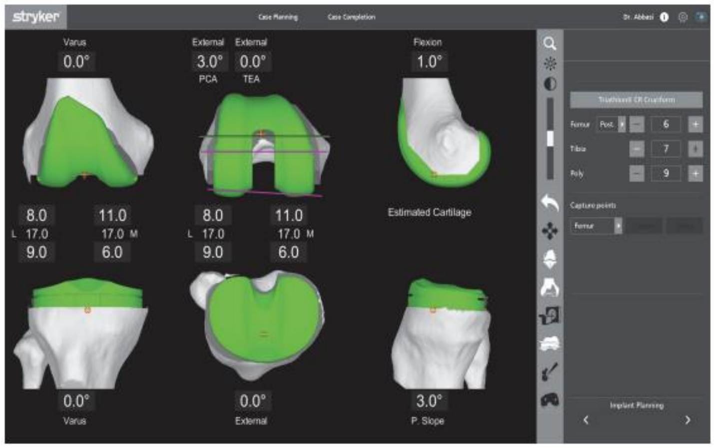

Figure 2.5: RIO system preoperative implant planning image [55]

This level of accuracy is significantly higher than that of any manual surgery. The use of the MAKO RIO system for PKA surgery can result in greater conservation of bony surfaces during arthroplasty[54][56].

2.4 Knee Arthroplasty Outcomes

2.4.1 Clinical Outcomes PKA vs TKA

PKA offers advantages over TKA, including reduced blood loss, faster postoperative recovery, increased postoperative activity[58]. Performing a TKA for medial OA results in greater ligament damage as TKA involves larger surgical trauma and treatment, whereas UKA retains knee ligament structure with less osteotomy[58][59]. More recent studies have found no difference between UKA and TKA in terms of preoperative and postoperative pain[50]. A study comparing UKA, BiKA and TKA found the highest clinical improvements (PROMs) were seen at 6 months postoperatively for the UKA group. Between 6-12 months, only modest improvements were noticed, with no improvements between 1-2 years for all groups [8].

Early UKA failures within the first year postoperatively can be attributed to surgical error and patient selection, which created high revision rates compared to TKA. This can be related to early implant generation, improper patient selection criteria and limited instrumentation [59] ,[60]. Optimal outcomes after UKA depend on patient selection and surgeon experience [7], [58], with studies currently showing no difference between UKA and TKA survivorship[50]. With the addition of robotic-assisted surgeries, implant accuracy has further improved [54][56]. One study performed a worst-case scenario analysis of robotic UKA and revealed similar survivorship to manual UKA. The overall robotic UKA survivorship was 97% which is higher than a manual UKA [54][56]. Within robotic assisted surgeries the prosthesis can be positioned up to 4 times more accurately, while in a manual UKA approximately 40% of components inserted differed by more than 2 degrees from the preoperative plan [54][56]. Prospective comparative studies with longer follow-up periods and higher follow-up rates are necessary to further compare the survivorship and satisfaction rates, among other outcomes, of robotic-assisted UKA/BiKA to conventional UKA/BiKA, and TKA. [54][56].

When looking into clinical outcomes, radiographic imaging and PROMs are most often used to measure surgical success. PROMs are considered the gold standard for evaluating patients' experiences with a clinical intervention or disease in patient-centered care[61]. By collecting data directly from patients, PROMs provide an efficient means of assessing their feelings, thoughts, and concerns[61]. They can be used to monitor the progress of individual patients, investigate the effects of medical and surgical interventions and assess the quality of care being delivered[61]. They enable healthcare providers to gain a better understanding of patients' perspectives and tailor their care accordingly[61]. A disadvantage of using PROMs is that they provide subjective measurements that can affect the accuracy and precision of diagnoses, follow-up, and treatment[39]. There are correlations between gait biomechanics measures assessed using PROMs, however, further biomechanical investigation is necessary to determine whether PROM effectively reflect changes in the quality of movement[61].

2.4.2 Gait Outcomes

Generally, gait outcomes vary between the types of surgeries with slightly greater improvements when performed robotically. When comparing gait outcomes, TKA are used as the baseline comparison as they are currently the standard of care for all knee OA in Canada. Looking at ROM, studies show a significant difference in postoperative ROM with higher values in the UKA group[50] of an approximately 20° postoperatively [56]. Alternatively, other studies have found UKA flexion at swing to be 0.4° less than a TKA (thought not statistically significant), and statistical difference in frontal plane angles, and spatiotemporal analysis was not significant[46]. In some instances, UKA knees show a better gait pattern in terms of velocity and step length symmetry when comparing to a TKA, but these comparisons did not account for preoperative patient mobility in each group [50],[62]. Kinematic specific studies have shown BiKA exhibit motion patterns like those seen in total knee arthroplasty, with slightly less flexion in stance compared to UKA but greater dynamic laxity during gait. However, in properly selected patients, BiKA knees can provide excellent functional outcomes that are similar to those observed in UKA [50],[60], [63]. Preservation of both cruciate ligaments during knee arthroplasty helps maintain some fundamental aspects of normal knee kinematics [63]. Ligament preservation is indicative of the level of disease severity, and excessive ligament laxity can negatively affect surgical outcomes [63]. Robotic surgeries did not significantly impact postsurgical range of motion [64].The greatest differences were found between the types of surgical intervention, with UKA surgeries having the highest results in terms of overall ROM [63],[64].

Overall, gait outcomes in TKA, UKA and BiKA are subject to limitations specifically when looking into the ROM around stance, swing and overall kinematic analysis. Determining which knee arthroplasty provides gait outcomes closest to normal gait are highly dependent on patient selection, surgeon experience, and patient OA severity.

2.5 Methodological Considerations in Clinical Biomechanics

Biomechanical data produced by 3D gait analysis is complex and variable in nature making it necessary to select specific parameters of interest from the data such as peak values during specified time points[27]. Although motion capture is the gold standard for capturing movement data that can be used to represent knee function, it is rarely used in clinical settings due to space restrictions, equipment, and personnel requirements. However, modified motion capture systems have been successfully implemented in clinics to assess knee function before and after surgery, showing potential for routine use in improving reporting of functional outcomes in orthopedics [65]. Using modified motion capture systems in clinical settings could be highly beneficial for objectively evaluating the success of specific surgical interventions, such as robotic-assisted PKA versus manual TKA through the assessment of gait parameters. This technology shows potential for routine use in clinical environments, by providing accurate and reliable biomechanical data. Motion capture systems could help clinicians make more informed decisions about patient care, leading to improved treatment and better patient outcomes

[66][67]. If successfully integrated into clinical practice, motion capture technology could offer a new level of precision and objectivity in the evaluation of knee function in orthopaedics.

CHAPTER 3 OPTOELECTRONIC MOTION CAPTURE PROTOCOL FOR IN-CLINIC ORTHOPAEDIC GAIT ANALYSIS

3.1 Introduction

Gait analysis is a standard procedure in the clinical setting, used to evaluate patients with gait abnormalities for the purpose determining severity, developing treatment plans and monitor progress[66]. Although most clinicians perform a subjective visual analysis of patient joint function, computerized gait collection using camera and sensors analysis have gained attention. Measures of gait changes, particularly in spatial and temporal parameters, can serve as important predictors of overall health and functional decline in individuals [66]. These gait parameters from computerized analysis can also serve as endpoints in assessing the effect of an intervention [66][67].

Optoelectronic motion capture systems are used in gait analysis, as they allow for the accurate measurement and tracking of continuous motion in three-dimensional (3D) space. This technology is known as the gold standard for kinematic gait collection providing valuable insights into gait abnormalities and the effectiveness of interventions. [23][24]. By quantifying kinematic and kinetic variables, motion capture systems can provide clinicians with objective data that can inform clinical decision-making and treatment planning [66]. Patient gait data is compared to the average healthy control as a reference which informs the basis of clinical decisions and serves as the standard when analyzing surgical intervention success [68].

Gait labs are typically set up in rooms designed to carefully control for all external factors and create ideal conditions for data collection. However, dedicated laboratory space can be a significant barrier for some institutions, limiting access to gait analysis services for patients.

Therefore, researchers and clinicians need to explore alternative approaches to gait analysis that can be implemented in a wider range of settings. When setting up a gait lab in a non-traditional environment, it is important to ensure reliable data can be collected. Measurement errors and variability is inevitable and can occur from varying sources including the examiner, the measurement system, environment, and the subject. When interpreting data, understanding potential deviations ais important to ensure proper interpretation. Degrees of deviation must be discussed with clinicians prior to data interpretation to ensure experimental error does not impact clinical care[68].

In addition to laboratory settings, motion capture technology can also be used in clinical settings to assess the success of a clinical or surgical procedure, such as knee arthroplasty. By measuring the range of motion, alignment, and function of the knee joint, motion capture systems can provide important information about the patient's postoperative recovery and help clinicians make informed decisions about ongoing care. The objective of this study is to design a system installation and motion capture protocol of a marker- based optoelectronic motion capture system for instrumented gait analysis in a hallway within the Fracture and Orthopaedics Outpatient Clinic at St. Joseph’s Healthcare in Hamilton, ON within the orthopedic fracture clinic hallway in St. Joseph’s Hospital in Hamilton, ON, and establish the feasibility and reliability of the system. It is hypothesized that, a reliable motion capture system and protocol will be installed and deemed feasible. This motion capture system and protocol will also provide knee kinematic outcomes that have similar reliability to lab-based protocols.

3.2 Methods

3.2.1 System Setup Constraints

Installation of the marker-based motion capture camera setup prioritized ease of patient data collection. Given the limited number of partial knee arthroplasties (PKA) performed, patient enrollment and adherence to gait collection timelines was crucial. To reduce the burden on the research participants, the scheduling of gait data collection was arranged to coincide with most of their standard clinic appointments. The setup of the motion capture system was constrained by the limited space available within the orthopaedic clinic, and the challenges associated with collecting high-fidelity data.

According to recommendations, the optimal minimum setup dimensions for data collection is within an area that is 9x9 meters (length x width) to provide a data collection area of 4x4x2 meters (length x width x height) [42]. Additional vertical space for data collection is advised, as it enables improved camera coverage. The camera layout recommendation is along the periphery of the capture volume at varying heights to prevent interference from infrared light sources, including sunlight. Ambient light should be minimized, and reflective flooring should be avoided within the capture volume[69].

The hallway dimensions in the fracture clinic were 7x1.4x2.5 meters (length x width x height). One wall along the length of the hallway was frosted glass, and the floor was a waxed vinyl floor (Figure 3.1). Sunlight and additional lights provided ample brightness to the hallway. Figure 3.1 shows an image of the hallway for reference.

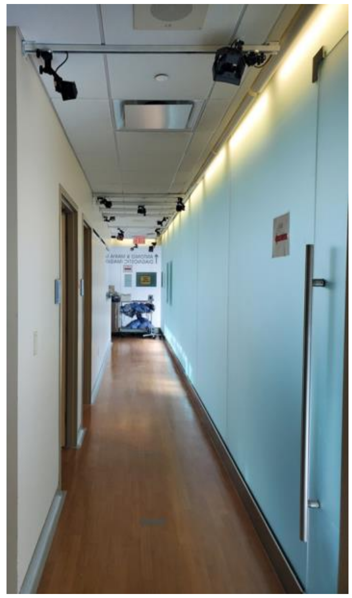

Figure 3.1: Image of the hallway at St. Joseph's hospital with cameras setup in the ceiling

A schematic of the clinic space can be seen in Appendix A.1. The quality of the motion capture data in the hallway can be affected by the lighting and reflections from the walls and other surfaces.

Prior to installation, all criteria and constraints were assessed to properly ensure the cameras could be setup in this location as seen in Table 3.1.

Table 3.1: Criteria and constraints of the hallway motion capture setup

Criteria & Constraints	Description
Space	The area for data collection is 7x1.4x8.5 meters (length x width x height).
Lighting	Lighting from the glass wall in unpredictable. There are fluorescent lights along the top of the glass wall adding minor reflections to the waxed vinyl floor
Marker placement	A reliable and repeatable protocol needs to be developed for placing markers on the body of the person being tracked. Markers should also be adaptable to different body sizes and shapes.
Marker tracking	The system needs to be able to track the movement of the markers reliably and accurately in real-time.
Safety	Considerations for equipment placement, marker placement, and potential hazards such as tripping or collisions with other people or objects in the hallway must be considered.
Flexibility	The setup should be designed to be easily set up and adjusted to minimize disruption to the hallway and allow for use in a variety of situations.
Time constraint	Data collection on participants must be limited to 20 minutes to not disrupt the flow of traffic within the space.

Safety of all staff and patients was a top priority. The system needed to be installed in a way to not obstruct flow of traffic or impede the regular duties of personnel. This includes all cameras, cables, and collection equipment. Testing the setup also had to be easy and manageable. Prior to installation we were unsure of the quality of the data we would be able to collect based on the initial camera setup. We anticipated the setup would require the testing of different configurations. This would entail data collection, processing, identifying which camera views could be improved then adjusting the setup and testing again. The testing process was repeated until the desired outcome is achieved. Overall, the installation of a motion capture system in a busy hospital hallway required careful planning and consideration of a number of criteria and constraints to ensure the safety and efficacy of the system[68].

3.2.2 Marker Placement

Spatial restrictions limited marker visibility. Initial marker placements followed previously published placement which can be seen in Figure 3.2[70]. Accurate tracking the locations of specific anatomical landmarks as the participant walks was necessary to model movement kinematics. Anatomical landmarks were identified through palpation using standardized protocols[44]. All anatomical and rigid clusters were placed on the participant during the calibration trials. Prior to the gait trials, anatomical markers were removed for the cameras to only track the clusters and minimize errors. Marker placement has been previously reported as a large source of variability[71]. Due to the camera placement, we anticipated not all clusters would track correctly, and would need to be slightly altered and optimized for the current setup. Understanding the limitations of the camera views, the marker placements were adjusted and tested until the data collected was providing consistent and continuous results.

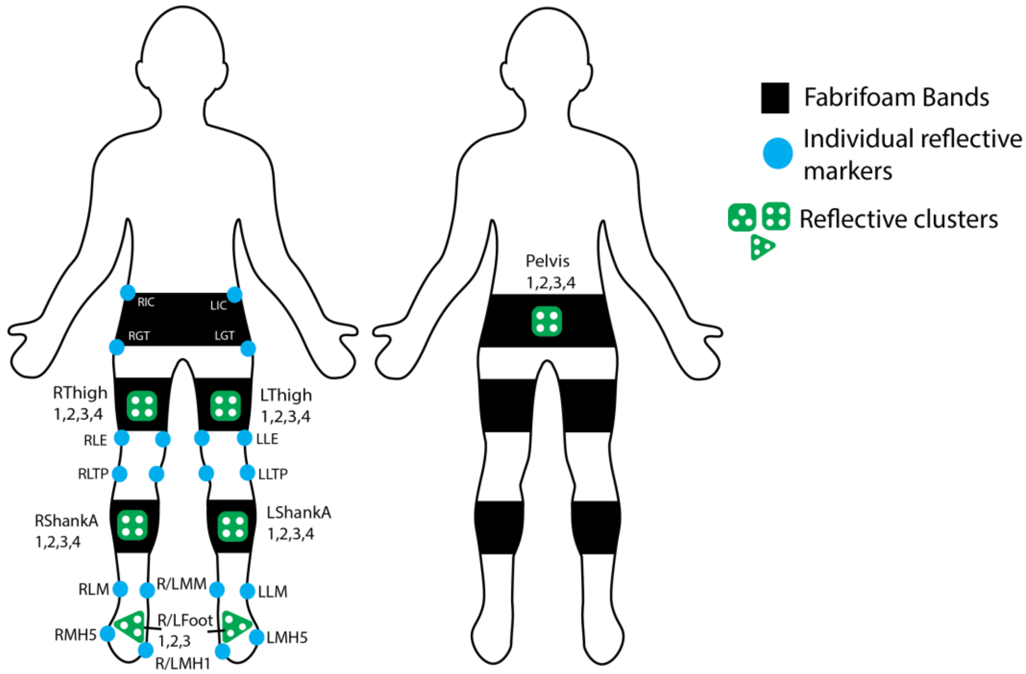

Figure 3.2: Initial marker placement setup of the anterior and posterior view respectively. Marker placement acronym definitions can be found in Appendix A.2. R: right side, L: left side, A: anterior part of the body

3.2.3 Participants

Participants (n=5) were healthy volunteers recruited by the research team through St. Joseph's Healthcare Hamilton, McMaster School of Biomedical Engineering, and the Surgical Methods Centre at McMaster University. Participants were recruited on a voluntary basis in good overall health with no history of osteoarthritis, lower extremity surgery, or any conditions that would affect gait. Participants were required to ambulate independently, ascend, and descend stairs reciprocally, jog a city block and be over the age of 18. Exclusion criteria included any recent lower limb injury or other condition affecting gait mechanics. Informed consent, in accordance with the Hamilton Integrated research Ethics Board was obtained from each participant prior to undergoing a complete gait analysis of the lower limbs. The participants were given instruction to wear pants and returned for two sessions separated by an average of one week.

Characteristics of the participants, such as age (years), height (in), and body mass index (BMI, lb/in^2), were obtained to describe the anthropometrics.

3.2.4 Gait Analysis for Reliability

Kinematic gait data was collected using the final setup of the 14-camera OptiTrack motion capture system. 3D motion of the lower extremity was recorded at 120 Hz. Camera positions remained the same throughout all trials and were calibrated before each day. Calibration steps included turning on the cameras then changing all camera exposures to what was found to be optimal for the space. The second step was to mask any reflections getting picked up by the cameras[42]. This allowed the cameras to ignore existing reflections to not interfere with data collection. Once the cameras were masked, a rigid body with predefined markers (wanding tool) was waved throughout the volume repeatedly allowing all cameras to capture sample points to compute each cameras relative position in 3D space[42]. Lastly the ground plane and origin of the space were set. This step created a global coordinate system that was used to reference the direction of movement for each of the markers used[42].

A series of three to four rigid retroreflective marker clusters were placed on each of the foot, anterior and posterior shank, thigh, and pelvis and tracked during the walking trials. Individual markers were placed based on standardized protocols to define anatomical and joint coordinate systems [72]. Marker clusters were placed based on the optimal placement protocol achieved. Once the markers were securely attached, the participant stood in a neutral position, with feet shoulder width apart for a standing calibration trial.

During gait analysis, participants walked at their self-selected walking speed along the 7-meter hallway. Green tape lines were placed on the ground 6 meters apart and used as start/finish lines. Data was only collected in one direction due to the layout constraints.

3.2.5 Data Analysis

Stride characteristics (walking velocity, step length, step width) and gait variables including knee and hip flexion/extension angles and adduction/abduction rotation angles were analyzed. A second order Butterworth filter was used to filter the data with cut off frequencies of 8Hz and 60Hz for 3D kinematic data. Three-dimensional knee and hip angles through the gait cycle were modeled using Visual 3D software (C-Motion Inc.). Kinematic modeling followed previously published work by Wilson et al[70].Range of motion (ROM) of the knees and hips were calculated by extracting the maximum and minimum values throughout the gait cycle in the sagittal plane, and during stance for the frontal plane [36]. Gait variables of interest in the sagittal and frontal planes shown in Table 3.2 along with the descriptions for calculation. The selection of these variables were informed by previously published research on test-retest reliability, as well as by a consideration of the specific gait variables that were most relevant to knee arthroplasty[43][44][73][74]. All gait waveforms were time normalized by having the gait cycle described with 101 data points ranging from 0% (first heel strike) to 100% (second heel strike) [72]. All frontal plane gait waveforms were graphed from 0-60% of the time normalized waveforms to display the stance phase. The average of seven good trials for each participant was used. A good trial was defined by the ability to maintain the stability of all clusters throughout the entire trial, while also allowing the participant to walk at their preferred speed without any disruptions from other individuals walking in the area. The mean and standard deviation for each participant and visit were plotted together to visualize average trends and make general comparisons between the data collected (Appendix A.3). All stride characteristics and gait variables were analyzed independently, and comparisons were made between participant visits. Using these parameters, change values between visits one and two were calculated for each participant to assess variability between data collected.

Speed, stride length and stride width were calculated using Visual 3D(C-Motion). Speed was computed using the actual stride length divided by the actual stride time [75]. Stride length was calculated by measuring the distance in the direction of walking between the position at the proximal end of the foot during the current ipsilateral heel strike and the position at the proximal end of the foot during the subsequent ipsilateral heel strike [75]. The width of the stride was determined by measuring the medio-lateral distance between the positions of the feet at the respective heel strikes[75]. Knee gait parameters in the frontal plane were normalized to the stance phase of the gait cycle (0-60% of the gait cycle). Both the right and left sides of participants were analyzed as data was collected in the same direction each time. The average of both the right and left was then calculated. Table 3.2 displays the calculations for all gait parameters analyzed.

Table 3.2: Gait parameter definitions

Frontal Plane Knee	
ROM Stance	Max (0-50% GC)-Min (0-20% GC)
Knee Mean Stance	Avg (0-60% GC)
Sagittal Plane Knee	
Stance Phase Peak	Max(0-50%GC)
Swing Phase Peak	Max (0-100% GC)
Stance ROM	Max (0-50% GC)- Min (20-80% GC)

Late stance ROM	Max (0-100% GC)-Min(20-80%GC)
Gait Cycle ROM	Max (0-100%GC)-Min(0-100%GC)
Frontal Plane Hip	
ROM Stance	Max(0-60%GC) - Min (0-20% GC)
Mean Value Stance	Avg (0-60% GC)
Sagittal Hip	
ROM	Max (0-20% GC)-Min(0-100%GC)

* Max: Maximum value, Min: Minimum value, GC: Gait cycle, Avg: Average

3.2.6 Statistical Methods

A test-retest reliability analysis was performed to test the extent of inconsistency in measurements from camera setup. Reliability of discrete parameters was assessed using the intraclass correlation coefficients ($ICC_{2,1}$) based on a two-way mixed model with absolute agreement and 95% confidence interval (CI) and standard error of the measurements (SEM) [76]. The ICC values were interpreted according to Koo and Li with the following cut-off points: less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 indicate poor, moderate, good, and excellent reliability, respectively [76]. The SEM was calculated using the formula [76]:

$$\mathrm{SEM} = \mathrm{SD}\sqrt{1 - \mathrm{ICC}} \quad (1)$$

Where SD is the standard deviation, and ICC is the intraclass correlation coefficient. All reliability analyses were performed using SPSS Statistics (IBM SPSS Statistics, v29, IBM Corp., Armonk, NY).

3.3 Results

3.3.1 Camera Setup

In December 2020, we took the initiative to install a total of 10 cameras based on the initial layout suggested by Optitrack. Over the course of two years, we tested and iterated through a total of four layouts to determine the optimal setup for data collection. We chose the final layout as it produced the best quality data. For the first iteration, we purchased six Primex13W and four Primex13 cameras with a resolution of 1.3MP [77]. We selected the Prime 13W for its ultra-wide field of view suitable for compact spaces, while the Prime 13 was recommended for distance.

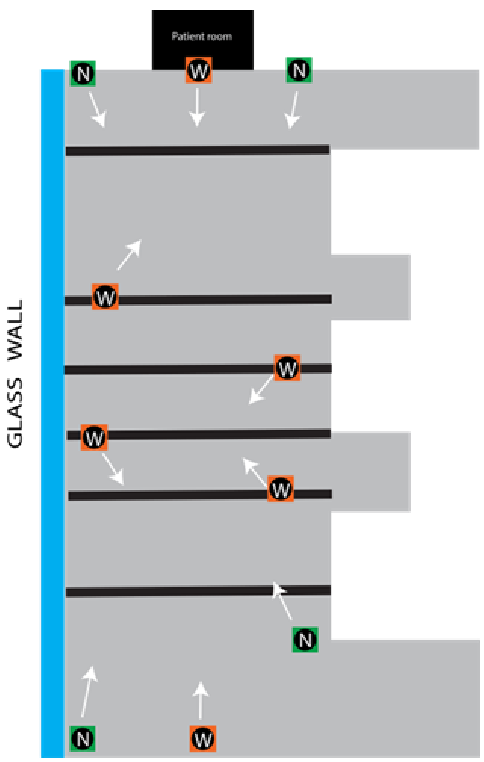

Figure 3.3: Camera Layout 1

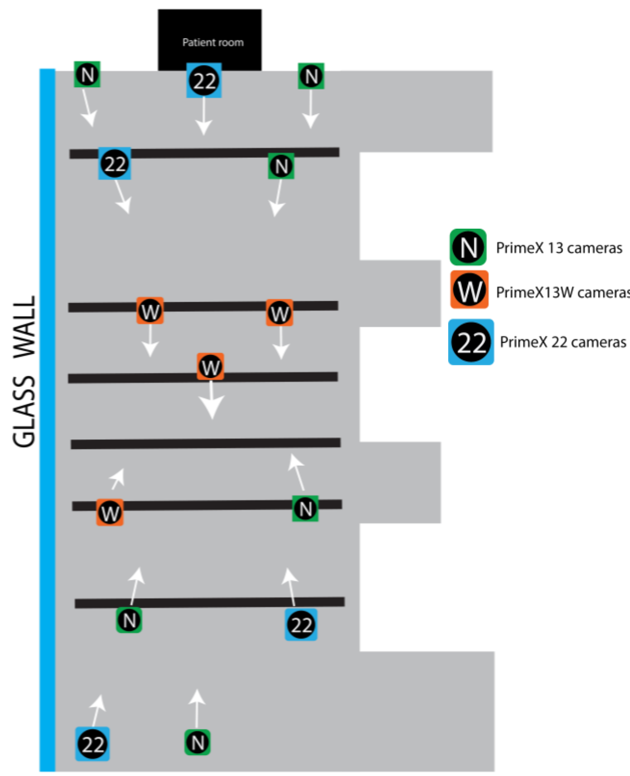

Figure 3.4: Camera Layout 2

We staggered the initial camera configuration throughout the hallway, placing all wide-angled cameras centrally and mounting the standard Prime 13 in each corner of the hallway (Figure

3.3), while following regular setup configuration to keep cameras along the periphery. We also ensured that all cameras were on 360-degree revolute camera mounts.

Central cameras were fixed on ceiling mounts installed across the width of the hallway drop ceiling for ease in adjustment. Cameras located at each end of the hallway were attached to camera mounts, permanently mounted to the wall. Cables were run through the drop ceiling above. Once the cameras were set up, a few walking trials were performed to test the systems performance with general marker placement[70]. This initial setup was not capable of collecting continuous gait data since the sagittal views not visible. Specifically, during the swing phase of the gait cycle, markers on the anterior part of the foot and leg were not visible. To address this problem, OptiTrack sent another six cameras for testing, including four Primex22 cameras with 2.2 MP resolution and wide field of view and two additional Primex13 cameras [77].

Error! Reference source not found.4 shows the second setup with 14 cameras. Noting the d ifficulty of data collection after the first layout, data from this point on was collected in one direction, with walking trials starting in front of the patient room up until the end of the hallway. Cameras were placed centrally along hallway with some cameras directed to capture a top view of the retroreflective markers. The Prime^{x}22 cameras were able to capture the markers placed on the front of the body (anterior markers) during the gait cycle based on the higher resolution and improved marker tracking at a distance.

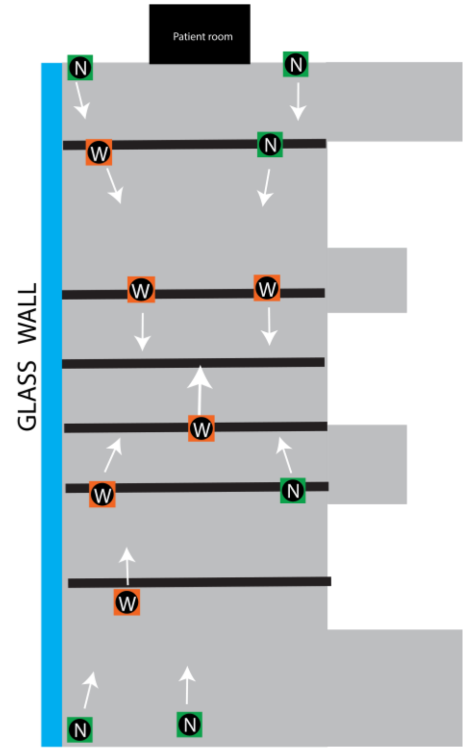

Figure 3.5: Camera Layout 3

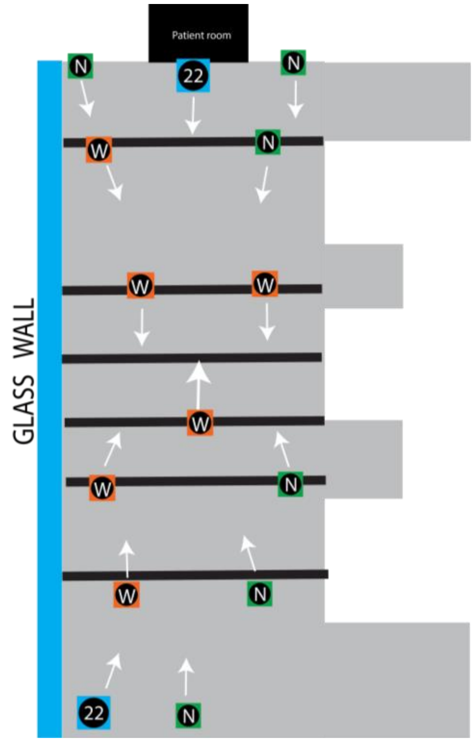

Figure 3.6: Camera Layout 4

The marker placement used for initial testing can be seen in Figure 3.2. Differences between setups 1 and 2 included four higher resolution cameras, and replacing two of the Prime^{x}13W with two Prime^{x}13 to test if the wider field of view was picking up accidental reflections from the glass wall and reflections the lights emitted from the cameras. Setup 2 produced gait waveforms that displayed consistently tracked marker waveforms, which was considered good data from this application. At least 2 good gait strides were able to be consistently collected from each of the clusters per trial.

After assessing the data collected from setup 2, and identifying the need for more cameras, two Prime^{x}13 and two Prime^{x}22 cameras were purchased. Setup 3 in (Figure 3.5) includes 12 cameras (two additional Prime^{x}13 from setup 1) and a similar layout as setup 2. Due to shipment delays, the Prime^{x}22 cameras took 6 months to arrive, and a temporary layout was created where data was able to be collected, but data quality was variable between different participants. Due to data collection timelines, data was collected with this setup. Once the final two cameras arrived, the final setup was complete (Figure 3.6) composed of six Prime^{x}13, six Prime^{x}13W and two Prime^{x}22 cameras. Further refinements on the software side of the cameras were considered. Due to the reflective floor and limited flexibility in changing the space, the camera exposure was lowered from 240 µs to 80 µs after testing and feedback from 120 Hz, Optitrack. Once the layout changes were complete, a test-retest reliability trial was conducted on this camera setup to ensure the data collected was repeatable. Sample data is shown in Appendix A.4 to display the progression and improvement of data over the course of the setups.

All cameras were permanently mounted in or near the ceiling to minimize interference from foot traffic and regular clinic duties. Because the hallway's width is less than half of the recommended space, cameras were installed throughout the entire length of the hallway. With this layout, sagittal views could not be captured, and the focus was on optimizing data collected from the anterior and posterior sides of the participant.

3.3.2 Marker Placement

Marker placement initially followed previous protocols[70]. Rigid tracking clusters consisting of three to four non colinear reflective markers were also fixed to the pelvis, thigh, shank, and foot (Figure 3.7). Five fabrifoam bands were secured on top of participants clothing around the hips, thighs, and shank to velcro the rigid clusters on top. Rigid clusters were used as they as they provide a more stable and consistent means of tracking the movement of body segments to improve the accuracy and reliability of data [70].

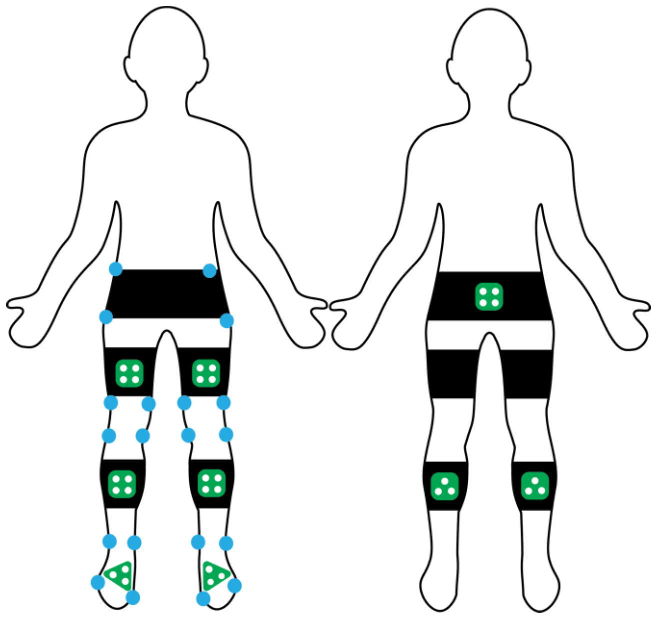

Figure 3.7: Final marker placement for anatomical and rigid clusters for the anterior and posterior side of the body

These bands were fastened on top of the participants' clothing with velcro, making it easy and secure to place the clusters. The bands provided flexibility to adjust to different patients' clothing sizes and limitations during their routine clinic visits. Data was collected with each marker placement variation. Each cluster of markers was visually inspected to see if at least 2 continuous gait strides were collected for each trial. Using this method, we found the front shank to not be able to continuously track during the swing phase of gait, and the decision to add more markers to the back of the shank was made. Protruding shank clusters attached to the sagittal side of the shank were attempted but resulting data was very noisy and unusable. Alternatively, additional rigid triad clusters were added to the posterior side of the shank, in addition to the frontal clusters, and the markers tracked continuously (Figure 3.7)

3.3.3 Participants

Using the marker-based motion capture system, the time required for each session including subject initiation and data collection was all less than twenty minutes. Demographic and anthropometric characteristics for all participants are summarized in Table 3.3 below.

Table 3.3: Participant characteristics for the reliability sub study (n=5). BMI refers to body mass index and SD refers to the standard deviation. Age is measured in years, weight is reported in pounds, height is reported in inches and BMI is reported in pounds/inches squared. * Weight and height are participant reported values.

Participant	Sex	Age (Years)	*Weight (lbs)	*Height (inches)	BMI (lbs/in^2)
1	F	21	140	65	23.3
2	F	21	162	67	25.3
3	M	36	176	73	23.2
4	F	34	120	64	20.6
5	F	45	130	61	24.5
Average (±SD)		31.4(10)	145.6(23)	66.0(4)	23.4(2)

3.3.4 Statistical Results

Gait waveforms for trials 1 and 2 for each participant were plotted and can be found in Appendix A.3. Trial 1 and 2 mean and standard deviations along with the corresponding ICC and SEM for the change values are listed in Table 3.4. ICC values are colour coded based on reliability with red, orange yellow and green indicating poor, moderate, good, and excellent reliability, respectively. ICC results for spatiotemporal parameters were excellent for speed and step width, but poor for step length. Average knee frontal gait parameters produced moderate reliability, and knee sagittal gait parameters produced good reliability. The average of the frontal hip parameters produced good reliability and the sagittal hip parameters produced moderately reliable results. The SEM for spatiotemporal parameters was on average 0.03 m/s for speed and 0.02m for step characteristics 1° for the frontal knee values, 0.8° for the sagittal knee values, and 2.3° for the sagittal hip parameters. When looking at the ICC values for the stride length the average values are the same which should correlate to a high ICC value. With the small sample size used to assess these values, the data captured from one person can significantly alter the results. The lack of variability between groups can also alter the ICC values to be lower[76]. This can be seen in the ICC values obtained for step length and do not directly correlate to the reliability of the data collected. The values collected for the standard error of measure (SEM), reflect the precision and accuracy of the system. The SEM values for the gait parameters are 0.03m/s for speed, 0.01m for stride width and 0.04m for stride length. When comparing the ICC and SEM values for stride length the ICC value produced poor reliability but the SEM is very small showing the system's error to be very low, although not directly reflected in the ICC value showing both ICC and SEM values should be used together to provide information about the system. The SEM for all other gait parameters in the sagittal plane is below 3 degrees showing the system's accuracy to be high, although some ICC values do not show moderate to good reliability.

Table 3.4: Gait parameter mean values and standard deviations for each trial with corresponding ICC and SEM values.

Gait parameters	Trial 1: Mean(±SD)	Trial 2: Mean(±SD)	$ICC_{2,1}$	SEM
Speed (m/s)	1.2(0.1)	1.2(0.1)	0.95	0.03
Stride Width (m)	0.1(0.0)	0.1(0.0)	0.9	0.01

Stride Length (m)	1.3(0.1)	1.3(0.0)	0.57	0.04
Knee Frontal Plane Data				
RK Stance Phase ROM (°)	2.3(1.3)	2.5(1.4)	0.52	0.91
LK Stance Phase ROM (°)	3. 8(1.4)	5.2(1.3)	0.50	0.97
Knee Stance Phase ROM (°)	3.1(1.5)	3.9(1.9)	0.63	1.04
RK Mean Value During Stance (°)	-0.2(1.3)	-1.6(1.9)	0.5	1.12
LK Mean Value During Stance (°)	0.9(0.8)	0.7(1.4)	0.26	0.94
Knee Mean Value During Stance (°)	0.4(1.2)	-0.4(2.0)	0.62	0.97
Knee Sagittal Plane Data				
RK Stance Phase Peak (°)	11.5(5.4)	11.3(5.3)	0.94	1.31
LK Stance Phase Peak (°)	13.2(4.6)	11.1(4.4)	0.88	1.55
Avg Knee Stance Phase Peak (°)	12.3(4.8)	11.2(4.6)	0.91	1.41
RK Gait Cycle Peak (°)	65.4(2.0)	65.4(2.7)	0.93	0.61
LK Gait Cycle Peak (°)	65.8(4.1)	64.4(5.2)	0.91	1.44
Knee Gait Cycle Peak (°)	65.6(3.1)	64.9(4.0)	0.90	1.11
RK Early Stance Phase ROM (°)	10.1(6.7)	9.0(6.0)	0.85	2.45
LK Early Stance Phase ROM (°)	11.5(5.6)	8.9(5.2)	0.74	2.75
Avg Early Stance Phase ROM (°)	10.8(5.9)	8.9(5.3)	0.79	2.55
RK Late Stance Phase ROM (°)	64.0(4.0)	63.1(3.2)	0.55	2.43
LK Late Stance Phase ROM (°)	64.1(4.0)	62.1(4.9)	0.88	1.54
Avg Late Stance Phase ROM (°)	64.1(3.8)	62.6(3.9)	0.67	2.22
RK Gait Cycle ROM (°)	65.5(2.0)	65.4(2.7)	0.94	0.57
LK Gait Cycle ROM (°)	65.9(4.3)	64.5(5.4)	0.91	1.46
Avg Knee Gait Cycle ROM (°)	65.7(3.2)	65.0(4.1)	0.91	1.08
Hip Frontal Plane Data				
RH ROM Stance Phase (°)	5.5(2.2)	4.8(1.8)	0.81	0.03
LH ROM Stance Phase (°)	6.6(3.6)	5.6(2.6)	0.93	1.61
Hip ROM Stance Phase (°)	6.1(2.9)	5.2(2.1)	0.89	0.82
RH Mean Value During Stance (°)	2.9(1.8)	2.9(0.8)	0.59	0.82
LH Mean Value During Stance (°)	4.3(2.5)	3.5(2.2)	0.96	0.47
Hip Mean Value During Stance (°)	3.6(2.2)	3.2(1.6)	0.78	0.88
Hip Sagittal Plane Data				
RH ROM (°)	39.9(3.4)	38.1(3.2)	0.43	2.49
LH ROM (°)	36.8(5.0)	36.3(5.6)	0.88	1.83
Hip ROM (°)	38.4(4.3)	37.2(4.4)	0.69	2.43

Note: $ICC_{2,1}$ = intraclass correlation coefficients model (2,1), SEM= standard error of measurement, ROM=Range of motion in degrees RH= Right Hip, LH= Left Hip, RK= Right Knee, LK=Left Knee. Units of measurement for stride width and length are presented in meters (m) and speed is presented in meters per second (m/s). Units for ROM, SEM, mean values during stance and peak values are in degrees.

3.4 Discussion

The purpose of this study was to design and set up a motion capture system and protocol in a hospital hallway capable of collecting reliable 3D motion capture data. This system had to be able to provide knee kinematic outcomes like those using a lab-based system and protocol while adapting to the constraints and criteria required for the space we were allocated. When first installing the cameras, the main challenge was creating a layout that could be easily moved and iterated through as we were unsure of the quality of the data, we would be able to collect after the first setup. The cameras placed in the middle of the hallway had to be able to be moved easily as we were unsure of the camera locations with these the most. We installed 6 brackets perpendicular to the length of the hallway, dispersed evenly throughout the length of the space. This was a drop ceiling and areas around lights, vents and sprinklers were avoided, as some brackets are closer together than others. These bars allowed us to mount the cameras to 360-degree revolute mounts and then to these brackets to move the cameras along the hallway width and length very easily if needed. As one wall was glass, this added additional lighting difficulties based on the day. When it was very sunny, additional reflections would be created. This error was avoided by calibration of the system daily prior to data collection. When calibrating the system, all reflections are masked to reduce noise and error from the data collected.

Once all cameras were up, we collected data using marker placements from previous literature published[44]. Using this marker layout, the hips, though and foot markers were tracked by the cameras but the markers on the font of the shank were not visible throughout testing. The original marker placements anticipate sagittal camera views to collect data, but in this case that was not possible. Marker placements are the largest contributor to gait analysis variability[71], as a result the camera layout and marker placements both had to be optimized. The marker placements were tested first, using the first camera layout, to see where improvements could be made. This resulted in the addition of clusters on the back of the shank. From here, we used the marker layout to map the camera views and see where improvements could be made. For the second camera layout, Optitrack sent us 4 additional cameras, as the layouts we tested were not producing consistent results between participants tested. The idea here was to use as many cameras as we had available to test if we could collect continuous gait waveforms on each cluster. Once we were able to do so, we looked through the camera views to see which cameras were not contributing. This idea has been previously used when looking into optimal camera placements form literature[45]. The most challenging clusters for tracking were located on the foot and the shank. When we optimized the cameras to collect the markers on the foot, the shank clusters did not track as well and finding a balance could only be done with the addition of 4 more cameras. For setup 3 we purchased 4 cameras but only received 2 due to shipping delays. Once all cameras arrived the data collected between participants was consistent, with the waveforms from each cluster producing consistent results. At this point in time the reliability trial was conducted. This is not the first motion capture setup within a hospital setting. Shriners Childrens hospital is centered around motion capture. These hospital centers are operating with a much larger space similar to what would be seen within a typical laboratory environment with 18 motion capture cameras.

The findings indicated that this system of camera in a hospital hallway had acceptable reliability $ICC_{2,1}$ values greater than 0.7 for knee and hip joint kinematic parameters[44]. Most (21 of 33) discrete parameters showed good or excellent reliability, with flexion angles of the knee angles showing the best reliability. Knee joint angles in the sagittal plane tend to produce values with the highest reliability, [44]. Knee adduction angles are much smaller and are more heavily influenced by experimental errors[68], [78].Parameters associated with frontal knee plane and hip ROM in the sagittal plane showed poor reliability. Our values of ICC were similar to results in the literature [44], for flexion/extension and adduction/abduction values, using a similar protocol within data collected within a lab setting, shown in Table 3.5. All participants had markers placed on top of the clothes they arrived in, as this would replicate motion capture within patients in a clinical setting. As a tradeoff the AL placement will always vary slightly based on the clothing, creating slight errors in the data[71][79]. Percent mean difference was calculated on the values found in literature using a similar protocol with an in-lab motion capture setup but on a population of mild to moderate arthritis participants. Those values were found to be around 5% for knee flexion, and total knee ROM (calculation in Appendix A.6.)

Table 3.5: ICC value comparison between literature values and those calculated in this study [44].

Variable	Literature ICC value	Study Values
Flexion angle early/mid-stance	0.77[44]	0.79
Flexion angle mid/late stance	0.74 [44]	0.67
Flexion angle swing	0.90 [44]	0.90
Flexion angle range	0.81 [44]	0.91

Mean and standard deviation values were not visibly as different as the ICC values displayed in Table 3.4 (ex. stride length mean values and standard deviations are very similar). SEM was used alongside ICC analysis to provide information about measurement errors related to discrete parameters. All SEM values were less than 3 degrees, indicating that the system's accuracy is below three degrees for all gait parameters. Given that the intended use of this system as part of a patient's standard of care within the context of total knee replacements, changes within the range of five degrees typically provide the same clinical conclusion for the sagittal plane[66][80].

Although the study had limitations, the data analysis was robust, using ICCs as a measure of repeatability[66][78]. The sample size was small, which may impact ICC interpretation [76]. The system was set up in the orthopedic fracture clinic with the intent to collect gait data in patients with end stage knee osteoarthritis, however, all the subjects were younger (31.4 ±10 years of age) and had a lower body mass index (23.4 ± 2) than the average population of patients who suffer with arthritis[80].

Participants were instructed to arrive wearing pants and comfortable footwear. Markers were placed on top of clothing of varying textures, and it was difficult to replicate the exact marker position, specifically around the knee[71][79]. One researcher placed all markers on each participant for consistency. The accuracy and precision of marker-based motion capture relies heavily on manually placing markers on a subject's anatomical landmarks. Measurement reproducibility is mostly affected by marker misplacement, therefore ensuring a detailed protocol is available for accurate marker placement is very important to minimize extrinsic errors[71]. Skin motion artifacts also play a factor in system reliability [44], and can be exacerbated by marker placement variability which makes up for approximately 90% of data variability[81]. Frontal plane angles such as knee ab/adduction angles are subject to error due to kinematic cross talk[40]. Finally, subject variability that has nothing to do with any limitation of the collection system or protocol may exist between test days, even in healthy subjects, which may affect reliability results[82].

In conclusion, this study found that the marker-based motion capture system set up in a hospital hallway was feasible and produced reliable results. The knee and hip kinematics using the new protocol produced values similar to those found in literature. Given the findings, the system can be used further to help design interventions to inform the decision of care provided.

CHAPTER 4 CLINICAL STUDY: GAIT OUTCOMES FOR ROBOTIC PKA VS MANUAL TKA

4.1 Introduction

Total knee arthroplasty (TKA) is the most commonly used surgical intervention for end-stage knee osteoarthritis (OA) and is associated with high levels of patient satisfaction [58]. TKA offers high survival rates and functional scores when arthritis affects all three compartments of the knee [60]. However, TKA has theoretical disadvantages, particularly for young patients who prefer a conservative approach for preserving as much ligaments and bone stock[60]. Moreover, with TKA surgeries doubling over the past decade [6] there are theoretical disadvantages, particularly for young patients with high functional demands and a high risk of potential revision surgery within their lifetime [58]. As an alternative, unicompartmental knee arthroplasty (UKA) has been shown to be an effective surgical option in patients with localized disease confined to one compartment. UKA can eliminate the need for TKA, making it a viable option for some patients[8].

Recent studies of UKA have shown promising advantages over TKA, including lower rates of complications[15], faster recovery[14], and improved range of motion[14],[58]. Historically, reviews of UKA reported poor results[8] leading to the belief that TKA was a more reliable and durable procedure, and therefore UKA procedures were not performed often [8].

For patients exhibiting medial tibiofemoral compartment arthritis with generalised patellofemoral joint (PFJ) arthritis, treatment exclusively with a UKA causes poor outcomes[8]. To bridge the gap between UKA and TKA surgeries, bicompartmental knee arthroplasties (BiKA) are proposed as a bone and ligament-sparing technique [8]. According to kinematic and gait studies, knees with either a UKA or BiKA in appropriately selected patients based on level of OA, and ligament structure can provide excellent functional outcomes in terms of ROM due to the ligament preservation [14][60][63], [43]. Early reviews of UKA reported poor outcomes commonly associated with technical errors of malalignment, and implant malpositioning [14][54][56]. Improvements in surgical techniques and instrumentation have led to better outcomes [12],[13].

Robotic-assisted surgery has emerged as a promising option for improving the precision and accuracy of knee arthroplasty procedures. Through intraoperative monitoring and control, critical parameters such as implant placement and leg alignment can be precisely adjusted[25]. Recently, robotic-assisted surgery has been shown to reliably improve lower leg alignment, soft tissue balancing and implant positioning when compared to conventional UKA surgery [14][54][56]. The use of the Robotic Arm Interactive Orthopedic MAKO Stryker (RIO; MAKO Stryker, Fort Lauderdale, Florida) robot for PKA surgery can result in greater conservation of bony surfaces during arthroplasty which can greatly benefit patients[14][54][56]. The use of robotic-assisted surgery has been associated with low revision rates at short-term follow-up, likely due to its ability to provide greater control over surgical variables and decrease the risk associated with malalignment[25]. Long-term survivorship data of robotic-assisted UKA are lacking and require further study[54][56].

Patient reported outcome measures (PROMs) are valuable tools used to assess outcomes of joint replacement surgery and the Oxford Knee Score (OKS) has been shown to be reliable and capable of measuring patient satisfaction after a knee arthroplasty[83][84]. However, PROMs only provide a broad overview of surgical outcomes and may not accurately capture functional limitations[21]. Prior research has indicated that there are similarities in patient-reported outcome measures (PROMs) between UKA and BiKA when compared preoperatively[85]. However, postoperatively, there are some minor inconsistencies among studies, with some concluding that there are no statistically significant differences between PKA and TKA[8], while others finding improved PROMs specifically in the PKA group[85].

Motion capture technology can be used to assess the success of a knee replacement surgery by measuring the range of motion, alignment, and function of the knee joint and have been related to patient satisfaction after surgery[24]. 3D gait analysis provides comprehensive joint kinematic and kinetic changes during walking that enhance our understanding of altered joint function and loading with pathologic conditions and treatment options such as TKA[25][58].

The purpose of this study was to to compare knee kinematic gait outcomes as change values between preoperative and postoperative knee kinematics for patients receiving robotic-assisted PKA and those receiving manual TKA. We hypothesized that there would be significant differences in knee kinematic outcomes between the two surgical procedures, with those receiving a PKA to have significantly better knee kinematic outcomes. Recent literature suggests patients receiving PKA have shorter hospital stays, faster recovery and decreased pain, with robotic outcomes improving alignment and subsequently surgical outcomes[52][53]. There have been correlations between PROMs and gait biomechanics[61], and with improved surgical outcomes it is expected for PROMs to show the same trends. Additionally, we will investigate PROMs between the two surgeries as secondary outcomes, and hypothesized robotic assisted PKA will have significantly better patie nt-reported outcomes.

4.2 Methods

4.2.1 Robot-Assisted Partial Knee Arthroplasty Versus Standard Total Knee Arthroplasty (RoboKnees) A Randomized Control Trial

Participants for this study were recruited as part of an ongoing randomized controlled clinical trial at St. Joseph's hospital investigating robot-assisted partial knee arthroplasty (PKA) compared to the current standard of care which is a total knee arthroplasty (TKA). The RoboKnees study is a pilot trial to assess the feasibility of creating a larger trial to assess robot assisted PKA compared to a TKA in terms of knee function, knee alignment, patient reported outcomes (PROMs) and knee kinematics during gait. The current study represents a sub-study of the RoboKnees trial where we examine the feasibility of using a newly installed optoelectronic motion capture system (Chapter 3) within the clinic to compare knee kinematic outcomes during walking. This study is registered on ClinicalTrials.gov (Identification No.: NCT04378049) and ethics approval was granted by the Hamilton Integrated Research Ethics Board (HiREB, Project Number: 1096).

4.2.2 Participants

Patients were recruited through St. Joseph's Hospital Hamilton as part of the RoboKnees trial. Patients enrolled into the pilot trial included adults presenting with unicompartmental (± patellofemoral) knee osteoarthritis requiring surgical treatment, where two surgeons independently agree that the patient is eligible for each treatment group. Patients were excluded if they have had any previous major knee surgery or trauma, if this was a revision surgery/ simultaneous bilateral knee surgery, a CT scan could not be obtained prior to surgery, the robot or required components were unavailable, and/or if the patient did not wish to participate. Figure 4.1 shows a flowchart of research design.

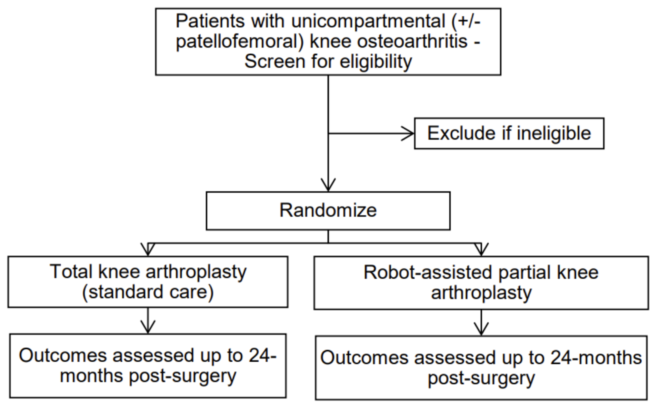

Figure 4.1 : Schematic of RoboKnees study design [86]

Consent in accordance with the ethics committee guidelines was obtained from all participants. After enrollment, patients were randomized to receive either a TKA or PKA. Regardless of their randomization, all patients received the same post-operative treatment of care.

4.2.3 Gait Analysis

Gait analysis was scheduled to be collected at four-time points: (1) during the preoperative standard of care visit (2) 3 months postoperatively, (3) 6 months postoperatively, (4) 12 months postoperatively. Figure 4.2 provides a comprehensive flow chart of the patient enrollment process and data collection values. Three-dimensional (3D) motion capture data was collected using a 14-camera motion capture system was installed into a hallway at St. Joseph's Hospital fracture clinic in Hamilton Ontario. Our previous work validated the reliability of the motion capture system which will be used to assess patient gait. Camera calibration was performed first, prior to any data collection, to ensure accurate data was collected that day. During each gait collection, reflective markers were placed on the patient's lower limb in strategic locations. Patients were asked to stand in the middle of the hallway with all markers, then all anatomical markers were removed for calibration and the patient was be asked to walk at their self-selected comfortable speed down the hallway five to seven times. Protocols for gait collection have been previously mentioned (Chapter 3). The motion capture system recorded the 3D positional information of the reflective markers at a rate of 120 Hz.

Once patient data was collected, tracking data was then exported for further processing. Visual 3D software (C-Motion Inc.) was used to for kinematic modelling following previously published models[70]. The analysis focused on various gait parameters relevant to arthroplasty functional recovery, including walking speed, step length, and step width, along with knee flexion and adduction angles. Other secondary outcome metrics that were calculated and analyzed included range of motion during stance, range of motion over the entire gait cycle and peak angles during stance/swing. Average gait waveforms per visit for each participant were plotted for the sagittal plane (Appendix B.1) and frontal plane (Appendix B.2).

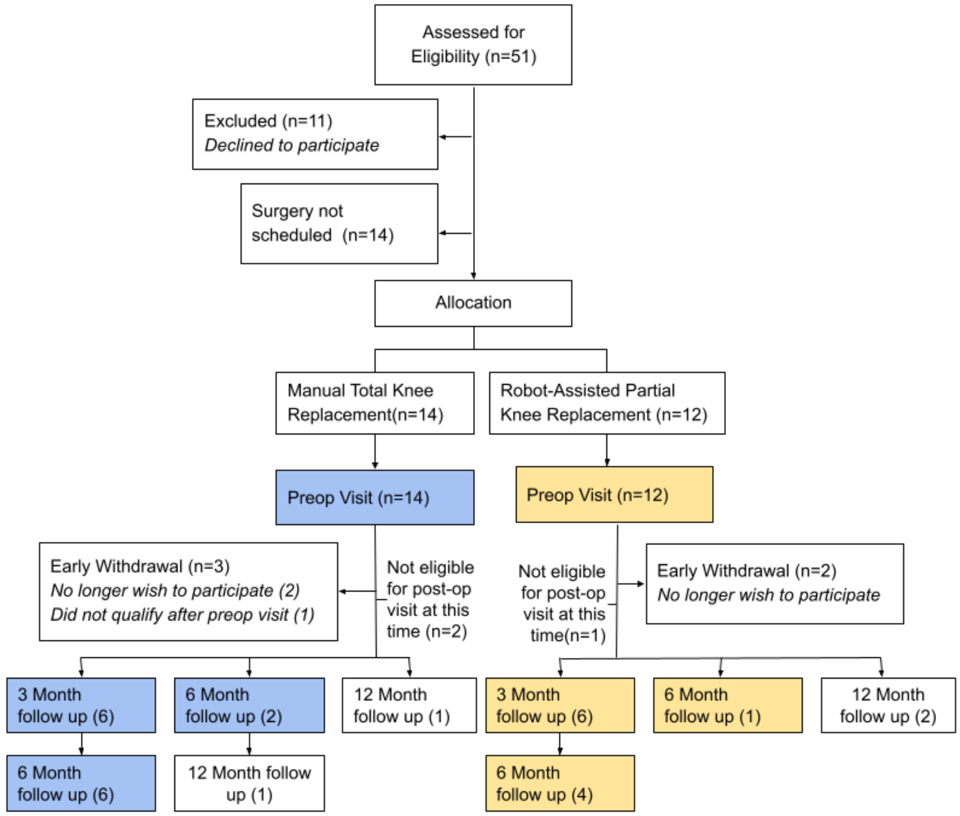

Figure 4.2 : RoboKnees patient flowchart for participants who participated in a gait analysis. Coloured visits indicate data used for analysis. Boxes highlighted in blue and yellow indicate data collected on patients receiving a TKA or PKA respectively.

4.2.4 Statistical Analysis

A one-way analysis of variance (ANOVA) of the change values of gait outcomes and patient reported outcomes from pre-operative to 3-month post-operative, pre-operative to 6-month postoperative, and 3 months to 6 months post-operative values were calculated for the purpose of between-group statistical analyses for each surgical intervention for gait parameters and PROMs. P values <0.05 were considered significant as this was a pilot study. All statistical analyses were performed using SPSS Statistics (IBM SPSS Statistics, v29, IBM Corp., Armonk, NY).

4.3 Results

4.3.1 Participants

Demographic and anthropometrics for participants are displayed in Table 4.1 . All partial knees performed were BiKA. A single factor ANOVA was also performed on the demographic and anthropometric values, there was no significant difference between the two groups. The data can be seen in Appendix B.3.

Table 4.1 : TKA & PKA patient demographics and anthropometric characteristics.

	Sex Male: Female	Side Right: Left	Age (± **SD**) (years)	*Weight (± **SD**) (lbs)	*Height (± **SD**) (inches)	BMI (± **SD**) (lbs/in^2)
TKA Average(n=9)	7:2	4:5	65.5(6.7)	208.0(48.2)	66.2(3.6)	30.4(11.9)
PKA Average(n=9)	4:5	4:5	59.9(6.1)	199.6(50.1)	68.4(3.8)	29.6(5.7)

Data is presented in the form: mean (SD). *Weight and height are self reported measurements

4.3.2 Statistical Results

4.3.2.1 Gait Outcomes

Average gait waveforms from participants who received a TKA and PKA can be seen in Figure 4.3 for a visual representation of the average differences in participant population. Overall, visually all PKA patients had better ROM preoperatively and postoperatively in comparison to the TKA group.

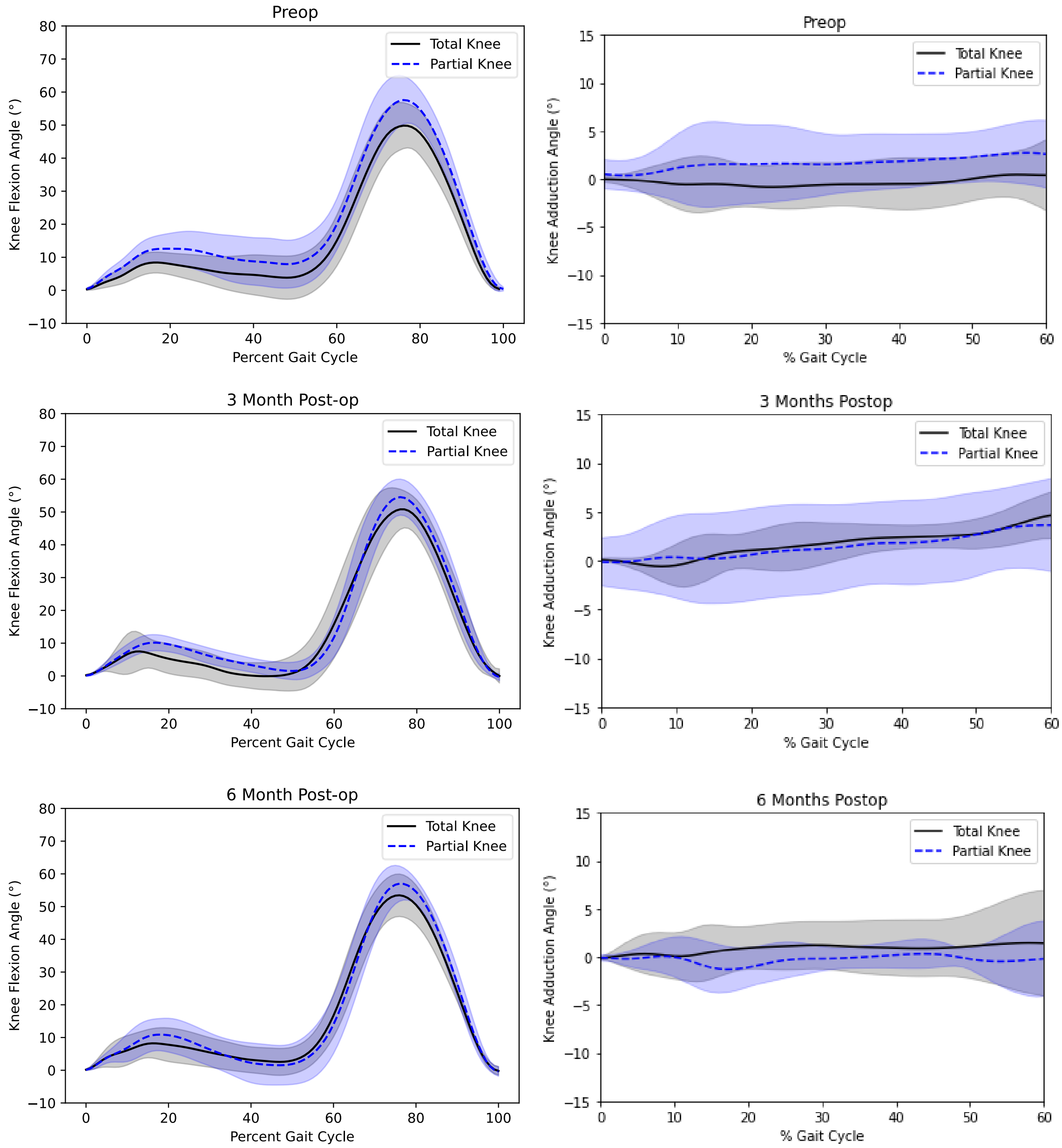

Figure 4.3: Sagittal and frontal plane gait waveforms representing mean gait waveforms for TKA and PKA gait cycle for preoperative, 3-month postop and 6-month postop gait cycle.

Change values calculated between preoperative and postoperative visits were significant for the peak knee adduction angles, and gait cycle ROM between TKA and PKA (Table 4.2). Peak knee adduction angles compared between preop, and 6-month values were found to be statistically significantly different. Participants who underwent a PKA had higher preoperative peak knee flexion values during the swing phase of gait, but after receiving a PKA, peak knee flexion during swing did not return to preoperative values. All other spatiotemporal and gait parameters were not significantly different.

Table 4.2: Change values of gait parameters comparing preop-3 months postop, preop- 6 months postop, and 3months postop to 6 months postop of patients who received a TKA or PKA

Preop-3M (6 TKA,6 PKA)	Preop Mean (± SD)	3M Mean (± SD)	Mean CV (± SD)	CI(+,-)	P value
Speed (m/s)					
TKA	0.9(0.1)	1.0(0.2)	0.0(0.2)	(-0.2,0.2)	
PKA	1.1(0.3)	1.0(0.3)	0.1(0.2)	(-0.1,0.3)	
All			0.1(0.2)	(-0.0,0.2)	0.69
Step Length(m)					
TKA	1.1(0.1)	1.0(0.5)	-0.1(0.4)	(-0.5,0.3)	
PKA	1.2(0.2)	1.0(0.4)	-0.2(0.6)	(-0.8,0.5)	
All			-0.1(0.5)	(-0.5,0.2)	0.85
Frontal Plane					
Peak Knee Adduction Angle During Stance(°)					
TKA	2.6(2.1)	4.9(1.9)	2.3(3.0)	(-0.87,5.4)	
PKA	5.6(2.9)	5.5(3.7)	-0.1(3.8)	(-4.1,3.8)	
All			1.1(3.5)	(-1.1,3.3)	0.25
Knee Abduction/Adduction Range of Motion during Stance(°)					
TKA	4.8(2.2)	6.3(1.9)	1.5(1.6)	(-0.2,3.1)	
PKA	7.2(3.7)	7.1(3.0)	-0.5(3.5)	(-3.7,3.6)	
All			0.7(2.5)	(-1.0,2.4)	0.36
Sagittal Plane					
Peak Knee Flexion During Stance(°)					
TKA	10.9(5.3)	10.8(5.7)	-0.95(9.0)	(-9.6,9.4)	
PKA	15.7(6.9)	10.3(2.4)	-5.4(7.0)	(-12.7,1.9)	
All			-2.8(8.2)	(-7.9,2.5)	0.28
Peak Knee Flexion During Swing(°)					
TKA	51.0(7.1)	52.1(5.6)	1.1(5.0)	(-4.2,6.3)	
PKA	59.3(6.9)	54.8(5.5)	-4.5(3.2)	(-7.9, -1.2)	
All			-1.7(4.9)	(-4.9,1.4)	**0.042**
Knee Range of Motion Early Stance					
TKA	7.4(2.6)	12.3(5.9)	5.0(5.8)	(-1.1,11.1)	
PKA	7.0(2.7)	9.0(1.9)	2.0(2.0)	(-0.1,4.1)	
All			3.5(4.4)	(0.7,6.3)	0.27
Knee Range of Motion Late Stance(°)					
TKA	47.5(9.5)	53.6(7.2)	6.1(9.1)	(-3.4,15.7)	
PKA	50.6(10.0)	53.5(5.5)	2.9(6.6)	(-4.0,9.9)	
All			4.5(7.8)	(-0.4,9.5)	0.50
Knee Range of Motion Gait Cycle(°)					
TKA	50.7(6.9)	52.5(6.0)	1.8(5.4)	(-3.8,7.4)	
PKA	58.8(7.2)	54.7(5.6)	-4.1(3.5)	(-7.8,-0.4)	
All			-1.1(5.3)	(-4.5,2.2)	**0.048**

Preop-6M (8 TKA,5 PKA)	Preop Mean(± SD)	6M Mean (± SD)	Mean CV (±SD)	CI(+,-)	P value
Speed(m/s)					
TKA	0.9(0.2)	1.1(0.2)	0.2(0.1)	(0.0,0.3)	
PKA	1.1(0.2)	1.2(0.2)	0.1(0.1)	(-0.1,0.3)	
All			0.1(0.1)	(0.0,0.2)	0.38
Step Length(m)					
TKA	1.1(0.2)	1.1(0.3)	0.1(0.3)	(-0.2,0.2)	
PKA	1.3(0.2)	1.2(0.2)	0.0(0.1)	(-0.2,0.1)	
All			0.0(0.2)	(-0.1,0.1)	0.54
Frontal Plane					
Peak Knee Adduction Angle(°)					
TKA	2.3(1.9)	4.2(3.5)	2.0(3.7)	(-1.2,5.1)	
PKA	5.6(2.5)	2.7(1.7)	-2.9(3.9)	(-7.7,1.9)	
All			0.1(4.4)	(-2.5,2.7)	**0.046**
Knee Abduction/Adduction Range of Motion during Stance(°)					
TKA	4.3(2.3)	5.4(2.9)	1.1(3.4)	(-1.7,3.9)	
PKA	7.1(4.1)	4.7(2.6)	-2.4(4.2)	(-7.5,2.9)	
All			-0.2(3.9)	(-2.6,2.2)	0.12
Sagittal Plane					
Peak Knee Flexion During Stance(°)					
TKA	9.9(4.9)	10.3(3.1)	0.35(6.1)	(-4.7,5.4)	
PKA	16.8(7.3)	11.1(4.9)	-5.7(11.1)	(-19.5,8.2)	
All			-2.0(8.5)	(-7.1,3.2)	0.23
Peak Knee Flexion During Swing(°)					
TKA	49.6(6.6)	53.7(6.3)	4.1(5.7)	(-0.7,8.9)	
PKA	62.4(4.8)	57.5(5.0)	-5.0(6.5)	(-13.0,3.1)	
All			0.6(7.4)	(-3.8,5.1)	**0.023**
Knee Range of Motion Early Stance(°)					
TKA	6.4(2.8)	9.1(3.4)	2.6(3.1)	(0.0,5.2)	
PKA	8.1(3.2)	9.8(2.8)	1.7(0.9)	(0.5,2.8)	
All			2.3(2.5)	(0.8,3.8)	0.53
Knee Range of Motion Late Stance(°)					
TKA	46.1(8.5)	52.5(9.9)	6.4(9.8)	(-1.7,14.6)	
PKA	53.7(10.3)	56.1(1.6)	2.4(9.9)	(-9.9,14.8)	
All			4.9(9.6)	(-1.0,10.7)	0.50
Knee Range of Motion Gait Cycle					
TKA	49.2(6.5)	54.2(7.1)	5.0(6.3)	(-0.2,10.3)	
PKA	62.0(5.1)	57.5(4.9)	-4.5(6.7)	(-12.3,3.8)	
All			1.4(7.98)	(-3.4,6.1)	**0.025**

3M-6M (6 TKA,4 PKA)	3M Mean (± SD)	6M Mean (± SD)	Mean CV (± SD)	CI(+,-)	P value
Speed(m/s)					
TKA	1.0(0.2)	1.1(0.2)	0.1(0.1)	(0.0,0.2)	
PKA	1.1(0.1)	1.1(0.1)	0.1(0.1)	(0.0,0.2)	
All			0.1(0.1)	(0.0,0.2)	0.60
Step Length(m)					
TKA	1.0(0.5)	1.1(0.3)	0.1(0.6)	(-0.5,0.8)	
PKA	1.2(0.0)	1.2(0.2)	0.0(0.2)	(-0.4,0.3)	
All			0.1(0.5)	(-0.3,0.4)	0.58
		Frontal Plane			
Peak Knee Adduction Angle(°)					
TKA	4.9(1.9)	3.1(3.0)	-1.8(4.0)	(-6.0,2.5)	
PKA	7.3(3.0)	3.2(0.9)	-4.1(3.6)	(-9.8,1.7)	
All			-2.7(3.9)	(-5.4,0.1)	0.38
Knee Abduction/Adduction Range of Motion during Stance(°)					
TKA	6.3(1.9)	4.6(2.5)	-1.7(2.4)	(-4.2,0.8)	
PKA	8.3(2.9)	5.6(2.0)	-2.6(2.6)	(-6.8,1.5)	
All			-2.1(2.4)	(-3.8,-0.4)	0.56
		Sagittal Plane			
Peak Knee Flexion During Stance(°)					
TKA	10.8(5.7)	10.4(3.1)	-0.3(4.0)	(-4.5,3.9)	
PKA	10.7(2.9)	11.3(5.7)	0.60(5.3)	(-7.8, -4.6)	
All			0.0(4.3)	(-3.0,3.1)	0.76
Peak Knee Flexion During Swing(°)					
TKA	52.1(5.6)	55.3(6.5)	3.3(4.9)	(-1.9,8.4)	
PKA	56.8(5.4)	58.0(5.6)	1.2(6.4)	(-8.9,11.3)	
All			2.4(1.7)	(-1.3,6.2)	0.58
Knee Range of Motion Early Stance					
TKA	12.3(5.9)	10.3(2.9)	-2.0(4.7)	(-6.8,2.9)	
PKA	8.9(2.2)	8.8(2.0)	-0.2(2.8)	(-4.6,4.3)	
All			-1.3(3.9)	(-4.1,1.5)	0.50
Knee Range of Motion Late Stance(°)					
TKA	53.6(7.2)	55.2(9.8)	1.6(4.8)	(-3.4,6.6)	
PKA	55.0(4.6)	55.5(1.0)	0.5(5.2)	(-7.8,8.8)	
All			1.1(4.7)	(-2.2,4.5)	0.73
Knee Range of Motion Gait Cycle(°)					
TKA	52.5(6.0)	56.0(7.3)	3.5(4.9)	(-1.6,8.6)	
PKA	56.8(5.4)	58.0(5.5)	1.2(6.3)	(-8.8,11.1)	
All			2.6(5.3)	(-1.2,6.4)	0.52

Data is presented in the form of mean (SD). The p-value corresponds to a single factor ANOVA analysis comparing the change value of gait outcomes to the surgical intervention. Significant differences are bold where $p<0.05$.

Table 4.3: Preoperative gait parameters of patients who received a TKA or PKA

Preop (9 TKA,9 PKA)	Preop Mean (± **SD**)	CI(+,-)	P value
Speed (m/s)			
TKA	0.93(0.1)	(0.8,1.0)	
PKA	1.0(0.3)	(0.8,1.2)	
All		(0.9,1.1)	0.31
Step Length(m)			
TKA	1.1(0.1)	(1.0,1.2)	
PKA	1.2(0.2)	(1.1,1.4)	
All		(1.1,1.2)	0.10
Frontal Plane			
Peak Knee Adduction Angle During Stance			
TKA	2.6(2.1)	(1.1,4.1)	
PKA	5.1(2.6)	(3.2,7.0)	
All		(2.6,5.1)	**0.030**
Knee Abduction/Adduction Range of Motion during Stance			
TKA	4.4(2.2)	(2.9,6.0)	
PKA	6.6(3.2)	(4.3,8.9)	
All		(4.1,6.8)	0.095
Sagittal Plane			
Peak Knee Flexion During Stance			
TKA	9.6(4.5)	(6.4,12.8)	
PKA	14.2(5.9)	(10.0,18.5)	
All		(9.3,14.5)	0.063
Peak Knee Flexion During Swing			
TKA	50.9(6.7)	(46.1,55.7)	
PKA	58.3(6.8)	(53.5,63.2)	
All		(51.0,58.2)	**0.024**
Knee Range of Motion Early Stance			
TKA	6.5(3.2)	(4.2,8.8)	
PKA	7.7(3.3)	(5.3,10.0)	
All		(5.6,8.6)	0.43
Knee Range of Motion Late Stance			
TKA	47.8(9.7)	(40.9,54.7)	
PKA	51.8(8.9)	(45.4,58.2)	
All		(45.4,54.2)	0.35
Knee Range of Motion Gait Cycle			
TKA	50.6(6.7)	(45.8,55.3)	
PKA	57.9(7.0)	(52.9,62.9)	
All		(50.7,57.8)	**0.028**

Data is presented in the form of mean (SD). The p-value corresponds to a single factor ANOVA analysis comparing preoperative gait outcomes to the surgical intervention. Significant differences are bold where $p<0.05$.

Graphed average gait waveforms from all TKA and PKA participants at varying time points for the sagittal and frontal views can be found in Appendix B.4 for a visual representation.

Individual waveforms at each time point for the sagittal and frontal plane can also be seen in Appendix B.5 and B.6 respectively. A summary of the mean values from Table 4.2 is shown in Appendix B.8 including all participants (n=26) while Table 4.2 only displays patient values who had their gait analyzed at both timepoints to calculate the change values for each participant. Table 4.3 includes all preoperative participants mean data, the upper and lower confidence interval and the p-value associated with the results. Table 4.3 shows there is significant differences between the preoperative patients' values. Specifically, the peak knee adduction angle during stance, the peak knee flexion during swing and the overall gait ROM. Although patients were randomly assigned a surgical intervention there is a difference between the two groups which could be due to the small sample size.

4.3.3 Patient Reported Outcome Measures

Preoperative Oxford Knee Score (OKS) values were analyzed and there were no significant differences between the surgical interventions Table 4.4.

Table 4.4: Preoperative OKS Values

Preop (9 TKA, 9 PKA)	**Mean (± SD)**	**CI(+,-)**	**P value**
	OKS Functional Outcomes		
TKA	57.5(10.7)	(48.6,66.4)	
PKA	56.3(18.9)	(40.5,72.0)	
All		(49.0,67.8)	0.87
	OKS Pain Outcomes		
TKA	43.7(13.2)	(32.7,54.8)	
PKA	40.6(16.0)	(27.3,54.0)	
All		(34.6,49.8)	0.68

*p<0.05 was used to determine statistical significance.

Mean OKS are displayed in Table 4.4**.** It was not possible to perform the analysis for the 12-month group due to missing data points. Overall, there was no significant difference of the mean OKS between any of the three time points between the two groups at any time point.

Table 4.5: Change values based on OKS outcomes

Preop-3M (9 TKA, 9 PKA)	**Preop Mean (± SD)**	**3M Mean (± SD)**	**Mean CV (± SD)**	**CI(+,-)**	**P value**
		OKS Functional Outcomes			
TKA	57.5(10.7)	72.5(13.4)	15.0(18.3)	(-0.3,30.3)	
PKA	56.3(18.9)	80.6(10.8)	24.4(26.5)	(2.2,46.5)	
All			19.7(22.5)	(7.7,31.7)	0.42
		OKS Pain Outcome			
TKA	43.7(13.2)	65.6(14.0)	21.9(15.6)	(8.8,34.8)	
PKA	40.6(16.0)	74.5(14.1)	34.0(18.7)	(18.3,49.6)	
All			27.9(17.7)	(18.4,37.4)	0.18
Preop-6M (9 TKA, 9 PKA)	**Preop Mean (± SD)**	**6M Mean (± SD)**	**Mean CV (± SD)**	**CI(+,-)**	**P value**
		OKS Functional Outcomes			
TKA	57.5(10.7)	78.8(16.4)	21.3(17.7)	(6.5,36.0)	
PKA	56.3(18.9)	85.6(8.6)	29.4(23.3)	(9.8,48.9)	
All			25.3(20.4)	(14.4,36.2)	0.45
		OKS Pain Outcome			
TKA	43.7(13.2)	78.5(20.9)	34.8(21.4)	(16.9,52.7)	
PKA	40.6(16.0)	78.5(20.9)	40.2(23.9)	(20.2,60.1)	
All			37.5(22.1)	(25.7,49.3)	0.64
3M-6M (9 TKA, 9 PKA)	**3M Mean (± SD)**	**6M Mean (± SD)**	**Mean CV (± SD)**	**CI(+,-)**	**P value**
		OKS Functional Outcomes			
TKA	72.5(13.4)	78.8(16.4)	6.3(12.7)	(-4.4,16.9)	
PKA	80.6(10.8)	85.6(8.6)	5.0(11.9)	(-5.0,15.0)	
All			5.6(12.0)	(-0.8,12.0)	0.84
		OKS Pain Outcome			
TKA	65.6(14.0)	78.5(20.9)	12.9(15.8)	(-0.3,26.2)	
PKA	74.5(14.1)	78.5(20.9)	6.3(10.9)	(-2.9,15.4)	
All			9.6(13.6)	(2.4,16.8)	0.34

*p<0.05 was used to determine statistical significance. No statistical significance was identified.

4.4 Discussion

Although patients were randomized to each surgical intervention, allocation of surgery is ultimately left to the discretion of the surgeon, based on the patient's level of osteoarthritis.

Patients who were assigned to the control group underwent a total knee arthroplasty (TKA) according to the local standard of care [87]. The surgeon's discretion governed the choice of implant and use of bone cement, following their standard practice. Patients with isolated medial or lateral compartment OA who were randomized to the intervention group and had one affected knee compartment received a robot-assisted UKA. However, those with medial or lateral OA plus patellofemoral OA received a BiKA also known as a partial knee arthroplasty (PKA). All PKA surgeries were performed using the Robotic Arm Interactive Orthopedic MAKO Stryker (RIO; MAKO Stryker, Fort Lauderdale, Florida) system in accordance with the manufacturer's instructions. The choice of implant and use of bone cement was recorded but left to the surgeon's discretion[87]. One patient was allocated to the PKA group but received a TKA due to extensive OA present at the time of surgery. One patient also received a robot assisted TKA rather than a manual TKA. Both participants are represented in the respective groups based on the surgical intervention. All participants received cemented BiKA and cemented TKA.

The study on patient gait analysis was initiated during the early stages of the COVID-19 pandemic, which posed a challenge for data collection as patients were required to physically visit the hospital. Hospital regulations and restrictions resulted in intermittent pauses in research visits, and postponed surgeries further complicating the process. Due to the timeline of collection, patients had the option to skip in-person visits at any time, leading to a smaller sample size than originally planned. Gait collection was anticipated to include 64 participants, 32 in each group[86][87], and data included in this thesis represents that collected from 26 participants total (n=14 TKA, n=12 PKA). Data collected from participants used the motion capture setups 3 and 4 from Objective 1. The main differences between the 2 setups was the total number of cameras and specific patient data collection at various time points and setups can be seen in Appendix B.7.

Gait data was assessed preoperatively for both surgical interventions, and patients were randomly assigned to each group. PKA patients had higher knee adduction during stance, higher knee flexion during swing, and higher ROM throughout the gait cycle. These values were found to be statistically significant (p value = 0.02, 0.03, 0.028 respectively). This shows the participants randomized to the PKA group had higher knee joint ROM preoperatively than the TKA population. The sample size for this population was small (5-8 participants used for analysis) and one participant can heavily influence the results. Other sources error can include one patient who was randomized to the PKA group but ended up receiving a TKA as they did not qualify for a PKA at the time of surgery. To avoid misinterpreting the actual surgical outcomes when assessing postoperative effects, it is crucial to understand that patients with preoperative knee ROM deficits may exhibit higher knee ROM values postoperatively. Therefore, instead of solely examining the total ROM postoperatively, it is essential to focus on the changes between preoperative and postoperative knee ROM values.

The comparison of change values in Table 4.2 normalizes gait parameters to the preoperative values to assess the overall postoperative change for both populations. This showed TKA patients received statistically more improvement in mean knee flexion angles, and overall gait ROM. Looking at the change values between preoperative and 3-month postoperative gait results, these values showed a lack of knee flexion in the sagittal plane for PKA patients after surgery. Knee flexion was greater during swing for the TKA group, but no difference was found during the stance phase. These results match some previous studies that found greater TKA mean knee flexion when compared to PKA[46].The same trends were seen when looking at the preoperative and 6-month postoperative gait outcomes. Other studies reported a decrease in knee peak flexion angles for both surgical options postoperatively, when compared to healthy controls[88]. Higher knee flexion in PKA was not observed as often found in literature[87]. TKA patients had less ROM in stance which was observed at 3 months but not statistically significant which corresponds to the trends found in literature[88].

Frontal knee angles assessing adduction/abduction were statistically significantly different between preoperative and 6 months postoperative gait data collection, showing lower peak adduction values in the PKA group. Mean PKA values were closer to healthy gait (1.1°), than TKA gait, which is closer to general OA gait (5.6°)[46]. Lower values indicated less varus frontal plane alignment which is closer to normal gait mechanics[89]. Comparing the 3 months to 6-month postoperative outcomes for each group showed no significant changes and this was expected. Literature findings show spatiotemporal parameters typically improve around 3 months while full gait ROM may not be completely improved at this point[90]. All gait parameter improvements tend to plateau around 6 months, with typically no clinically significant improvement after[91]. When analyzing functional outcomes, preoperative and postoperative values for patients randomized to PKA were statistically higher (Table 4.3), whereas TKA patients had lower preoperative and postoperative values (Table 4.3). Although the PKA values are greater in magnitude, this did not correlate with improved gait outcomes as the change values showed more improvement in the TKA group. Studies have shown increased

ROM in the PKA group for gait analysis, but did not compare preoperative function, which could produce similar results as shown here[88].

Comparisons in literature for both the TKA and PKA often directly compare the surgical outcomes, where the patients receiving a TKA do not qualify for a PKA, leading to comparisons between different preoperative functional goups[8][60]. These results can be biased when showing higher levels of improvements in the PKA population as patients have less disease severity than the TKA population[8][60]. To determine the best surgical option, it is crucial to conduct thorough research and compare outcomes of different surgical procedures on the same population. Overall, gait data from previous studies is variable when looking to compare between robotic assisted BiKA/PKA and TKA and needs to be studied further.

Preoperative anthropometric and demographic data was analyzed and showed no statistical differences in the patient population (Appendix B.3). The TKA population assessed seven males and two females while the PKA group assessed four males and six females. Previous literature shows sex related differences in walking biomechanics[92]. Females tend to walk with knee biomechanics similar to a normal population, except when looking at the coronal plane during stance[92]. Males tend to also generate the largest joint angles, with women producing a lower range of flexion/extension between late stance and mid swing[92][93]. These sex differences can also contribute why the TKA group produced higher change values of ROM which had more men than women.

Data collected from PROMs was collected at each time point and was not impacted by COVID-19 restrictions as they could be done remotely. PROMS are valuable tools used to assess outcome of a joint replacement surgery and the OKS has been shown to be reliable and capable of measuring change after a knee arthroplasty[83][84]. A greater improvement in the OKS has shown to correlate with patient satisfaction on the outcome of their surgery[83]. The OKS is one of the most common PROMs for a knee replacement [94]. Due to time constraints for patient data collection, limited results are available for 12-month postoperative outcomes, therefore data collected up to 6 months was the primary focus. There were no differences in OKS of patient functional and pain outcomes preoperatively and postoperatively. However, there are trends of greater improvement in the PKA group postoperatively which is in agreement with previous studies [85].

When interpreting the results of this study, it is important to acknowledge the limitations of the motion capture system used as well. Chapter 3 investigates the sources of error in both data collected in the sagittal and frontal planes. Marker placement and skin motion artifacts play a large role in the quality of the data collected and must also be addressed as a limitation[74]. Chapter 3 reliability analysis showed the highest levels of accuracy were found when looking at the sagittal knee ROM, while the frontal planes produced poor to moderate reliability. Although the SEM values were around 1-degree, frontal plane angles must be assessed carefully. Overall, the sample size was small, results are comparable to previously published trends for TKA and PKA outcomes [85][88].

In conclusion, this study found the marker-based motion capture system set up in a hospital hallway was feasible to collect patient data receiving a joint replacement surgery. PKA was shown to have less knee flexion during swing when compared to a TKA, and PROMs were not statistically different at any time point. Further data on gait outcomes with this sample population is needed for a more robust comparison of TKA and robotic PKA.

CHAPTER 5 GENERAL CONCLUSIONS & FUTURE DIRECTIONS

5.1 Thesis Overview

Robotic assisted PKA are now associated with various improvements over the current standard of care (TKA), such as improved implant alignment for better longevity, bone sparing techniques, faster recovery, improved outcomes, and better kinematics after surgery [14][54][56]. There is significant interest into improving surgical outcomes for such a common procedure with approximately 1 in 5 people being dissatisfied with the result [14][54][56]. While both surgical interventions have been linked to gait outcomes, this was the first robotic assisted PKA offered in Canada as of 2019[95]. The work presented in this thesis aimed to improve the understanding and integration of a marker-based motion capture system, and how such technologies can be used in better understanding knee replacement outcomes.

The first objective of this thesis aimed to determine the optimal layout and protocol for a marker-based motion capture setup within a narrow and frequently used hallway. This aim involved investigating and iterating camera placement, marker placement, camera setup, software specifications, and data collection protocol. A reliability trial was then conducted to ensure high-quality data collection and accurate tracking of lower limb kinematics. Due to space constraints, data was only collected in one direction, and thus it was necessary for both the left and right sides of the body to be tracked accurately. The repeatability trial demonstrated that most gait parameters analyzed had moderate to excellent reliability, indicating that the collected data is repeatable for both the right and left sides of the body. When looking at the mean values at each time point for the ICC calculations, many were very similar at face value, but the correlation coefficients do not demonstrate this similarity. This finding may be the result of the small sample size and lack of variability between participants and not necessarily reflect the quality of the data [76]. The SEM values were less than 3 degrees in the sagittal plane, less than the 5 degrees error in clinical applications and therefore is able to provide valuable data more accurately than what is currently used for knee ROM testing [68][96].

The cameras were positioned in the hallway rather than the typical laboratory set up with a Non-standard camera layout. However, this approach was taken because clinic-based gait data collection has the best results for patient retention and clinician engagement. Patients were more willing to come to the clinic and participate in a gait study immediately after visiting with their surgeon during a regularly scheduled visit, rather than having to go elsewhere for the data collection. Minimizing patient research burden increased the number of patients enrolled and willing to participate in a gait analysis. While marker-based motion capture is widely accepted as the gold standard for collecting gait data, it is crucial to evaluate the quality of data collected in non-ideal environments [23].

The second objective of this thesis was to investigate the gait outcomes when analyzing specific gait parameters of patients undergoing a PKA or TKA, i.e. a pilot clinical trial with gait outcomes. The same motion capture system setup and tested in *Objective 1* was used for all participant analysis. This analysis included looking at the knee flexion angles during stance, swing, the total ROM, and ROM during early and late stance. Spatiotemporal parameters such as step width, step length and walking velocity were also analyzed. Patient specific parameters were analyzed preoperatively and at 3 and 6 months. Significant differences were found when looking at the peak knee flexion during swing and the total gait cycle ROM., with patients who received a PKA having less ROM than a typical TKA. There was also a difference in knee adduction angle, where PKA had less knee adduction angle after surgery when compared to a TKA which is more closely related to natural gait biomechanics. There were trends for the PROMs similar to previous studies [83], although not statistically significant

5.2 Implications of Thesis Results

Previous research investigating kinematic differences in a UKA, BiKA, and TKA have been published [54][56][97] but this was the first research study randomizing participants to either a manual TKA or a robotic UKA/BiKA and assessing kinematic results using an in-clinic optoelectronic motion capture system. This study is different as it investigates robotic assisted BiKA surgeries to the standard of care and assesses specific gait outcomes. Considering the first robotic assisted UKA was performed in 2019 in Canada[95], this is a newer area of research in Canada. Robotic assisted UKA/BiKA are newer to the field of orthopedics and are still lacking significant mid- to long term. Robot assisted BiKA specifically are the newest addition to PKA and as a result do not have extensive literature surrounding the results. Considering the research available based on the small number of surgeries performed, collecting kinematic data on this population was a logical extension to further research outcomes in this area.

Marker based motion capture is currently the best way to capture knee kinematics[41][97] and therefore a gait lab was setup in the clinic where patients visit with their orthopaedic surgeon pre- and postoperatively. The main motivation on objective 1 was to maximize the number of participants who would enroll into this study by minimizing the research burden on participants. Adding a gait analysis to be performed during regularly scheduled visits made it very simple to maximize participant interest. Setting up a marker based motion capture system took time and investigation to optimize the space and work around inevitable constraints that come with collecting data in a regular space. A variation of a typical marker based setup was created, and used more cameras than initially anticipated. A standard protocol was created for data collection and marker placement that was adapted based on the space restrictions. Due to all of these changes, a reliability study was done calculating ICC and SEM values which were similar to values published in literature using the same system but in an optimal space. One large limitation of marker-based motion capture is the controlled environment required for data collection. Chapter 3 went into detail about the planning and setup required to install and develop a protocol for gait data collection is an environment with multiple constraints and not meeting the recommended space restrictions[71][79]. This improves the accessibility for motion capture system use to not be limited to the constraints of a lab setting. This system specifically can also be used to track patient gait kinematics over time. Since gait can be used as an indicator of overall health[67][98], and treatment success, gait analysis has the potential to be used to track preoperative ROM and assess the potential surgical outcomes and even help inform clinicians about the best treatment options preoperatively based on the patient's joint kinematics.

With objective 2 we were looking to assess kinematic variation between the surgical interventions. Due to literature around robotic assisted UKA surgeries indicating improved range of motion and more natural biomechanics compared to TKA [68][96], the same was expected for the BiKA group. This hypothesis did not match our findings. The hypothesis was primarily based around the literature surrounding the outcomes typically associated with robotic assisted UKA outcomes. Literature assessing the differences between UKA and TKA surgeries often times compares the results of the 2 surgical outcomes, but the participants receiving the surgical interventions in the TKA group often times have higher levels of disease progression and will not produce the same results. These results showed gait parameters for robotic UKA/BiKA need to be further assessed. There is variability in the findings from studies that investigate spatiotemporal parameters such as the number of steps, stride length, gait speed and overall ROM [68][96]. In general, most report minimal changes between the two surgeries. This study was unique as patients were randomized to receive a robotic assisted PKA or a TKA. Initially all patients qualified for a UKA, but at the time of surgery any patient randomized to a PKA received a robotic assisted BiKA. There are limited studies comparing robotic assisted BiKA with a manual TKA in terms of gait outcomes.

Chapter 4, shows the preoperative and postoperative range of motion associated with partial and total knee ROM. Further using this gait analysis for larger studies on different surgeries could help provide insight into surgical outcomes through gait. Chapter 4 also displays the outcomes for robotic assisted PKA surgeries. The current standard of care in Canada is receiving a TKA. This study has shown there are not many gait differences between the 2 in terms of surgical outcomes on a small sample population. Having properly assessed gait outcomes early in these types of surgeries can inform future ideas of standard of care. Although no significance was found, those who received a PKA reported slightly higher PROMs than those receiving TKA. The research collected in this study further assesses the need for a larger sample population and greater research in this field of study due to the limited number of studies assessing robotic assisted BiKA and manual TKA in terms of knee kinematic outcomes during gait. Longer outcomes also need to be assessed for the types of surgical interventions received as robotic assisted BiKA are newer surgeries and technology is continuously evolving.

5.3 Limitations and Considerations

There are certain limitations that should be considered when looking at the results of this research. First is the data collection timeline and the resulting number of participants enrolled. This project started in September of 2020, with a motion capture system set up in December 2020. During this time, COVID-19 had a significant impact on the data setup and collection capabilities. The camera setup was intended to be done and tested by OptiTrack. Due to travel and hospital access restrictions, all setup was done by the research team at McMaster University and tested virtually. Camera and equipment purchases were impacted by unforeseen disruptions in the global supply chain. These reasons contributed to the length of time for setting up a successful motion capture system. During the pandemic, hospital restrictions posed limitations to the implementation of the camera setup. Due to the unpredictable nature of the pandemic, subsequent testing of the camera setup was only possible after hours with minimal individuals present to comply with the hospital restrictions. For *Objective 1,* a reliability trial was not performed until the final camera setup was done and was therefore limited to a much smaller sample size than intended. The variability between height, weight and age of all participants was limited and did not reflect the general patient population this system would be used on [44],[54]. To ensure accurate kinematic data collection for a patient population with abnormal gait, it was necessary to collect hip variables for the reliability analysis. This is because hip joint angles can significantly impact the functioning of the knees[38][49]. Therefore, it was imperative to capture correct kinematic data for both the hips and knees using the motion capture system. It should be noted that this system is expected to be utilized for patients undergoing hip replacement surgeries as well, further highlighting the importance of capturing hip joint angles during gait analysis. By ensuring accurate data collection for both the hip and knee joints, the motion capture system can provide more reliable and informative data for clinical decision making.

Several factors, such as the reflectivity of the hallway, clothing worn by participants, and camera locations, cannot always be fully controlled. Therefore, it is essential to examine the potential impact of these environmental factors on the accuracy and validity of the data collected. Understanding the limitations of gait data collected (such as error in measurements) in non-ideal environment can affect the interpretation and applicability of the data in clinical and research settings. This system was also installed only for the collection of kinematic gait variables, and was not anticipated for the collection of kinetic variables. Any inaccuracies or inconsistencies in the data collected can result in erroneous conclusions, leading to incorrect diagnosis and treatment plans for patients. This thesis quantifies the accuracy associated with this system and provides a baseline to interpreting this type of data.

Objective 2 also has significant limitations. Due to the timing, patient data collection was temporarily suspended. Elective knee replacement surgeries were postponed and follow up visits during the specified timeline were done over the phone, preventing gait data collection. Patients enrolled were also allowed to opt out of in-person gait collection, therefore gait data collection results were less than planned. Data used for analysis only looked at preoperative, 3 month and 6-month postoperative results because 12 -month postoperative data was limited as surgeries were postponed by a few weeks to a couple of months and due to the sample size, was not sufficient to perform any meaningful statistics.

5.4 Future Work

Expanding on the current reliability trial, further data can be collected to create a database of normal gait function for this motion capture setup. A larger sample size of varying demographics will allow for the potential use of comparison between normal and abnormal gait for this particular setup and protocol. Not all motion capture protocols follow the same setup, data collection, and data analysis, and this will be particularly useful if newer gait recording technologies are used. Kinetic analysis would also benefit this population in the future to better understand joint loading forces associated with muscle activation patterns during gait[99]. Kinetic data would be used to identify abnormal loading patterns, muscle imbalances, and compensatory mechanisms that may affect the outcomes of TKA[99].

Further work is needed in the Roboknees pilot trial. The study is powered as a pilot study for 64 participants but only 26 were used for the data analysis in this thesis. In this instance, a single patient would have a larger influence on the data results than what would be expected with sufficient enrollment. To address these limitations, data collection and analysis should continue to fully gain a better understanding of the objectives assessed.

Alternative data collection methods can also be used for this population. Specifically, markerless motion capture technology which captures human motion without the need for physical markers[100][101]. This technology has advantages over traditional marker-based motion capture, particularly in clinical settings. Marker-based systems require subjects to wear markers on their bodies, which can be restrictive, particularly for patients with mobility issues. Markerless motion capture systems, on the other hand, use advanced computer vision techniques to track movements, allowing for more natural and unrestricted motion capture[101]. This markerless system reduces the time needed for patient setup and data collection is simpler, faster and more user friendly but still needs further improvement in tracking accuracy[100].

In conclusion, this thesis expanded on the current understanding of knee joint differences between robotic assisted PKA and manual TKA using a randomized control trial. A motion capture system was installed in a hospital hallway for patient gait analysis, and a motion capture protocol for data collection and marker placement was created to feasibly collect data that is reliable and repeatable. Of the small sample size analyzing preoperative and postoperative knee kinematic differences, small changes were found between the two surgical interventions. Preoperatively patients randomized to the control group had higher levels of peak knee flexion during stance, and higher knee ROM overall than compares to TKA. When assessing the postoperative change at 3 and 6 months, there was no statistical difference between any kinematic gait outcomes. At both 3 and 6 months TKA peak knee flexion in the sagittal plane and ROM throughout the gait cycle was statistically higher than the PKA group. At 6 months knee adduction during stance in the frontal plane was significantly lower than the TKA group. No differences in spatiotemporal metrics between the two groups were found. PROMs were also assessed preoperatively at 3 and 6 months postoperatively and no differences between the 2 groups were found. Overall robotic assisted PKA and the manual TKA only showed significant differences in the sagittal plane during peak knee flexion, total

ROM and peak adduction during stance. This research provides valuable insights into setting up a motion capture laboratory within a hospital hallway and collecting patient data during regularly scheduled clinic visits. The data collected from this population provides insight on the impact of these surgical interventions on knee joint kinematics and patient outcomes, which could inform decision-making by clinicians and patients. In future studies, a larger scope of data analyzed including ankle and hip kinematics could also be assessed for a complete lower body kinematic understanding. Different types of data should also be analyzed in terms of radiographic imaging, PROMs, and surgical events to assess the surgical outcomes. Functional gait analysis is one aspect of analyzing surgical success and looking at the wider scope available will allow a thorough understanding of the data presented.

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Appendix A Chapter 3 Supplementary Material

Appendix A.1 Fracture clinic layout image and diagrams of the hallway from both views of the clinic with measurements. Figure A.1.1 shows a picture of the hallway with setup 2, while Figures A.1.2 and A.1.3 show the hallway schematics with measurements, with camera locations for the Prime^{x}13 (green) and Prime^{x}13W cameras(orange)

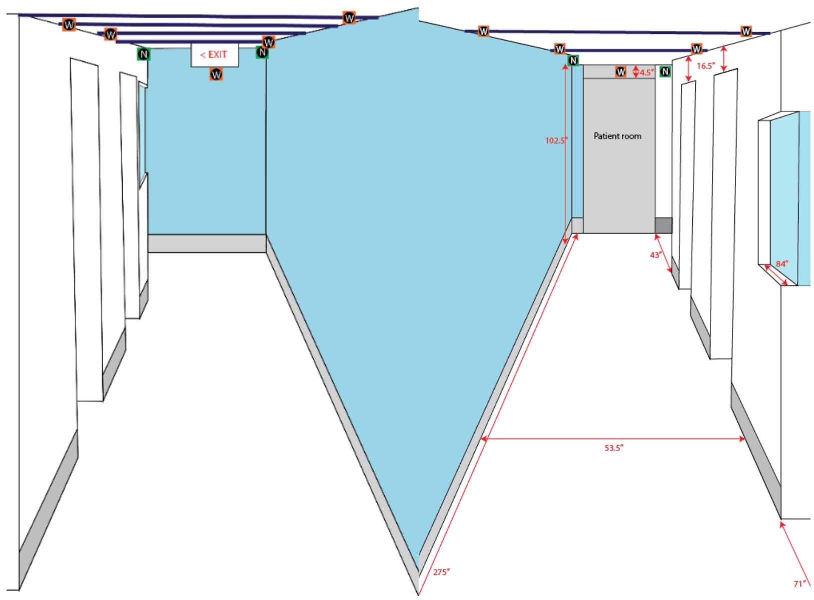


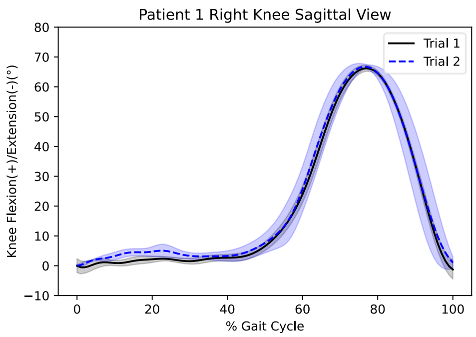
Fig A.1.1 Front view schematic   Fig A.1.2 Back view schematic

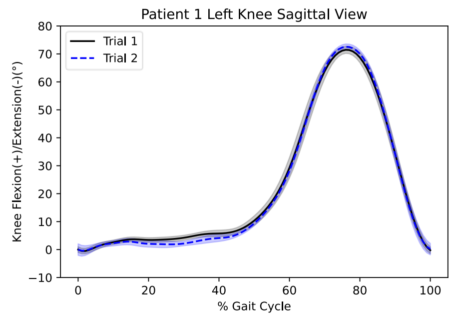
Appendix A.2: Anatomical marker locations for the marker-based motion capture system

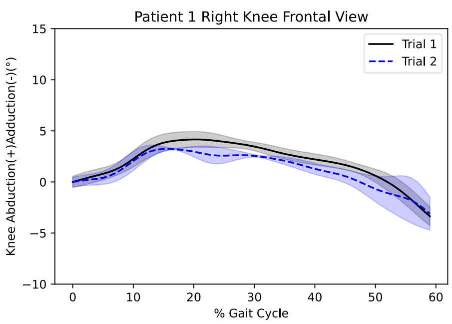
Anatomical Markers (n=24)	Acronyms
Pelvis	
Right and left iliac crest	RIC LIC
Right and left anterior superior iliac spine	RASIS LASIS
Thigh	
Right and left greater trochanter	RGT LGT
Right and left medial epicondyle	RME LME
Right and left lateral epicondyle	RLE LLE
Shank	
Right and left medial tibial plateau	RMTP LMTP
Right and left lateral tibial plateau	RLTP LLTP
Right and left medial malleoli	RMM LMM
Right and left lateral malleoli	RLM LLM
Foot	
Right and left head of the 1st metatarsal	RMH1 LMH1
Right and left head of the 5th metatarsal	RMH5 LMH5

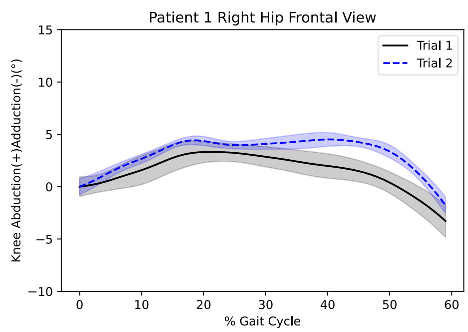
Appendix A.3: Participants 1-5 sagittal and frontal knee and hip gait waveforms. Plotted are the average waveforms for each participant along with the standard deviation from trials 1 and 2. This provides a visual comparison of similarity between data collected on the same participant during two different data collection times.

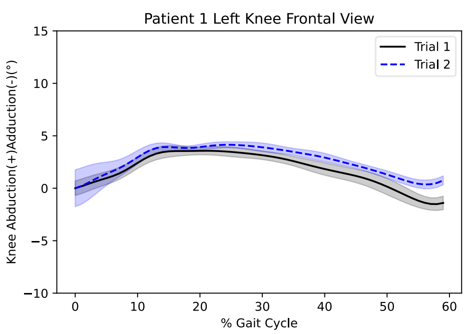
Participant 1

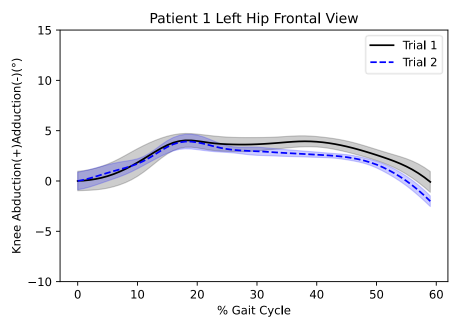


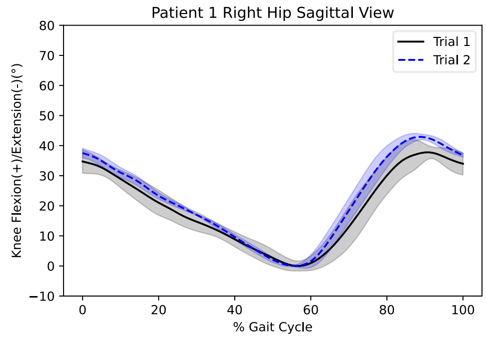


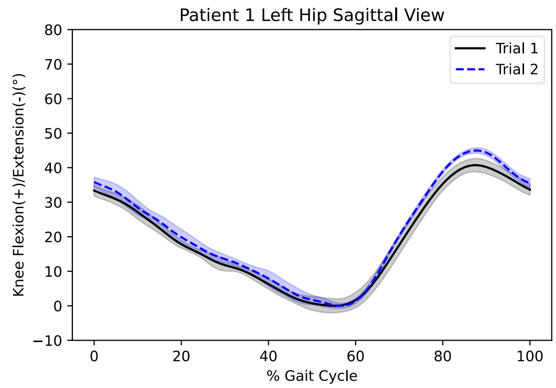




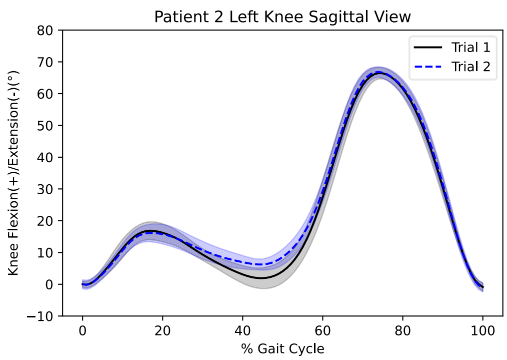


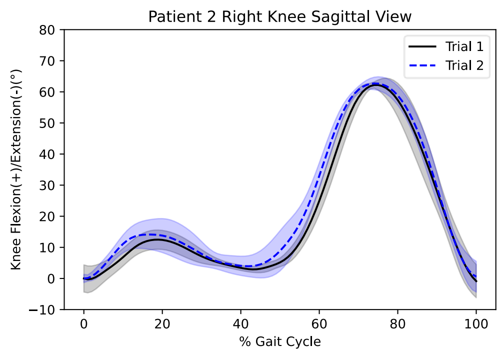


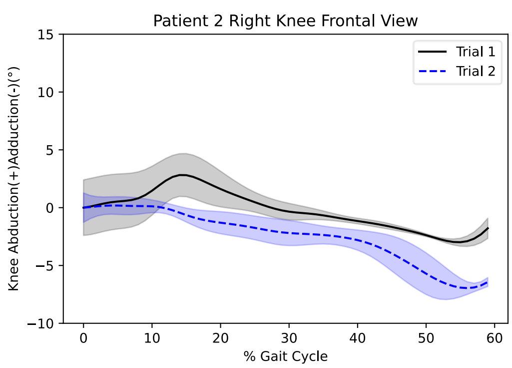


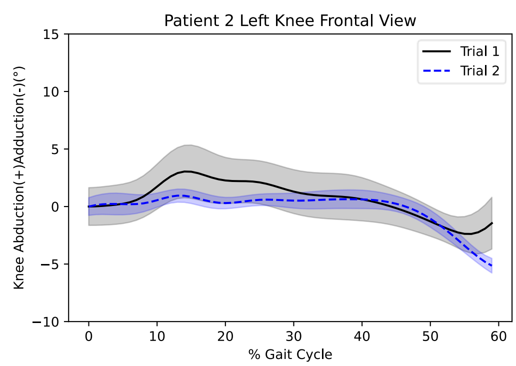


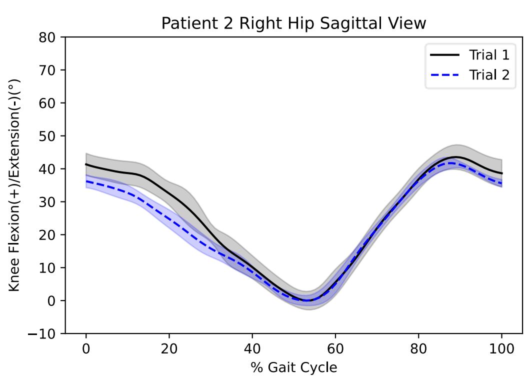
Participant 2

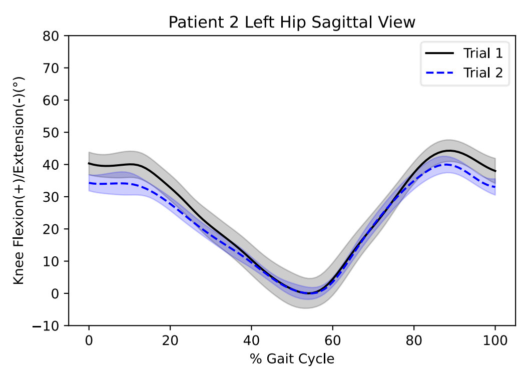


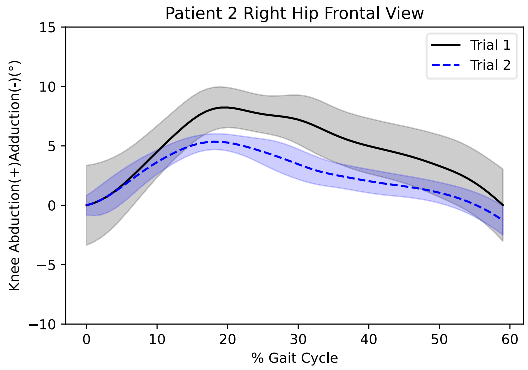


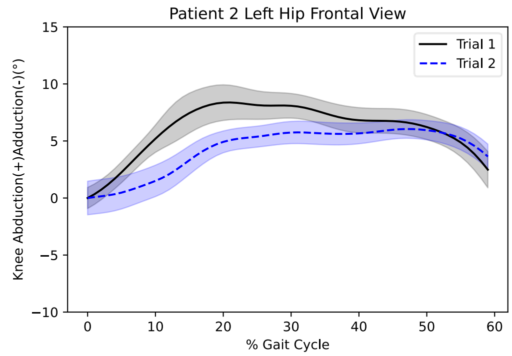




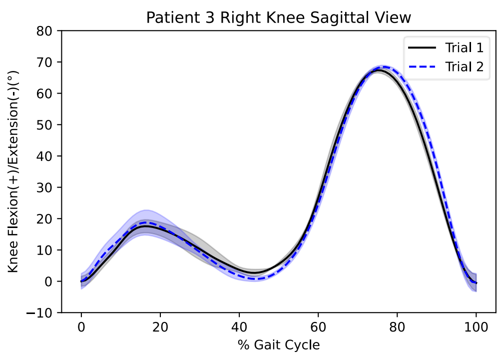


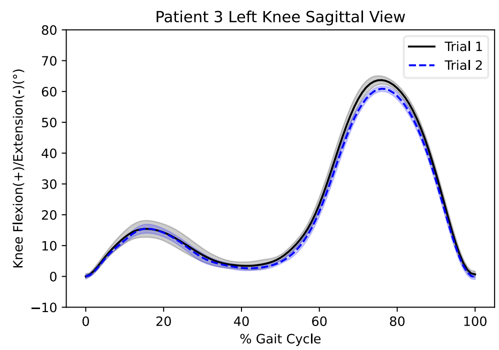


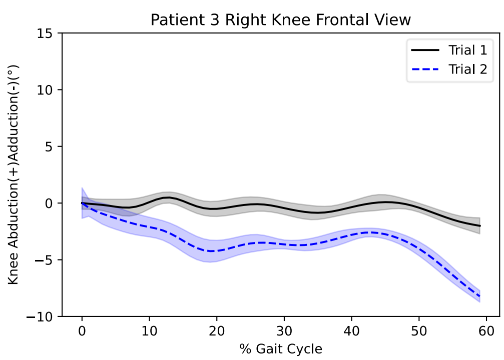


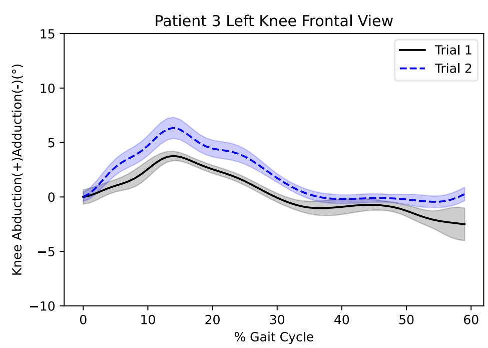


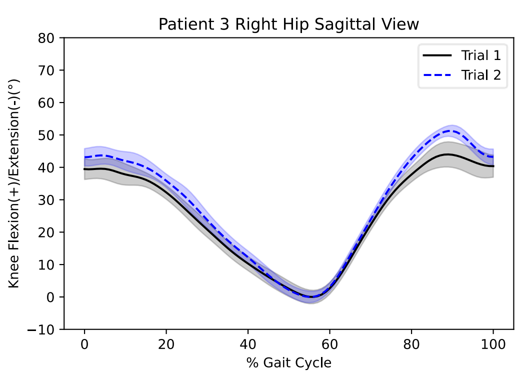
Participant 3

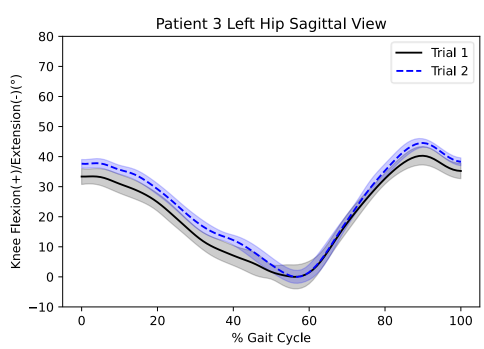


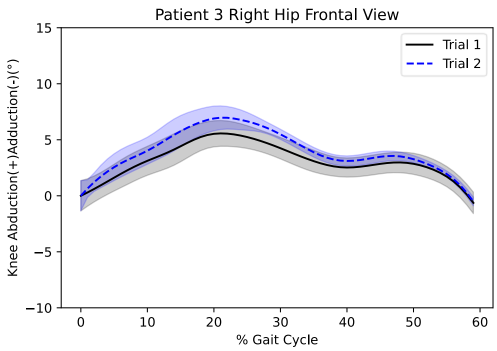


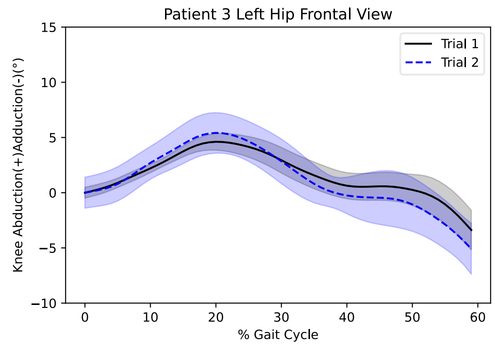




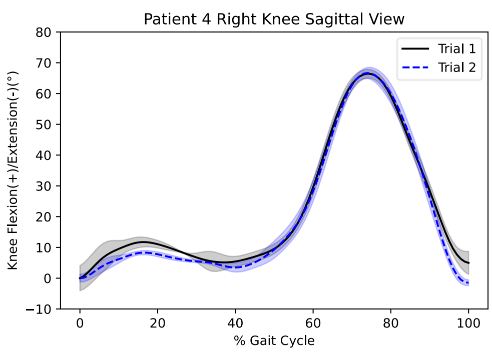


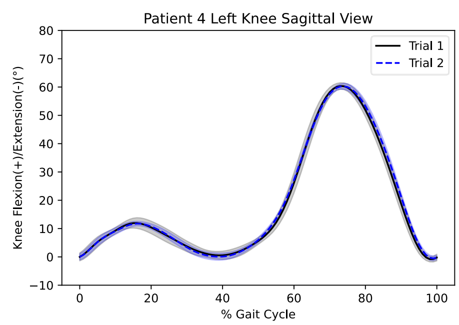


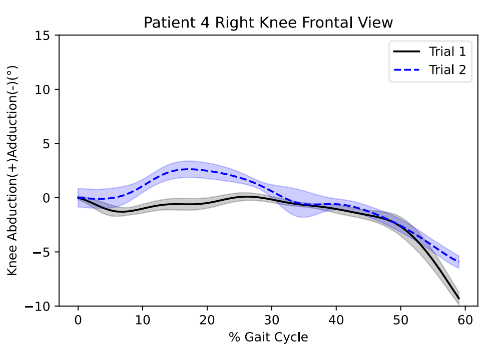


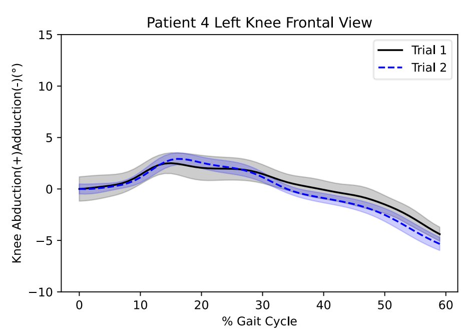


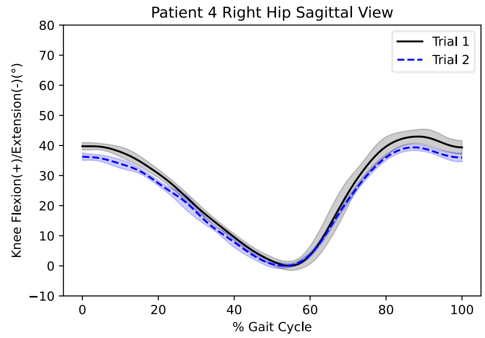
Participant 4

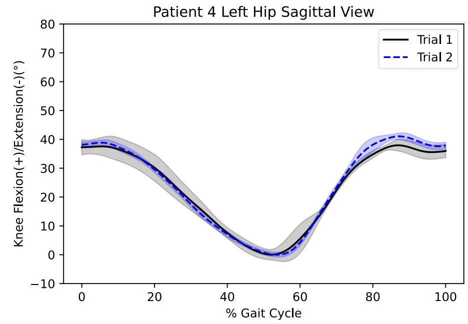


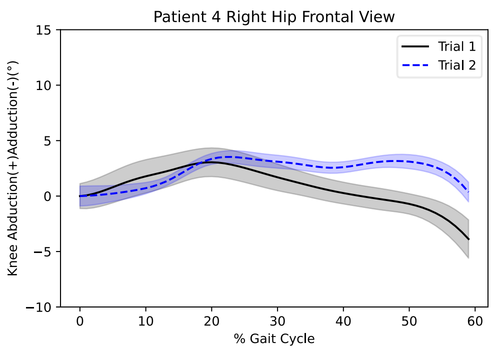


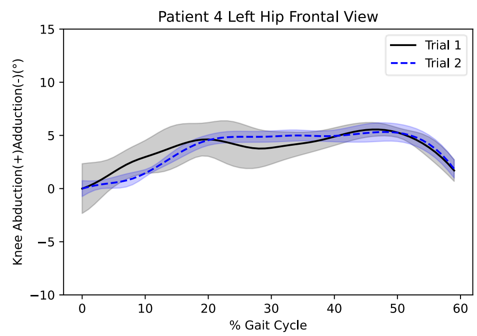




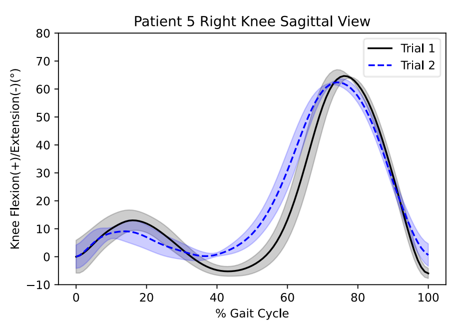


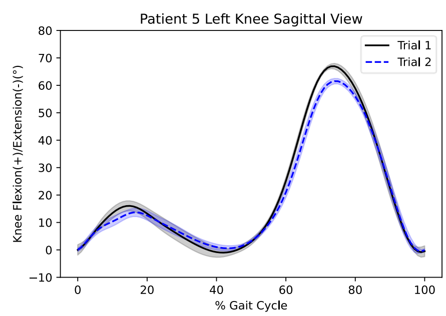


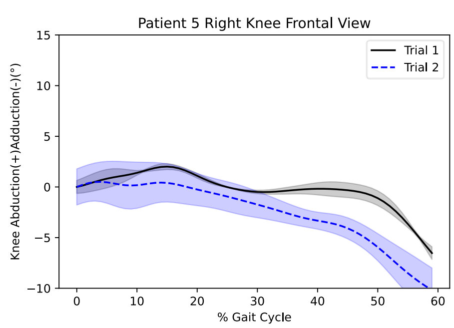


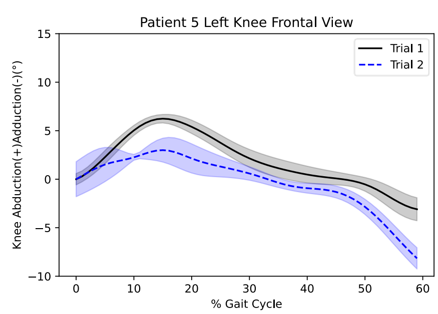


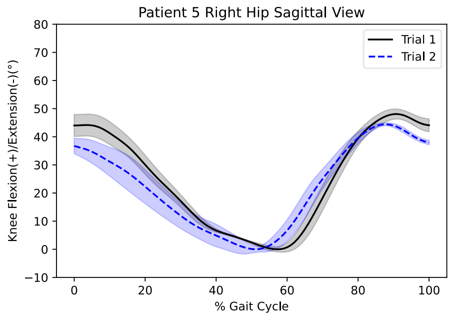
Participant 5

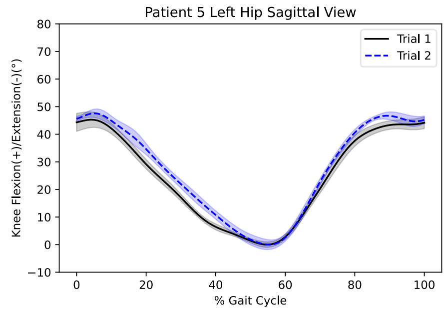


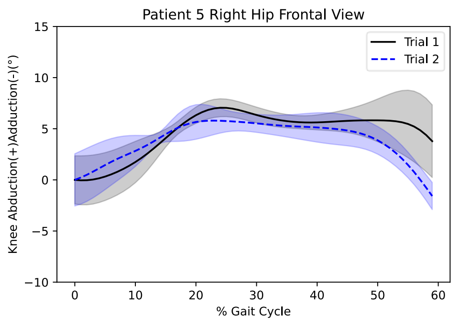


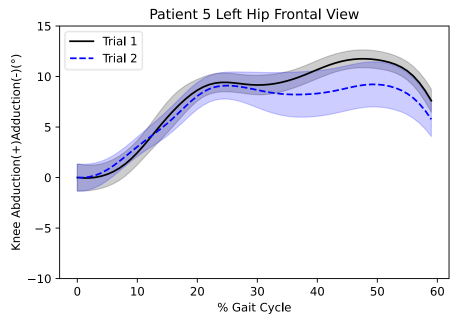












Appendix A.4 Gait waveforms associated with camera progression over time. Fig A.2.1-3 display the changes in the quality of data over time from setup 1,3 and 4 from the software Motive (Optitrack, NaturalPoint, Corvallis, OR USA). used to collect gait data. Some gaps are still present in the data at this point but can be interpolated and gap filled due to the small number of missing frames for continuous data. Small orange circles represent individually tracked markers.

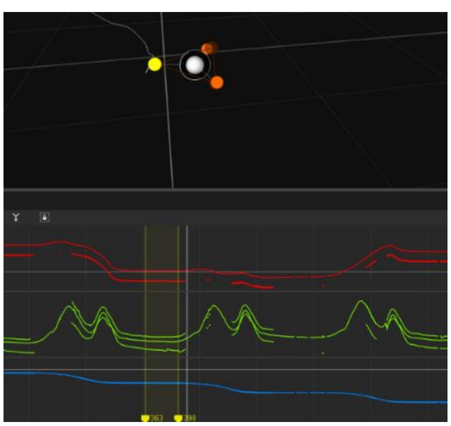


Figure A.2.1: Data Setup 1

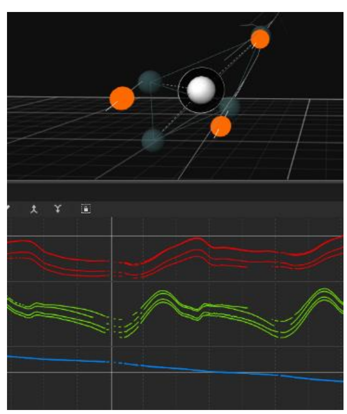


Figure A.2.2: Data Setup 3

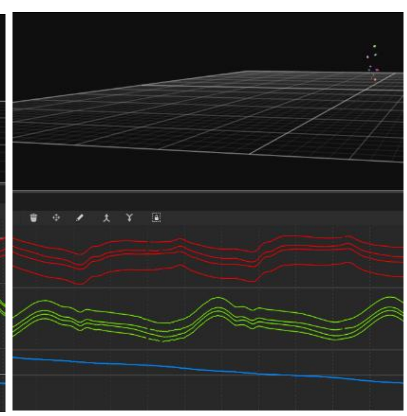


Figure A.2.3: Data Setup 4

Appendix A.5: Percent mean difference between study knee kinematic and those found in literature.

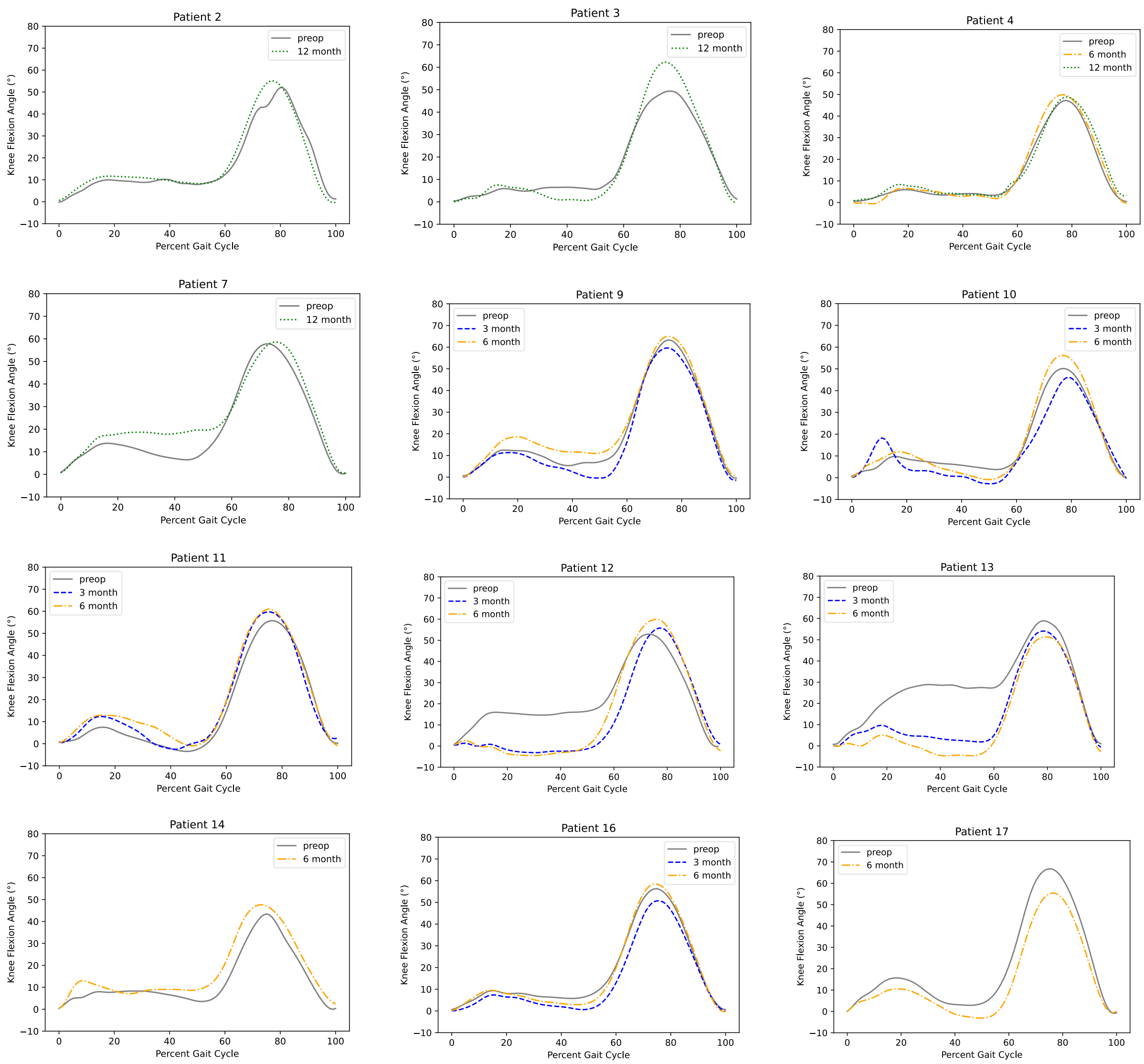
Variable	Literature ROM (°)[44]	Study ROM (°)	% Mean Difference
Flexion angle early/mid-stance maximum	13.0 12.4	10.8 8.9	9.2 16.4
Flexion angle mid/late stance minimum	5.4 5.0	1.6 1.7	33.3 38.9
Flexion angle swing	59.0 59.7	65.6 64.9	5.3 4.2
Flexion angle range	64.2 68.8	65.7 65.0	1.2 2.8

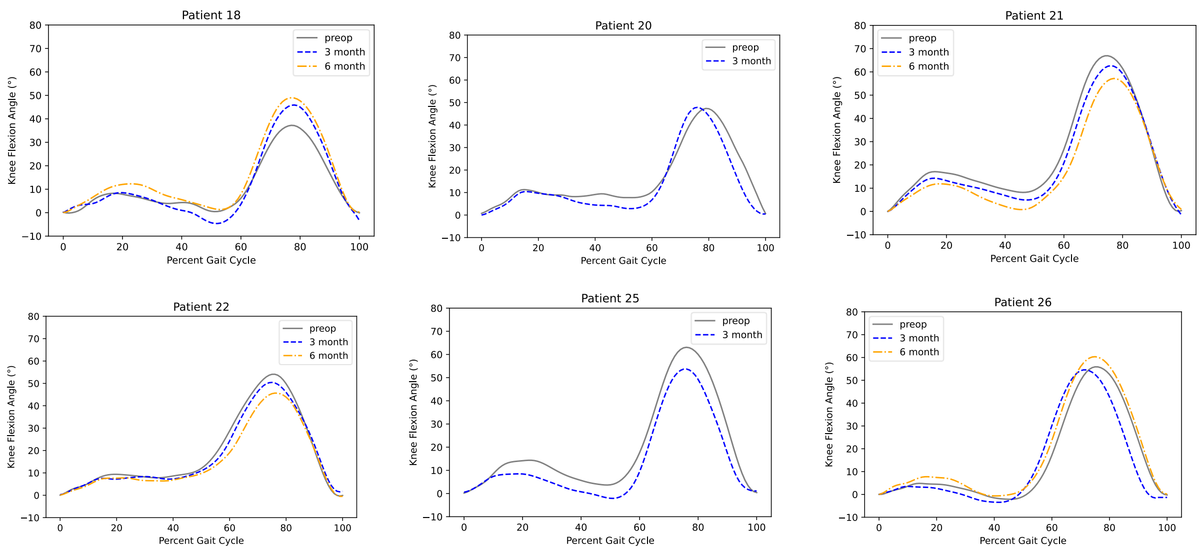
Appendix A.6: The calculation used for percent (%) mean difference, where value 1 represents a value from literature and value 2 is a number from the study.

$$\text{Percent difference} = \frac{|\text{value 1} - \text{value 2}|}{\frac{\text{value1} + \text{value 2}}{2}} * 100$$

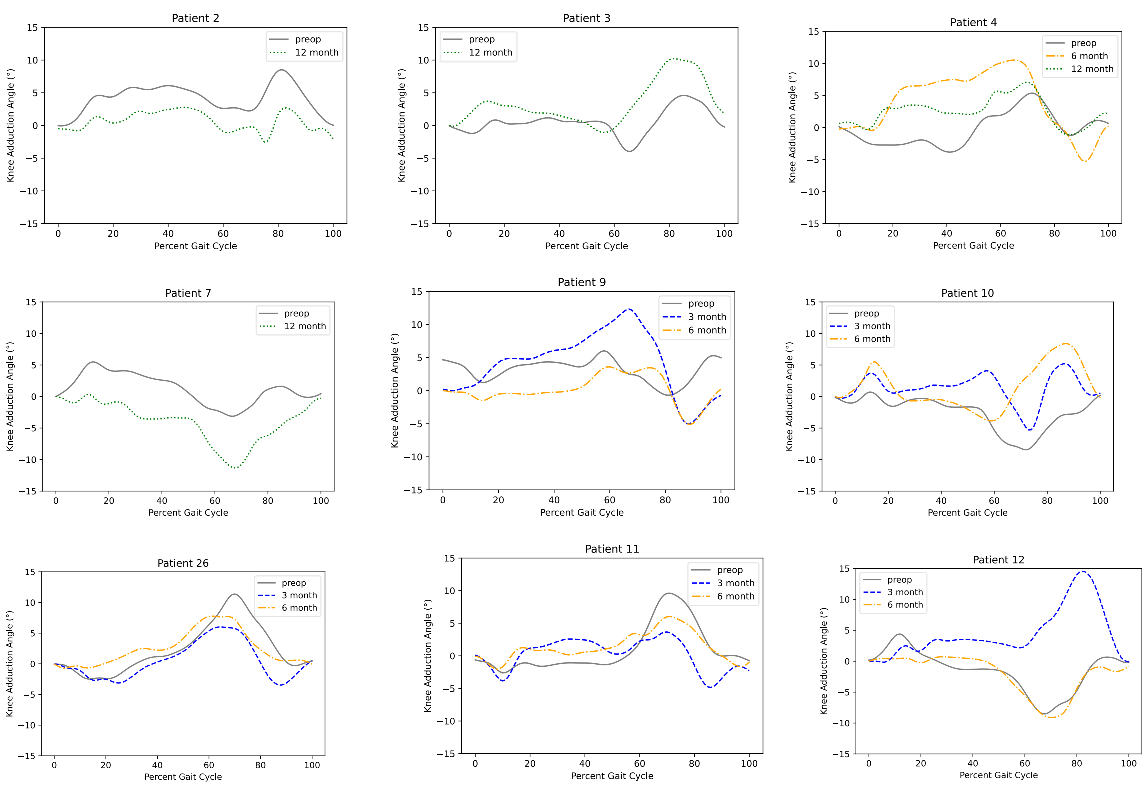
Appendix B Chapter 4 Supplementary Material

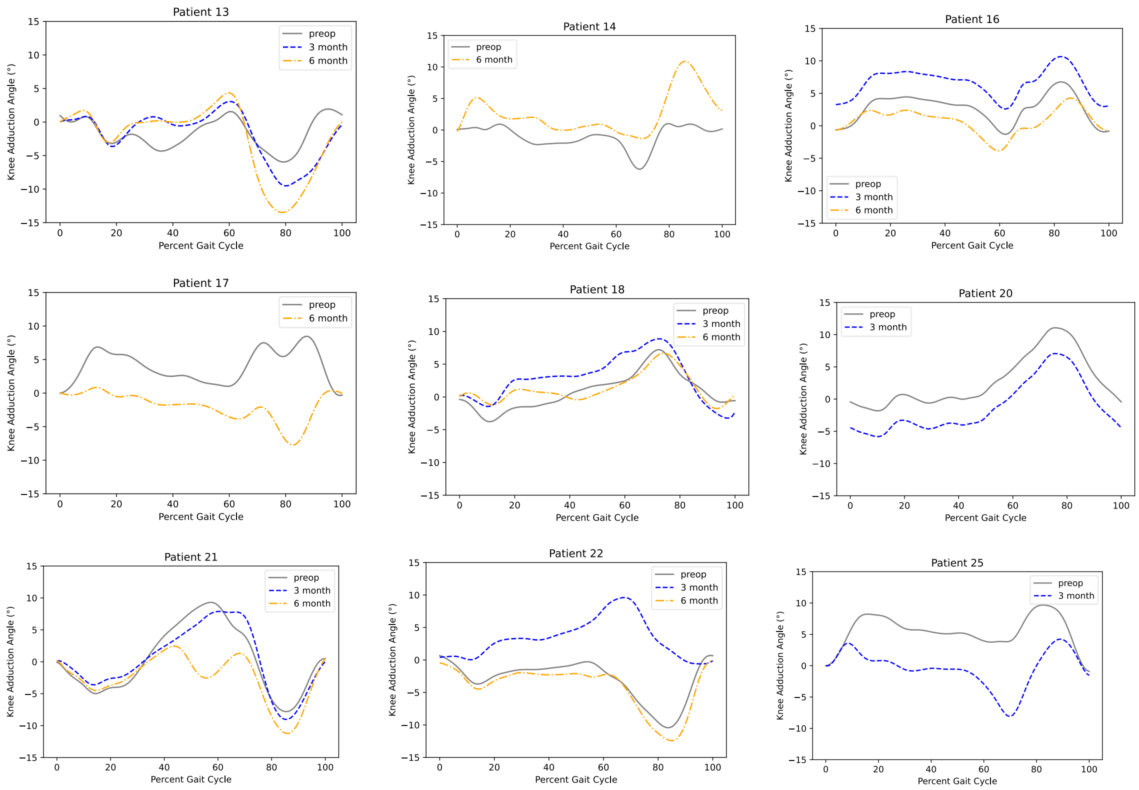
Appendix B.1 Sagittal Plane Knee Flexion/Extension Graphs for all patients enrolled in the RoboKnees study who participated in the gait analysis.





Appendix B.2 Frontal Plane Knee Adduction/Abduction Graphs for all patients enrolled in the RoboKnees study who participated in the gait analysis.

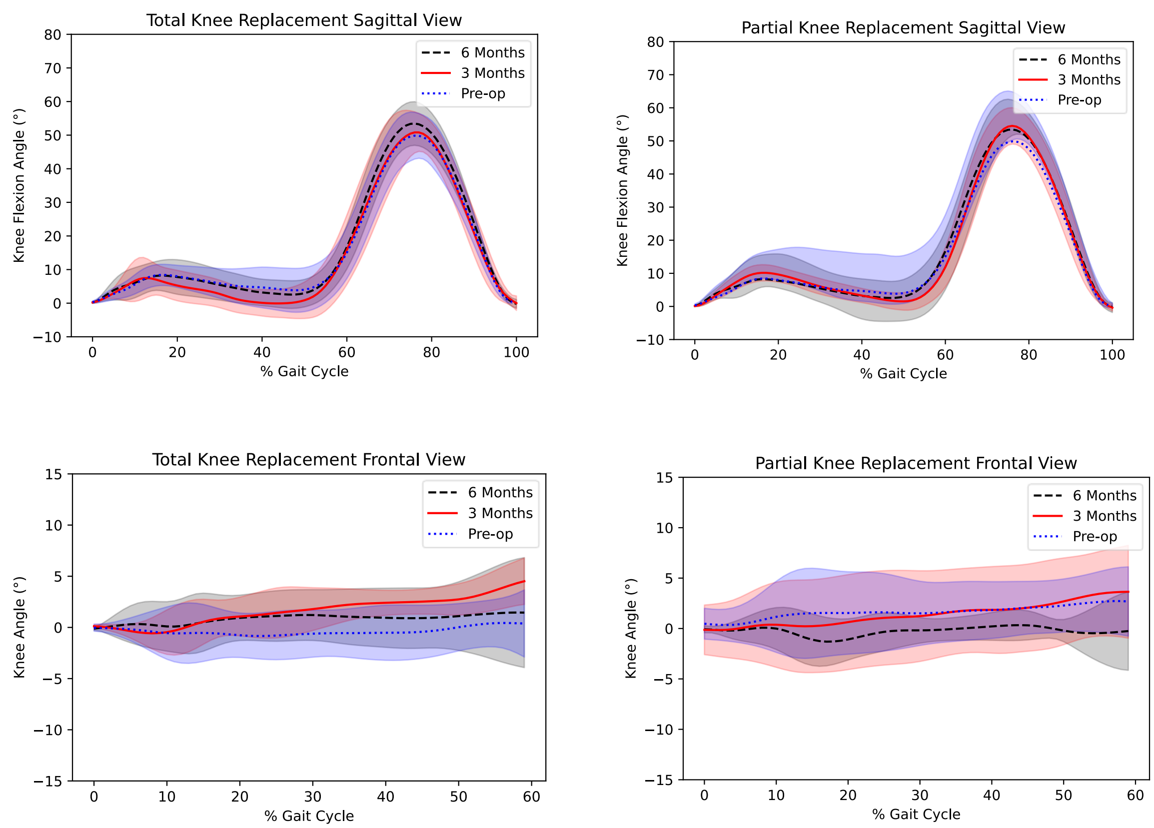




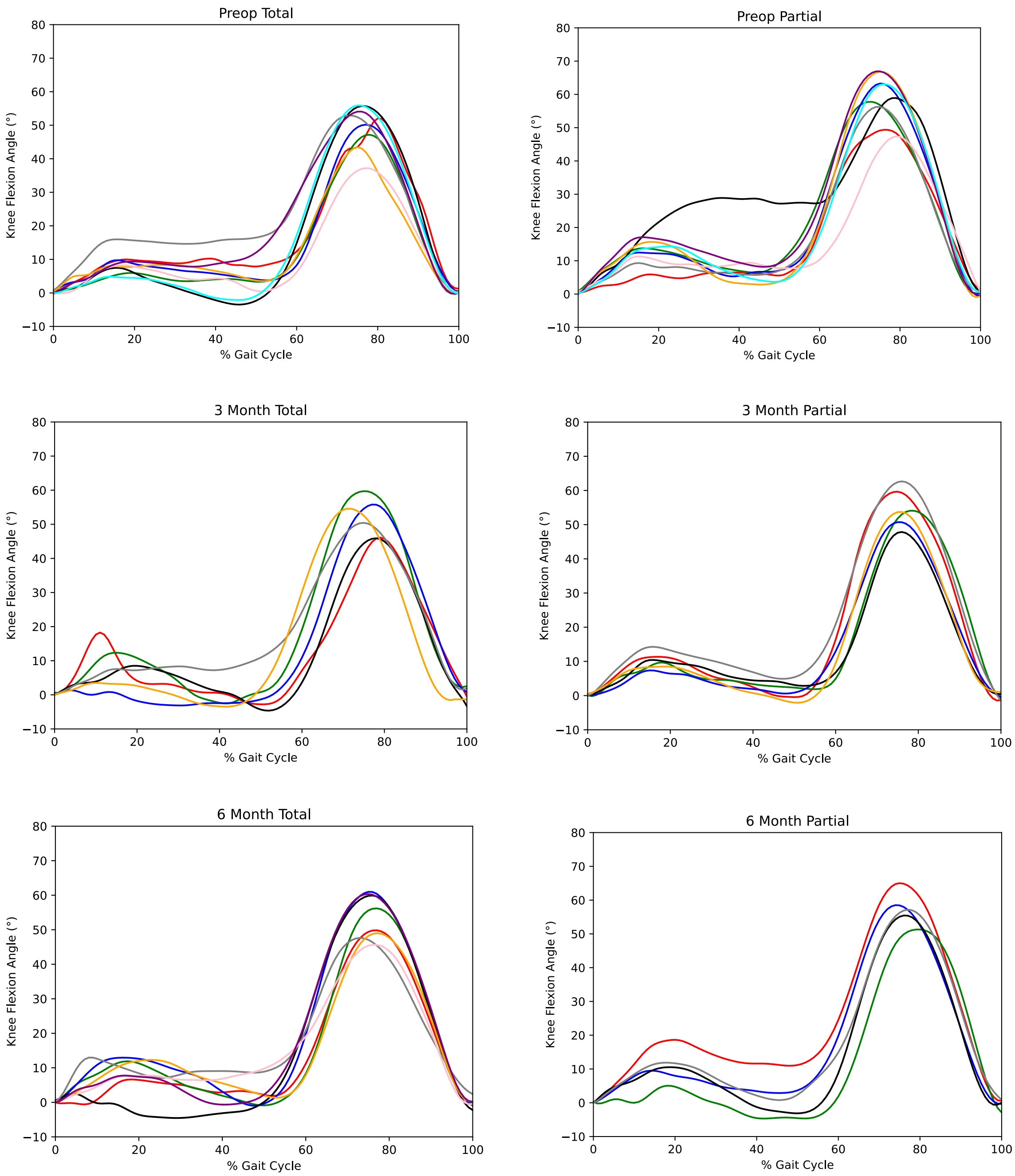
Appendix B.3 Single factor ANOVA on the anthropometric and demographic data for the sample population used to analyze postoperative data

(9 TKA,9 PKA)	Mean (± **SD**)	CI(+,-)	P value
Age(years)			
TKA	65.5(6.7)	(61.0,70.0)	
PKA	59.9(6.1)	(55.2,64.6)	
All		(59.7,66.2)	0.068
Weight (lbs)			
TKA	208.0(48.2)	(175.6,240.4)	
PKA	199.6(50.1)	(161.1,238,1)	
All		(181.8,226.6)	0.71
Height (inches)			
TKA	66.2(3.6)	(63.8,68.6)	
PKA	68.4(3.8)	(65.5,71.4)	
All		(65.4,70.0)	0.19
BMI(lbs/in^2)			
TKA	30.4(11.9)	(22.3,38.4)	
PKA	29.6(5.7)	(25.3,34.0)	
All		(25.6,34.4)	0.87

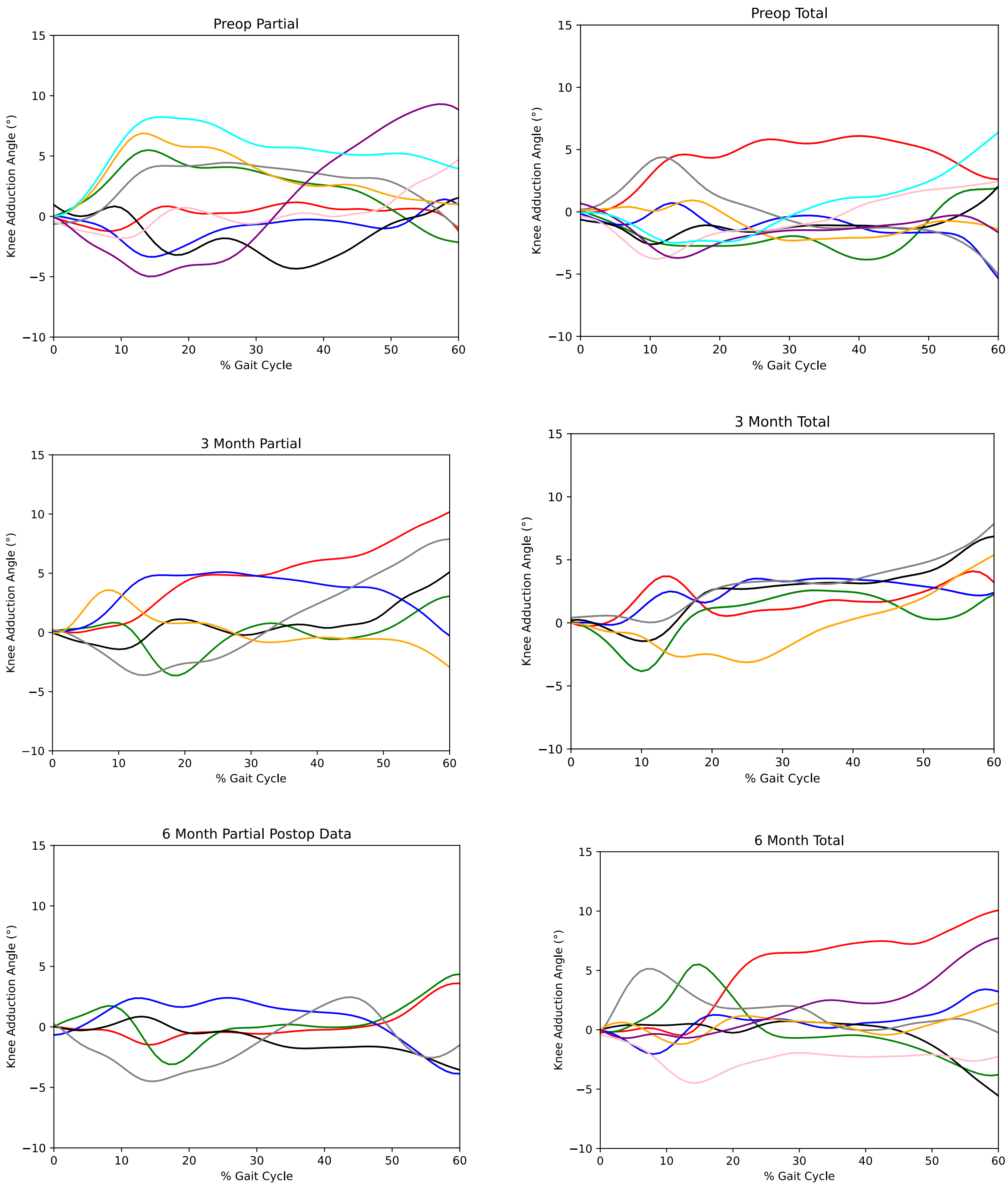
Appendix B.4 Sagittal Plane Knee Flexion/Extension Graph and Frontal Plane Knee Adduction/Abduction Graphs for all patients who received a TKA or PKA. Each graph displays the average patient gait waveforms and standard deviation during the preoperative, 3 month and 6 month follow up appointment.



Appendix B.5 Sagittal Plane Knee Flexion/Extension Graphs for all patients who received a TKA or PKA. Each graph displays the individual patient gait waveforms during the preoperative, 3 month and 6 month follow up appointment.



Appendix B.6 Frontal Plane Knee Adduction/Abduction Graphs for all patients who received a TKA or PKA. Each graph displays the individual patient gait waveforms during the preoperative, 3 month and 6 month follow up appointment.



Appendix B.7: Table of patient data collection using Setup 3 or Setup 4 from Objective 1.

	Preop	3M	6M	12M
TKA Group				
P2	3			3
P4	3		3	3
P10	3	3	4	
P11	3	3		
P12	3	4	4	
P14	3		4	
P18	3	3	4	
P22	3	4	4	
P26	3	4	4	
PKA Group				
P3	3			3
P7	3			3
P9	3	3	4	
P13	3	3	4	
P16	3	3	4	
P17	3		4	
P20	3	4		
P21	3	4	4	
P25	3	4		

*P refers to patient,3: Setup 3, 4: Setup 4

Appendix B.8 Summary of knee gait parameter mean values and standard deviation for TKA and PKA for all participants (n=26).

	Preop		3M		6M	
Frontal Plane	TKA	PKA	TKA	PKA	TKA	PKA
Peak Adduction Angle	2.6(2.1)	5.1(2.6)	4.9(1.9)	5.5(3.7)	4.2(3.5)	2.7(1.3)
ROM Stance	4.4(2.2)	6.6(3.2)	6.3(1.9)	7.1(3.0)	5.4(2.9)	4.7(2.6)
Sagittal Plane						
Stance Phase Peak	9.6(4.5)	14.2(5.9)	10.8(5.7)	10.3(2.4)	10.8(3.1)	11.1(4.9)
Max Swing	50.9(6.7)	58.3(6.8)	52.1(5.6)	54.8(5.5)	52.1(6.3)	57.5(5.0)
ROM during Stance	6.5(3.2)	7.7(3.3)	12.3(5.9)	9.0(1.9)	12.3(3.4)	9.8(2.8)
Late Stance ROM	47.8(9.7)	51.8(8.9)	53.6(7.2)	53.5(5.5)	53.6(9.9)	56.1(1.6)
Gait Cycle ROM	50.6(6.7)	57.9(7.0)	52.5(6.0)	54.7(5.6)	52.5(7.1)	57.5(4.9)